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Preface

The present subvolume VI/3c is the third part of volume VI/3 "Astronomy and Astrophysics". The first part, VI/3a, has been published in 1993 and the second part, VI/3b, three years later in 1996. Concerning the general concept I therefore refer to the preface of subvolume VI/3a. Volume VI/3 is an extension and supplement to the preceding volume VI/2. Therefore the following pages give again a synoptic list of contents for subvolumes VI/2c and VI/3c.

Unfortunately the publication of the present subvolume was delayed in the past for several reasons, especially, we had to wait quite a long time for some of the manuscripts. I therefore have to apologize to those authors who submitted their contributions in time, some of them already six years ago.

Contrary to volume VI/2 consisting of three subvolumes in total, the present subvolume, VI/3c, of volume VI/3 will be followed by a fourth subvolume, VI/3d, covering such topics as peculiar stars and chemical elements. In addition it will contain the comprehensive index for all the seven subvolumes of the VI/2 and VI/3 series on astronomy and astrophysics.

My thanks first of all are due to the authors of the various sections. They had to do the scientific work proper in collecting the data and bear the final responsibilty. They followed the suggestions of editor and publisher without grambling.

I also want to thank the editorial staff of Landolt-Börnstein, especially Frau G. Burfeindt and Dr. W. Finger who are responsible for the editing and preparation of the camera-ready pages of the present Landolt-Börnstein volumes on astronomy and astrophysics. Thanks are also due to Springer, being willing to follow our wishes as far as possible.

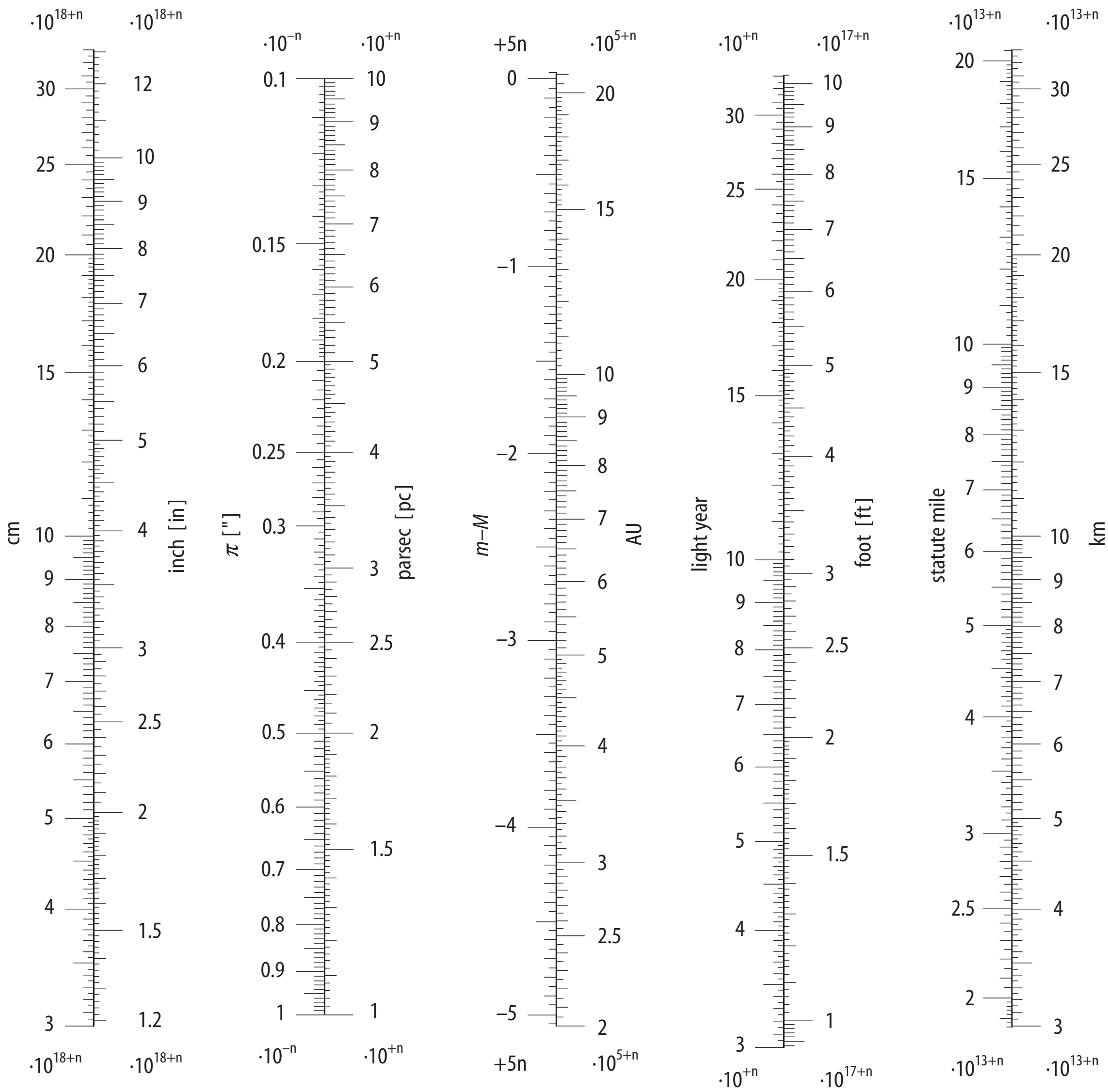
Göttingen, December 1998 **The Editor**

Logarithmic scales

Scale	Interval	Correspondence*)	
		interval	ratio
exp	exponential interval	n exp	e^n
dex	interval in powers of 10	n dex	10^n
dB	decibel: interval in 0.1 powers of 10	n dB	$10^{0.1n}$
mag	interval of magnitudes	n mag	$10^{-0.4n}$

*) Correspondence of logarithmic interval and ratio of intensity variable.
1.000 dex = 10.000 dB = 2.303 exp = – 2.5 mag

Conversion of distance scales



Nomogram • Conversion of distance scales

With this nomogram, distance data given in different units can be converted into each other. For this purpose we make use of the index line which is always put into horizontal position. Horizontal position is easily realized with the help of the outer scales at left (cm) and at right (km): since the two scales are identical (there is only a difference in the powers of 10 associated with them), the index line is in horizontal position if it crosses these two scales at points which do exactly correspond to each other.

When using the nomogram, always a suitable value — positive or negative integer — is to be taken for the number n which appears at top and at bottom of the scales.

Example: given the distance 3650 pc.
The numerical values for "parsecs" are on the right-hand side of the second (from left) double scale. We write $3650 = 3.650 \cdot 10^3$; the value $n = 3$, therefore, is to be used in all scales. We put the index line through the point 3.650 of the parsec-scale; with the help of the outermost scales (cm and km) it is made horizontal. Then we can read off:

$3.650 \cdot 10^3$ pc $= 1.124 \cdot 10^{22}$ cm $= 4.426 \cdot 10^{21}$ in $= 7.529 \cdot 10^8$ AU
$= 1.190 \cdot 10^4$ light years $= 3.688 \cdot 10^{20}$ ft
$= 6.985 \cdot 10^{16}$ statute miles $= 1.124 \cdot 10^{17}$ km.

Moreover, we find the parallax $\pi = 2''\!.74 \cdot 10^{-4}$ and the distance modulus $(m - M) = 12.811$.

Nomogram and text are taken from LB, NS Vol. VI/1 (H. Strassl)

7 Interstellar matter

7.1 Phenomena of the generally distributed medium

7.1.1 General references

List of LB Vol. VI/2c subsect. 7.1.1, p. 45, updated:

Allamandola, L.J., Tielens, A.G.G. (eds.): Interstellar Dust. IAU Symp. 135. Dordrecht: Kluwer (1989).
Bailey, M.E., Williams, D.A. (eds.): Dust in the Universe. Cambridge: Univ. Press (1988).
Beck, R., Kronberg, P.P., Wielebinski, R. (eds.): Galactic and Intergalactic Magnetic Fields. IAU Symp. 140. Dordrecht: Kluwer (1990).
Bohren, C.F., Huffman, D.R.: Absorption and Scattering of Light by Small Particles. New York: John Wiley & Sons (1983).
Bowyer, S., Leinert, C. (eds.): The Galactic and Extragalactic Background Radiation. IAU Symp 139. Dordrecht: Kluwer (1990).
Hollenbach, D.J., Thronson Jr., H.A. (eds.): Proceed. Symp. on Interstellar Processes. Astrophys. Space Sci. Libr. 134. Dordrecht: Reidel (1987).
Mathis, J.S.: Interstellar Dust and Extinction. Annu. Rev. Astron. Astrophys. **28** (1990) 37.
Tenorio-Tagle, G., Moles, M., Melnick, J. (eds.): Structure and Dynamics of the Interstellar Medium. IAU Coll. No. 120, Lect. Notes Physics 350. Berlin: Springer (1989).
Tielens, A.G.G.M., Snow, T.P. (eds.): The Diffuse Interstellar Bands. Dordrecht: Kluwer (1995).
Whittet, D.C.B.: Infrared Spectroscopy of Interstellar Dust, Quarterly J. Roy. Astron. Soc. **28** (1987) 303.

7.1.2 Interstellar extinction

7.1.2.0 Symbols

$A(\lambda)$	interstellar extinction in mag at wavelength λ
A(B), A(V)	interstellar extinction in mag for the blue (B; λ = 0.43 µm) and the visual (V; λ = 0.55 µm) wavelength of the UBV system, respectively
E_{B-V}	colour excess in mag, defined as the difference between the blue and visual extinction: A(B) – A(V)
R_V	ratio $A(V)/E_{B-V}$
λ_{max}	wavelength at which the maximum interstellar linear polarization occurs.

7.1.2.1 Mean values and fluctuations

See LB VI/2c subsect. 7.1.2.1, p. 45, however, contrary to the statement that at the galactic latitude $|b| \approx 90°$ the mean colour excess $\overline{E}_{B-V} \approx 0^m$ de Vaucouleurs and Buta [83D2] found that for objects outside the galactic absorbing layer the mean colour excess $\overline{E}_{B-V}(b)$ can be described for all latitudes by the relation

$$\overline{E}_{B-V}(b) = 0\overset{m}{.}05 \text{ cosec } |b|.$$

The interstellar extinction $A(B)$ at the galactic poles amounts to

$$A(\mathrm{B})|_{b-90°} = 0\overset{m}{.}200 \pm 0.018 \qquad [83D2].$$

7.1.2.2 Interstellar reddening law

Table 1. Wavelength dependence of the interstellar extinction, $A(\lambda)$, normalized to the extinction at the spectral region J ($\lambda \approx 1.25$ µm), A(J), for a line-of-sight through the diffuse low-density interstellar medium, ($R_V = 3.1$), and a line-of-sight penetrating interstellar clouds ($R_V = 5$) [90M1]. For $\lambda > 0.9$ µm, $A(\lambda)/A$(J) is the same for all lines-of-sight, to within present errors.

The entries for $\lambda > 15$ µm are uncertain by at least a factor of two. The 9.7-µm and 18-µm-feature profiles, as given by "astronomical silicate" [84D], have been added to a power-law interpolation of an underlying continuum fitted between 7 and 250 µm. The extinction law in the far-infrared spectral region should be extrapolated to longer wavelenths with a λ^{-2} dependence [90M1].

λ [µm]	λ^{-1} [µm^{-1}]	$A(\lambda)/A$(J) $R_V = 3.1$	$A(\lambda)/A$(J) $R_V = 5.0$	λ [µm]	λ^{-1} [µm^{-1}]	$A(\lambda)/A$(J)
0.002	500.0	1.35		1.25	0.800	**1.00**
0.004	250	3.39		1.65	0.606	0.624
0.023	43.5	7.31		2.2	0.455	0.382
0.041	24.4	9.15		3.4	0.294	0.182
0.073	13.7	19.1		5	0.200	0.095
0.091	11.0	17.2		7	0.143	0.070
0.12	8.33	12.71	5.32	9	0.111	0.157
0.13	7.69	11.09	4.89	9.7	0.103	0.208
0.15	6.67	9.44	4.57	10	0.100	0.192
0.18	5.56	8.93	4.66	12	0.0833	0.098
0.20	5.00	10.08	5.32	15	0.0667	0.053
0.218	4.59	11.29	6.03	18	0.0556	0.083
0.24	4.17	9.03	5.13	20	0.0500	0.075
0.26	3.85	7.63	4.59	25	0.0400	0.048
0.28	3.57	6.90	4.34	35	0.0286	0.013
0.33	3.03	5.87	4.12	60	0.0167	0.0071
0.365	2.74	5.53	4.07	100	0.0100	0.0041
0.44	2.27	4.70	3.67	250	0.0040	0.015
0.55	1.82	3.55	3.06			
0.7	1.43	2.66	2.43			
0.9	1.11	1.70	1.70			

For the transformation of $A(\lambda)/A(\mathrm{J})$ to $A(\lambda)/A(\mathrm{V})$ the mean value $\langle A(\mathrm{J})/A(\mathrm{V})\rangle = 0.282$ for $R_\mathrm{V} = 3.1$ and $\langle A(\mathrm{J})/A(\mathrm{V})\rangle = 0.327$ for $R_\mathrm{V} = 5.0$ can be used [89C].

The environment dependence of interstellar extinction curves is considered, e.g., by Jenniskens and Greenberg [93J].

Extinction bump at 2175 Å

A catalogue of equivalent widths of the 2175-Å-band is given by Friedemann [88F].

For the wavelength of the bump maximum observations give $\lambda_0 = (2174 \pm 9)$ Å with only a few stars having larger deviations from λ_0 [90M1]. The width of the band, however, shows significant variations [88C1]. The band strength is anticorrelated with R_V [88C2]. For an interpretation of the 2175-Å-feature see, e.g., [88D, 89D, 90M1, 90S, 94M, 96W1].

About dust-related spectral features superposed to the continuous interstellar extinction curve see subsect. 7.4.1.3a.

Very Broad-Band Structure, Extended Red Emission

Between about 4500 and 7800 Å the interstellar extintion curve shows a broad depression with the maximum at $\lambda \approx 5700$ Å [90D]. The depth of this *Very Broad-Band Structure*, a broad emission feature, seems not to exceed $0.1E_{\mathrm{B-V}}$ [86K]. Because of the shallowness the determination of the central wavelength as well as the profile is uncertain. About proposed theoretical interpretations of the feature see, e. g., [90D]. An *Extended Red Emission* band, usually between about 6000 and 8000 Å, is detected in reflection nebulae, planetary nebulae, HII regions, and the galactic cirrus [96W1]. For a possible theoretical interpretation see subsect. 7.4.1.3a.

7.1.2.3 Ratio of total to selective extinction

The ratio $R_\mathrm{V} = A(\mathrm{V})/E_{\mathrm{B-V}}$ depends upon the environment of the dust particles responsible for the interstellar extinction. In lines-of-sight penetrating only the diffuse low-density interstellar medium, having densities of up to several hundreds H atoms per cubic centimeter, usually a value of $R_\mathrm{V} \approx 3.1$ is observed. Lines-of-sight penetrating dense interstellar clouds have values in the range $4 < R_\mathrm{V} < 6$ with a typical mean value $R_\mathrm{V} = 5$, but a dense cloud is not necessarily connected with a high value of R_V [90M1].

The relation $R_\mathrm{V} = 5.5\lambda_{\max}$ given in LB VI/2c subsect. 7.1.2.3, p. 47, seems not to be valid for all lines of sight. Chini and Krügel [83C] found, e. g., for heavily reddened stars in M17 $R_\mathrm{V} = 8.5\lambda_{\max}$.

7.1.2.4 Extinction or reddening as a function of position (*l*, *b*) and distance *r*

Supplement to LB VI/2c subsect. 7.1.2.4, p. 47.

Author	Data	
Burstein, D., Heiles, C. [82B]	$0° \le l \le 360°$, $\lvert b\rvert > 10°$	Contour maps of relative reddening
Perry, C.L., Johnston, L. [82P]	3450 stars	Northern A, F stars, $r < 300$ pc, ubvyβ photometry; plots of interstellar dust distribution
Savage, B.D., et al. [85S]	1415 stars	Ultraviolet extinction at $\lambda \approx 1550$ Å, 1800 Å, 2200 Å, 3300 Å; extinction bump at ≈ 2175 Å

7.1.3 Interstellar polarization of starlight

7.1.3.1 Symbols and definitions

$A(\lambda)$	interstellar extinction in mag at wavelength λ
A(B), A(V)	interstellar extinction in mag for the blue (B; λ = 0.43 µm) and the visual (V; λ = 0.55 µm) wavelength of the UBV system, respectively
E_{B-V}, E_{U-K}	colour excess in mag, defined as the difference between the blue and visual extinction: A(B) – A(V), and the ultraviolet (U; λ = 0.350 µm) and the infrared (K; λ = 2.2 µm) extinction: A(U) – A(K), respectively
$P(\lambda)$	linear polarization at wavelength λ
λ_{max}	wavelength at which the maximum interstellar linear polarization occurs.

7.1.3.2 Degree and angle of linear polarization

Supplement to LB VI/2c subsect. 7.1.3.2, Table 3, p. 49.

Table 2. Catalogues of interstellar polarization.
n = number of stars

Author	Publication	n	Observed spectral region
Wilking, B.A., Lebofsky, M.J., Rieke, G.H.	Astron. J. **87** (1982) 695	13	J(1.25 µm), H(1.6 µm), K(2.2 µm)
Korhonen, T., Reiz, A.	Astron. Astrophys. Suppl. **64** (1986) 487	476	B(0.435 µm)
Nagata, T.	Astrophys. J. **348** (1990) L13	30	K(2.2 µm), L'(3.8 µm)

7.1.3.3 Wavelength dependence of linear polarization

The empirical relation for the wavelength dependence of linear polarization $P(\lambda)$, normalized to the maximum polarization $P_{max} = P(\lambda_{max})$, can be expressed in the wavelength range 0.30 µm < λ_{max} < 2.2 µm by the formula

$$P(\lambda)/P_{max} = \exp\{-K[\ln(\lambda_{max}/\lambda)]^2\}$$

with

$$K = -0.10 + 1.86\lambda_{max}$$

(λ_{max} in µm) [90M1]. Whittet et al. [92W2] revised the empirical relationship between K and λ_{max} to

$$K = (0.01 \pm 0.05) + (1.66 \pm 0.09)\lambda_{max}.$$

For wavelengths > 2.5 µm the absolute nonnormalized polarization $P(\lambda)$ follows a relation $P(\lambda) \sim \lambda^{\beta}$, with β typically in the range 1.6…2.0 [96W2]. For the polarization in the UV, especially at the 2175-Å-extinction bump, see [95D, 95M].

7.1.3.4 Interdependence of linear polarization and extinction

There is a relationship between the extinction law and the wavelength λ_{max} at which the maximum interstellar linear polarization occurs (cf. 7.1.3.3). Characterizing the extinction law by one of the various colour ratios, the relationship can be expressed, e. g., by

$$E_{U-K}/E_{B-V} = (3.03 \pm 0.48) + (3.42 \pm 0.7)\lambda_{max},$$

in a generalized form by

$$E_{i-K}/E_{j-k} = (C \pm \delta C) + (D \pm \delta D)\lambda_{max},$$

where i, j, and k represent the filters U, B, V, R, I, and J. The numerical values of the parameters C, δC, D, and δD are given by Clayton and Mathis [88C3].

For the ratio $P(\lambda_{max})$ to the interstellar extinction $A(\lambda_{max})$ at the wavelength λ_{max}, $P(\lambda_{max})/A(\lambda_{max})$, observations give ≤ 0.03 mag^{-1} [90M1].

7.1.4 Scattering of starlight by interstellar dust

See LB VI/2c subsect. 7.1.4, p. 52.

7.1.5 Interstellar absorption lines and bands in stellar spectra

A bibliographic compilation catalogue of papers providing data on interstellar absorption lines has been collected from the literature (up to 1988.5) by García [91G].

7.1.5.1 Lines of the spectral region 3000…9000 Å

Table 3. Visible and near-ultraviolet atomic and molecular interstellar lines and their equivalent widths W_λ in the spectrum of the star ζ Ophiuchi = HD 149 757 in addition to the lines listed in LB VI/2c subsect. 7.1.5.1, Table 9, p. 55.

New measurements of equivalent widths give values partly somewhat different to the data listed in LB VI/2c. Values separated by a fraction line are from different measurements. Uncertain values are marked with a colon.

Molecule	λ [Å]	Transition		W_λ [mÅ]	Ref.
Cr I	3578.687			0.25 ± 0.06	90M2
CN	3873.998	$B^2\Sigma^+ – X^2\Sigma^+$	(0,0)R(1)	2.504 ± 0.045	95R
	3579.963		(1,0)R(0)	0.67 ± 0.06	90M2
	3579.453		(1,0)R(1)	0.14 ± 0.06	
^{13}CN	4048.3	$B^2\Sigma^+ – X^2\Sigma^+$	(0,0)R(0)	0.19	88C4
$^{13}CH^+$	3958.127	$A^1\Pi – X^1\Sigma^+$	(1,0)R(0)	0.31 ± 0.06	87H
	3580.021		(3,0)R(0)	0.12 ± 0.06	90M2

Molecule	λ [Å]	Transition		W_λ [mÅ]	Ref.
NaH	3990.88	$A^1\Sigma^+–X^1\Sigma^+$	(8,0)R(0)	0.04	87C
C_2	8757.66	$A^1\Sigma_u{}^+–X^1\Sigma_g{}^+$	(2,0)R(0)	0.7	82H
	8753.92		(2,0)R(2)	1.6	
	8750.82		(2,0)R(6)	1.7	
	8753.56		(2,0)R(10)	0.4	
	8761.16		(2,0)Q(2)	1.2	
	8763.69		(2,0)Q(4)	1.5	
	8767.71		(2,0)Q(6)	1.4	
	8773.19		(2,0)Q(8)	1.9	
	8751.64		(2,0)R(4)	1.06	83D1
	8751.43		(2,0)R(8)	0.50	
	8780.13		(2,0)Q(10)	0.65	
	8788.53		(2,0)Q(12)	0.50	
	7719.327	$A^1\Pi_u–X^1\Sigma_g{}^+$	(3,0)R(0)	0.38	86V
	7716.528		(3,0)R(2)	0.25/0.33	
	7714.944		(3,0)R(4)	0.20/0.36	
	7714.574		(3,0)R(6)	0.15:/0.29	
	7715.415		(3,0)R(8)	0.14/0.20	
	7722.095		(3,0)Q(2)	0.56/0.60	
	7724.219		(3,0)Q(4)	0.50	
	7727.557		(3,0)Q(6)	0.48/0.53	
	7732.117		(3,0)Q(8)	0.25/0.31	
	7737.904		(3,0)Q(10)	0.15:/0.30	
	7731.663		(3,0)P(4)	0.21/0.23	
	7738.737		(3,0)P(6)	0.1:/0.15:	

7.1.5.2 Lines of the UV region λ < 3000 Å

Table 4. Far-ultraviolet interstellar atomic lines and their equivalent widths W_λ in the spectrum of the star ζ Ophiuchi = HD 149 757, in addition to the lines listed in LB VI/2c subsect. 7.1.5.2, Table 11, p. 57.

For λ vacuum wavelengths are quoted. New measurements of equivalent widths give values partly somewhat different to the data listed in LB VI/2c. Uncertain values are marked with a colon.

* First-excited fine-structure state
** Second-excited fine-structure state

Ion	λ [Å]	W_λ [mÅ]	Ref.	Ion	λ [Å]	W_λ [mÅ]	Ref.
B II	1362.461	1.78	93F	C I*	1270.408	0.85	93F
					1287.608	0.80	
C I	1121.452	9.2	79D		1656.266	31.0	86P
	1122.260	9.5			1657.370	31	
	1122.644	2.5			1657.890	36	
	1123.065	5.2					
	1560.310	60.2	86P	C I**	1274.109	1.70	93F
	1656.93	117.5			1658.110	11.2	86P

Ion	λ [Å]	W_λ [mÅ]	Ref.
C II]	2325.403	0.52	93C1
N I]	1159.817	7.56	91C
	1160.937	2.68	
N V	1238.821	1.0	96B
O I]	1355.598	7.36	91C
O I*	1304.858	5	86P
O I**	1306.029	4.5	96B
Na I	2853.649	7.49	91C
	2853.850	4.51	
Mg I	1707.061	5.63	91C
	1747.794	9.42	
	1827.940	16.0	86P
	2026.477	34.0	
Si II]	2335.123	0.48	94C
Si II*	1309.276	1.3	96B
S I	1241.905	0.90	95F
	1247.160	1.35	
	1262.860	2.15	93F
	1270.780	6.08	95F
	1295.653	16.99	
	1296.174	11.42	
	1303.430	4.08	
	1316.543	13.57	
	1401.514	9.87	
	1425.030	20.54	
	1425.188	14.46	
	1444.296	1.40	93F
	1472.971	12.88	
	1473.994	18.78	
	1474.379	11.85	
	1474.571	1.56	
	1401.514	9.87	95F
	1807.311	23.97	
P I	1230.356	2.2	96B
P II	1532.510	10	86P
P III	1334.866	9	86P
Ti II	1321.70	1.0	96B
	1882.478	4.8	86P
Cr II	2055.59	13	86D
	2056.248	12	86P
	2062.200	5	
	2066.120	9.3	
Mn II	2576.107	137	86P
Fe I	2483.271	16	92W1
Fe II	1081.875	31	83S
	1106.360	14:	
	1125.448	39	
	2249.179	19	92W1
	2260.080	50	88V
Co II	1466.203	0.49	93F
	2011.546	5.6	79S
Ni II	1317.220	15.5	86P
	1345.878	1.20	93F
	1449.997	0.36	
	1454.842	4.19	
	1467.259	0.68	
	1467.756	1.45	
	1709.600	5	86P
	1741.560	17.3	
Cu II	1367.971	0.42	93F
Zn II	2026.165	77	86P
	2062.675	73	
Ga II	1407.7	6.4	86P
	1414.402	3.79	91C
Ge II	1164.272	1.75	91C
	1237.059	9.59	
	1602.48	7	86P
As II	1263.77	0.68	93C2
Se II	1192.29	2.25	93C2
Kr I	1164.86	2.61	91C
	1235.83	3.40	
Sn II	1400.44	2.69	93C2

Table 5. Far-ultraviolet interstellar molecular lines and their equivalent widths W_λ in the spectrum of the star ζ Ophiuchi = HD 149 757, in addition to the lines listed in LB VI/2c subsect. 7.1.5.2, Table 12, p. 59.

For λ vacuum wavelengths are quoted. New measurements of equivalent widths give values partly somewhat different to the data listed in LB VI/2c.

Molecule	λ [Å]	Transition		W_λ [mÅ]	Ref.
H_2	1071.497	$B^1\Sigma_u^+ – X^1\Sigma_g^+$	(4,0)P(6)	5.0	76S
	1072.990		(4,0)R(7)	4.2	
	1274.537		(3,0)R(0)	0.34	95F
	1274.922		(3,0)R(1)	0.33	
C_2	2313.191	$D^1\Sigma_u^+ – X^1\Sigma_g^+$	(0,0)R(0)	3.2	78S
CO	1246.059	$A^1\Pi – X^1\Sigma^+$	(12,0)R(0)	2.90	82W
	1263.433		(11,0)R(0)	6.86	
	1447.355		(3,0)R(0)	66	92S
	1477.568		(2,0)R(0)	74	
	1509.750		(1,0)R(0)	86	
	1544.451		(0,0)R(0)	43	
	1366.213	$a'^3\Sigma^+ – X^1\Sigma^+$	(6,0)(17,0)	1.06	94F
	1419.533		(4,0)(14,0)	17.46	
	1480.789		(2,0)(11,0)	1.43	
	1366.439	$d^3\Delta_i – X^1\Sigma^+$	(6,0)(12,0)	1.82	
	1464.142		(2,0)(7,0)	0.94	
CO	1449.544	$e^3\Sigma^- – X^1\Sigma^+$	(3,0)(5,0)	2.36	
	1471.240		(2,0)(4,0)	0.60	
^{13}CO	1370.648	$A^1\Pi – X^1\Sigma^+$	(6,0)R(0)	1.4	92S
	1395.220		(5,0)R(0)	3.6	
	1421.340		(4,0)R(0)	6.3	
	1478.778		(2,0)R(0)	24	
H_20	1114.225	$\tilde{F} – \tilde{X}\ 1_{11}–0_{00}$		1.04	81S

A list of gas-phase abundances in the diffuse clouds toward ζ Ophiuchi from absorption-line observations is given by Savage and Sembach [96S].

7.1.5.3 Diffuse interstellar absorption bands

Symbols

W_λ	equivalent width
A_c	central depth relative to the continuum
$\Delta\lambda$	total width at half-depth

Table 6. Diffuse interstellar absorption bands observed in the spectrum of the star HD 183 142, updated version of LB VI/2c subsect. 7.1.5.3, Table 13, p. 60 [95H].

Uncertain numbers are marked with a colon.

λ [Å]	W_λ [mÅ]	A_C	$\Delta\lambda$ [Å]	λ [Å]	W_λ [mÅ]	A_C	$\Delta\lambda$ [Å]
4066:	350:	0.02	15	6234.1	20	0.03	0.9
4180:	700:	0.03	25	6269.73	222	0.110	1.9
4428	3400	0.15	18	6283.86	1945	0.318	4.5
4501.7	190	0.065	2.8	6307	220:	0.025:	9:
4726.4	175	0.054	3.4	6318	210:	0.025:	8:
4760	700:	0.03	25	6353.5	38	0.019	2.0
4762.7	160	0.047	3.1	6358.5	8	0.010	1.1
4779.9	67	0.038	1.7	6362.44	43	0.021	2.1
4882	890:	0.048	25:	6367.26	12	0.015	0.8
4963.8	24	0.032	0.8	6376.12	64	0.043	1.4
5359.3	55	0.015	3.5:	6379.20	123	0.104	1.1
5404.51	54	0.039	1.3	6396.9	61	0.026	2.3
5414.8:	40	0.009	4.8:	6412.6:	116:	0.014	8.8
5420.2:	35	0.012	3.2:	6413.90	17	0.013	1.3
5450.3	356	0.029	12.7	6425.41	25	0.022	1.2
5487.53	196	0.047	3.7	6439.49:	40	0.023	2.1
5494.06	40	0.045	0.8	6445.33	71	0.050	1.4
5508.0:	72:	0.040:	1.8:	6449.20	72:	0.031:	2.4:
5535	530	0.025:	23:	6494	130	0.019	7
5544.6	35	0.035	0.8	6533	1300:	0.6	21:
5705.12	290	0.075	3.5	6597.35	22	0.024	0.9
5762.72	7	0.010	0.8	6613.62	358	0.236	1.3
5766.05	39	0.027	1.2	6660.67	< 84	0.070	1.1
5772.49	31	0.023	1.3	6699.3	60	0.043	1.4
5775.94	12	0.015	0.8	6701.8	27	0.023	1.1
5778.3	950	0.6	17	6709.5	10	0.008	1.3
5780.45	801	0.32	2.2:	6741.8	55	0.20	
5793.08	18	0.016	2.2:	6767.59	10	0.10	
5795.3	62:	0.04	1.8:	6768.59	6	0.004:	
5796.98	238	0.20	1.1	6770.07	22	0.023	0.8
5809.13	34	0.025	1.4	6779.02	4	0.007	
5828.42	10	0.010	1.0	6780.46:	6:	0.007	
5843.6	118	0.025	4.8	6788.64	10	0.010	0.9
5844.8	16	0.018	0.9	6792.39	20	0.015	
5849.65	82	0.069	1.1	6795.20	16	0.012	
6004.9	48	0.018	2.8	6801.42	12	0.016	
6010.1	173	0.044	4.1	6803.28	6	0.012:	
6089.73	26	0.027	0.9	6809.31	4	0.007	
6113.16	31	0.025	1.2	6811.14	49	0.024	
6177	2390	0.066	29	6820:		0.006:	
6195.95	80	0.084	0.9	6821.56	14	0.010	
6203.06	325	0.121	1.8	6823.32	6	0.007	

λ [Å]	W_λ [mÅ]	A_C	$\Delta\lambda$ [Å]	λ [Å]	W_λ [mÅ]	A_C	$\Delta\lambda$ [Å]
6827.23	27	0.022		7405.5:	117:	0.009	15
6832.75	4	0.005		7429	560:	0.026	21:
6834.46	9	0.010		7559.20	54	0.031	1.8
6836.09:	2:	0.008		7562.0	140	0.052	2.7
6837.71	10	0.014		7569.7	73	0.014	5.5
6839.31:	2:	0.005:		7580.6:	60	0.020	3.1:
6841.64	11	0.014		7585.7	26	0.012	2.2
6843.47	44	0.033		7719.7	21	0.022	1.0
6845.31	7:	0.009:		7721.7	56	0.036	1.6
6846.56	6	0.010		7832.68	32	0.027	1.2
6847.58	6:	0.008:		7927	360	0.026	14
6852.50	16:	0.015		8026.16	50	0.038	1.3
6860.13	25	0.026		8037.7:	66:	0.024	2.9:
6862.47	10	0.012:		8040.8:	49:	0.020	2.3:
6887.05:	50:	0.041:	1.3:	8620.75	420	0.084	4.3
6919.15:	49	0.041	1.2	8649:	370?	0.028?	14:
6940	410:	0.023	18	8763.45	13	0.009:	
6993.07	182	0.135	1.2	9577	470:	0.1	4:
7224.01	368	0.211	1.6	9632	780:	0.1	4:
7334.5	52	0.038	1.5	11797.5	170	0.06	2.7
7357.45	53	0.030	1.7	13175	420	0.11	4.0
7367.0	67	0.044	1.5				

A bibliographic compilation catalogue of papers providing data on interstellar diffuse bands has been collected from the literature (up to 1988.5) by García [91G].

Identification of the interstellar diffuse bands

An extensive review and critique of hypotheses on possible carriers of the diffuse interstellar absorption bands is given, e.g., by Herbig [95H] and Snow [95S].

7.1.6 Radio line emission and absorption

21-cm-line emission of neutral hydrogen

A table of available (up to 1992) 21-cm emission surveys of the Milky Way is given by Burton [92B].

7.1.7 Continuous emission of interstellar origin

Symbols

ν frequency
λ wavelength
θ beam width

Table 7. Larger continuum surveys at ultraviolet or submillimetre wavelengths.

Author	λ [µm]	θ [']	Region
Winkler, C., et al. [84W]	0.356	60	$0° \le l \le 360°$ $-40° \le b \le 40°$
Hauser, M.G., et al. [84H]	150/250/300	10	$-5° \le l \le 62°$ $-3° \le b \le 3°$

A summary of high-resolution radio emission galactic continuum surveys prior to ≈ 1988 is given by Wielebinski [85W] and Kassim [88K].

Table 8. Larger radio continuum surveys in addition to [85W] and [88K].

Authors	Publication	ν [Mhz]	θ [']	Region
Handa, T., Sofue, Y., Nakai, N., Hirabayashi, H., Inoue, M.	Publ. Astron. Soc. Japan **39** (1987) 709	10050/10550	2.66	$-5° \le l \le 56°$ $-1.5° \le b \le 1.5°$
Condon, J.J., Broderick, J.J., Seielstad, G.A.	Astron. J. **97** (1989) 1064	4850	3.7×3.3	$0° \le \delta \le 75°$
Condon, J.J., Broderick, J.J., Seielstad, G.A.	Astron. J. **102** (1989) 2041	4850	7	$-40° \le \delta \le +5°$ $2^h \le \alpha \le 20^h$
Reich, W., Fürst, E., Reich, P., Reif, K.	Astron. Astrophys. Suppl. **85** (1990) 633	2700	4.4	$-2° \le l \le 76°$ $-5° \le b \le 5°$
Fürst, E, Reich, W., Reich, P., Reif, K.	Astron. Astrophys. Suppl. **85** (1990) 691	2700	4.4	$76° \le l \le 240°$ $-5° \le b \le 5°$
Duncan, A.R., Stewart, R.T., Haynes, R.F., Jones, K.L.	Publ. Astron. Soc. Austr. **12** (1995) 54	2400	9	$238° \le l \le 365°$ $\|b\| \le 5°$
Jonas, J.L., de Jager, G., Baart, E.E.	Astron. Astrophys. Suppl. **62** (1985) 105	2300	20	$-63° \le \delta \le -24°$ $12^h \le \alpha \le 22^h$

7.1.8 Interstellar radiation field

Symbols

R	galactocentric distance
$R_\odot$	galactocentric distance of the sun
r	stellar radius
$W = \dfrac{r^2}{4R^2}$	geometric dilution factor

The stellar contribution to the interstellar radiation field consists of four components [83M]:

(1) Ultraviolet emission from early-type stars, which dominates the interstellar radiation field between 0.09 and 0.25 µm.
(2) Emission due to disk stars, described by diluted blackbody radiation with T = 7500 K and a dilution factor $W = 1\cdot10^{-14}$,
(3) The same as (2), but T = 4000 K, $W = 1\cdot10^{-13}$.
(4) Emission due to red giants (or supergiants), described by blackbody radiation with T = 3000 K, $W = 4\cdot10^{-13}$.

Table 9. The interstellar radiation field between 0.09 and 8 µm at selected galactocentric distances R [83M].

λ	Average radiation intensity $4\pi J_\lambda(R)$ [10^{-2} erg cm^{-2} s^{-1} µm^{-1}]				
[µm]	R = 5 kpc	6 kpc	8 kpc	10 kpc	13 kpc
0.091	3.01	2.52	1.70	1.07	0.485
0.10	4.43	3.67	2.40	1.47	0.645
0.11	6.56	5.36	3.40	2.04	0.854
0.13	6.99	5.64	3.48	2.05	0.848
0.143	6.40	5.12	3.14	1.82	0.746
0.18	4.27	3.42	2.10	1.24	0.516
0.20	3.22	2.62	1.68	1.04	0.471
0.21	2.74	2.26	1.50	0.961	0.468
0.216	2.47	2.06	1.40	0.917	0.463
0.230	2.05	1.73	1.21	0.825	0.426
0.250	1.41	1.26	0.979	0.727	0.404
0.346	3.67	2.79	1.97	1.30	0.629
0.435	5.36	3.90	2.40	1.50	0.701
0.55	8.28	5.49	2.82	1.57	0.685
0.70	11.5	7.14	3.10	1.53	0.598
0.90	12.0	7.77	2.97	1.32	0.470
1.20	9.35	5.79	2.18	0.926	0.311
1.8	3.88	2.48	0.960	0.406	0.133
2.2	2.18	1.41	0.561	0.241	0.0802
2.4	1.62	1.06	0.431	0.189	0.0638
3.4	0.475	0.318	0.139	0.0649	0.0232
4.0	0.262	0.177	0.0796	0.0379	0.0139
5.0	0.120	0.0809	0.0367	0.0176	0.00648
6.0	0.0615	0.0417	0.0191	0.00921	0.00341
8.0	0.0213	0.0145	0.00665	0.00322	0.00119

Table 10. The interstellar radiation field between 8 and 1000 µm in the solar vicinity ($R_\odot$ = 10 kpc) [83M]. Average radiation intensity $4\pi J_\lambda(R_\odot)$.

λ [µm]	$4\pi J_\lambda(R_\odot)$ [10^{-5} erg cm^{-2} s^{-1} µm^{-1}]	λ [µm]	$4\pi J_\lambda(R_\odot)$ [10^{-5} erg cm^{-2} s^{-1} µm^{-1}]
8	4.33	80	4.20
10	3.26	90	3.62
12	2.21	100	3.16
20	0.713	150	1.36
25	1.14	200	0.561
30	1.70	300	0.139
40	3.06	400	0.0561
50	4.08	600	0.0132
60	4.76	800	0.00420
70	4.51	1000	0.00214

The interstellar radiation field between 8 and 1000 µm is dominated by reemitted radiation from dust grains [83M].

The integrated mean radiation intensity in the solar vicinity is according to [83M]:

$$\int_{0.09\mu m}^{8\mu m} 4\,\pi J_\lambda(R_\odot)\,d\lambda = 2.17\cdot 10^{-2}\ \mathrm{erg\ cm^{-2}\ s^{-1}},$$

$$\int_{8\mu m}^{1000\mu m} 4\,\pi J_\lambda(R_\odot)\,d\lambda = 5.0\cdot 10^{-3}\ \mathrm{erg\ cm^{-2}\ s^{-1}}.$$

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7.2 Cool interstellar clouds

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7.2.2 Dark nebulae and globules

Table 1. Catalogues of dark nebulae, in addition to LB VI/2c subsect. 7.2.2, Table 1, p. 67.
n = number of objects

Author	Publication	*n*	Data
Feitzinger, J.V., Stüwe, J.A.	Astron. Astrophys. Suppl. **58** (1984) 365 Astron. Astrophys. Suppl. **63** (1986) 203 (Corrigendum)	2622	dark nebulae, globules, position, size, opacity
Hartley, W., Manchester, R.N., Smith, R.M., Tritton, S.B., Goss, W.M.	Astron. Astrophys. Suppl. **63** (1986) 27	1101	dark clouds, southern sky, $\delta < -33°$, position, size, optical data
Clemens, D.P., Barvainis, R.	Astrophys. J. Suppl. **68** (1988) 257	248	molecular clouds position, optical and infrared data

Maps showing the distribution of the dark clouds and globules listed by Feitzinger and Stüwe are given in [86F].

7.2.3 Statistical description of interstellar cloud structure

Galactic cirrus

In addition to the types of interstellar clouds listed in LB VI/2c subsect. 7.2.3, Table 4, p. 70, IRAS observations at 100 µm and 60 µm show at high galactic latitudes so-called cirrus clouds. At $\lambda \approx$ 100 µm the cirrus clouds have a mean surface brightness, I(100 µm), of about 10^7 Jy sr^{-1} [84L]. The infrared emission is well correlated with the mean column density of H atoms, N_{HI}:

$$I(100\ \mu\mathrm{m}) = (1.4 \pm 0.3)\cdot 10^{-14} N_{\mathrm{HI}} \quad \mathrm{Jy\ sr}^{-1},$$

N_{HI} in atoms cm^{-2} [85B]. An all-sky map and a catalogue of 516 significant cirrus clouds are presented by Désert et al. [88D].

The bulk of the emission is provided by interstellar dust grains, radii > 100 Å, heated by absorbed galactic radiation with temperatures of about 25 to 30 K [91P]. Very small grains undergo transient heating to temperatures > 150 K, dominating the infrared emission up to about 60 µm.

At optical wavelengths the cirrus clouds are optically thin. The volume filling factor of the galactic cirrus is ≈ 0.2 [89V].

7.2.4 Molecular clouds

7.2.4.1 Survey of molecular line emission

Symbols

θ beam width
Δv spectral resolution

Table 2. In addition to LB VI/2c subsect. 7.2.4, Table 7, p. 85, surveys of CO line emission with observations spaced uniformly along the galactic equator.

Author	Transition	θ [']	Δv [km s^{-1}]	Region
Israel, F.P., et al. [84I]	J = 2–1	5.5	1.3/0.3	270° ≤ l ≤ 355° b = 0°
Knapp, G.R., et al. [85K]	J = 1–0	1.7	0.65/2.6	4° ≤ l ≤ 90° b ≈ 0°
Sanders, D.B., et al. [86S] Clemens, D.P., et al. [86C]	J = 1–0	0.75	1.0	8° ≤ l ≤ 90° – 1.05° ≤ b ≤ 1.05°
Dame, T.M., et al. [87D]	J = 1–0	8.7	1.3	0° ≤ l ≤ 360° b = 10'…30°
May, J., et al. [88M]	J = 1–0	30		210° ≤ l ≤ 270° – 5° ≤ b ≤ +5°
Bronfman, L., et al. [89B]	J = 1–0	8.8	1.3	300° ≤ l ≤ 340° – 2° ≤ b ≤ +2°
^{13}CO				
Liszt, H.S., et al. [81L]	J = 1–0	1.1	1.3	28° ≤ l ≤ 40° b = 0°
Stark, A.A., et al. [88S]	J = 1–0	1.7	0.68	– 5° ≤ l ≤ 122° – 1° ≤ b ≤ +1°
Jacq, T., et al. [88J]	J = 1–0	4.4	0.27	38° ≤ l ≤ 67.5° b = 0°

7.2.4.2 Physical properties of molecular clouds

There is no uniformity in nomenclature about the term "molecular cloud" due to the wide range of size scales over which molecular gas is found in the Milky Way. Table 3 gives representative characteristics of three major categories of molecular regions: giant molecular clouds (associated with high-mass star formation), dark clouds (sometimes associated with low-mass star formation), and circumstellar molecular clouds (associated with evolved stars) [87G].

Table 3. Physical properties of molecular regions in the interstellar medium [87G].
$\mathcal{M}_\odot$ = solar mass

		Giant molecular cloud	Dark cloud	Circumstellar cloud
Cloud complex	Size [pc]	20…80	6…20	
	Density [cm^{-3}]	100…300	100…1000	
	Mass [$\mathcal{M}_\odot$]	$8 \cdot 10^4 \ldots 2 \cdot 10^6$	$10^3 \ldots 10^4$	
	Linewidth [km/s]	6…15	1…3	
	Temperature [K]	7…15	≈ 10	
	Examples	W51, M17, W3	Taurus, Sco-Oph	
Cloud	Size [pc]	3…20	0.2…4	≈ 0.2
	Density [cm^{-3}]	$10^3 \ldots 10^4$	$10^2 \ldots 10^4$	$10^2 \ldots 10^7$
	Mass [$\mathcal{M}_\odot$]	$10^3 \ldots 10^5$	5…500	$\approx 10^{-2}$
	Linewidth [km/s]	4…12	0.5…1.5	20…40
	Temperature [K]	15…40	8…15	10…100
	Examples	Orion OMC1, W33, W3 A	B227, B335 (ISO), B5, B18 (Compl)	IRC+10216
Core	Size [pc]	0.5…3	0.1…0.4	
	Density [cm^{-3}]	$10^4 \ldots 10^6$	$10^4 \ldots 10^5$	
	Mass [$\mathcal{M}_\odot$]	$10 \ldots 10^3$	0.3…10	
	Linewidth [km/s]	1…3	0.2…0.4	
	Temperature [K]	30…100	≈ 10	
	Examples	Orion (Ridge)	B335, L1535	
Clump	Size [pc]	< 0.5		
	Density [cm^{-3}]	$> 10^6$		
	Mass [$\mathcal{M}_\odot$]	$30 \ldots 10^3$		
	Linewidth [km/s]	4…15		
	Temperature [K]	30…200		
	Examples	M17 (Kleinmann-Wright), Orion (Hot Core), W3(OH)		

Scoville and Sanders [87S] found a distribution of the number N of giant molecular clouds with diameter $D > 10$ pc as $N(D) \sim D^{-2.32}$, and with the mass $\mathcal{M}$ as $N(\mathcal{M}) \sim \mathcal{M}^{-1.61}$.

7.2.4.3 Chemical properties of molecular clouds

Table 4. Observed interstellar and circumstellar molecules as of December 1995 [97M], arranged according to the number N of atoms in the molecule.

Molecule		Molecule		Molecule		Molecule	
***N* = 2**							
H_2	[2]) [3])	SO	[3])	SiO	[3])	SiC	[1])
OH	[2]) [3])	SO^+		SiS		SiN	[1])

Molecule	Molecule	Molecule	Molecule
***N* = 2** (continued)			
NH [2]	CH^+ [2] [3]	CS [2] [3]	KCl [1]
NO	CH [2] [3]	C_2 [2]	AlF [1]
NS	CN [2] [3]	CP [1]	
HC	CO [2] [3]	NaCl [1]	
PN	CO^+	AlCl [1]	
***N* = 3**			
H_2O [3]	NH_2	HCS^+	N_2O
H_2S	N_2H^+ [3]	C_2H [3]	NaCN [1]
SO_2	HCO	C_2S	MgNC [1]
HNO	HCO^+ [3]	C_2O	MgCN [1]
HCN [3]	HOC^+	c-SiC_2 [1]	
HNC [3]	OCS	C_3 [1]	
***N* = 4**			
NH_3 [3]	H_2CN	c-C_3H	C_2H_2
H_3O^+	HNCO [3]	l-C_3H	$HOCO^+$
H_2CO [3]	HNCS	C_3S	$HCNH^+$
H_2CS	C_3N	C_3O	HCCN [1]
***N* = 5**			
HC_3N [3]	NH_2CN	H_2CCC	SiH_4 [1]
C_4H	HOCHO	CH_4	SiC_4 [1]
CH_2NH	c-C_3H_2 [3]	HCCNC	C_5 [1]
CH_2CO	CH_2CN	HNCCC	
***N* = 6**			
CH_3OH [3]	CH_3SH	C_5O (?)	HC_3NH^+
CH_3CN [3]	NH_2CHO	C_5H	C_2H_4 [1]
CH_3NC	HC_2CHO	H_2CCCC	
***N* = 7**			***N* = 8**
HC_5N	CH_3NH_2	CH_2CHCN	CH_3OCHO
CH_3CCH [3]	CH_3CHO	C_6H	CH_3C_3N
***N* = 9**	***N* = 10**	***N* = 11**	***N* = 13**
HC_7N	CH_3C_5N	HC_9N	$HC_{11}N$
CH_3OCH_3	CH_3COCH_3		
CH_3CH_2OH			
CH_3CH_2CN			
CH_3C_4H			

[1]) Purely circumstellar molecules
[2]) Molecules identified in diffuse molecular clouds with visual extinction $A_V \le 1$ mag [93W]
[3]) Molecules identified outside the Galaxy [93M]

Table 5. Molecular abundances for several interstellar regions [87I].

All values are beam-averages. The H_2 column densities are obtained from CO column densities and with the assumption of a CO abundance of $8 \cdot 10^{-5}$ with respect to H_2.

Region:	Orion Ridge		TMC-1		Sgr B2	
Assumed H_2 column density:	$10 \cdot 10^{22}$		$1 \cdot 10^{22}$		$20 \cdot 10^{22}$	
CO	8000	[1])	8000	[1])	8000	[1])
CH_4	< 80					
C	> 1000					
C_2			5			
OH			30			
CH			2			
C_2H	1		5…10		> 0.5	
C_3H			0.05			
C_4H	< 0.03		2			
C_3H_2			2		0.1	
CH_3C_2H	0.5		0.6		0.4	
CN	0.5		3		2	
HCl	≈ 1					
HCN	2		2		2	
HNC	0.04		2		0.3	
$HCNH^+$					0.1	
CH_3CN	0.04/0.08	[2])	0.1		0.07	
HC_3N	0.04		0.6		0.2	
HC_5N	0.006		0.3		0.04	
CH_2CHCN			0.02		0.02	
C_3N	< 0.006		0.1		< 0.02	
C_3O	< 0.003		0.01		< 0.002	
CH_3C_3N			0.05			
CH_3C_4H			0.2			
HNCO	< 0.03		0.02		0.9	
N_2H^+	0.02		0.05			
NH_3	20		2		1…10	
HCO^+	0.3		0.8		1	
$HOCO^+$	< 0.02				0.3	
HDO	< 0.04/0.4	[2])				
CH_3OH	/40	[2])	0.4		20	
H_2CO	3/30	[2])	2		2…10	
H_2C_2O	/0.2	[2])	0.01		0.08	
CH_3OCH_3	/2	[2])			0.25	
$HCOOCH_3$	/2	[2])	< 0.1		0.2	
CS	0.4		1		1	
CHS^+	0.02		0.06		0.02	
H_2CS	/0.2	[2])			0.3	
H_2S	< 0.1					
OCS	/0.9	[2])	0.2		1	

Region:	Orion Ridge	TMC-1	Sgr B2
Assumed H_2 column density:	$10 \cdot 10^{22}$	$1 \cdot 10^{22}$	$20 \cdot 10^{22}$
SO	0.2/0.5 [2]	0.5	0.2
SO_2	/0.4 [2]	< 0.1	0.3…2
SiO	< 0.1	< 0.0005	0.04
SiS	< 0.001		0.03
HC_7N		0.1	
HC_9N		0.03	
$HC_{11}N$		0.01	
HOC^+	< 0.001	< 0.002	0.003
HCO	< 0.02		
CH_3CHO	< 0.02	0.06	0.1
HC_2CHO		< 0.06	
CH_2CHCHO	< 0.02		
CH_3CH_2OH	< 0.05		0.3
HCOOH	/0.03 [2]		≈ 0.2
CH_3COOH	< 0.5		
CH_3NC	< 0.005	< 0.01	
CH_3CH_2CN	< 0.03	< 0.1	0.03
NH_2CN	< 0.02	< 0.01	0.01
NH_2CHO	< 0.03	< 0.2	0.04
CH_3SH	< 0.06		0.08
HNCS			0.01
$(NH_2)_2CO$	< 0.07		
NH_2CH_2COOH	< 0.05	< 0.04	
C_4H_4O	< 0.07		
C_4H_5N	< 0.03	< 0.04	
$C_3N_2H_4$	< 0.1	< 0.03	
CH_3NH_2	< 0.1		
PN	< 0.003		
PO	< 0.1		
NO	< 5		≈ 10

[1]) Adopted values
[2]) Orion ridge values given as x/y refer to the extended and the compact ridge, respectively.

Table 6. Mean isotope ratios from observations of interstellar molecular clouds in comparison with the isotope ratios in the solar system [80W].

	Molecular clouds	Solar system
$C/^{13}C$	60	89
$O/^{15}O$	500	500
$^{15}O/^{17}O$	5.5	5.5
$N/^{15}N$	333	272
$S/^{34}S$	20.3	23

For the $C/^{13}C$ ratio of the diffuse interstellar gas Jura [87J] gives a mean value of 43 ± 4.

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7.3 HII regions

7.3.1 General references

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7.3.2 Catalogues, surveys, statistical data

LB VI/2c subsect. 7.3.2, Table 2, p. 88, updated.

Survey of hydrogen recombination line observations of HII regions.

Author	Region of the Milky Way	λ [cm]	Lines
Lockman [89L]	$350° \le l \le 358°$ $2° \le l \le 255°$ $b \approx 0°$	≈ 3	H85α or H87α, H88α partly H100α, H101α, or H110α or H125α, H127α

7.3.3 Classification

Ultracompact HII regions

In addition to the classes of HII regions listed in LB VI/2c subsect. 7.3.3, p. 91, high-resolution observations suggest the existence of ultracompact HII regions, i.e. small, photoionized nebulae with diameters ≤ 0.1 pc, electron densities $> 10^4\ \mathrm{cm}^{-3}$, and emission measures $\ge 10^7\ \mathrm{pc\ cm}^{-6}$ [89W]. A description of 75 ultracompact HII regions is given by Wood and Churchwell [89W].

7.3.4 Individual HII regions

7.3.4.1 Properties of selected objects

See LB VI/2c, subsect. 7.3.4.1, p. 91.

7.3.4.2 Infrared brightness distribution

See LB VI/2c, subsect. 7.3.4.2, p. 96.

7.3.4.3 Spectrum of HII regions

The compilation of physical data for the Orion nebula by Goudis [82G], derived from radio recombination lines and radio continuum measurements, can be used as a supplement to LB VI/2c subsect. 7.3.4.3, Table 9, p. 101.

Table 1. Emission lines observed in the Orion nebula in the wavelength region from 3100 Å to 10950 Å [92O], in addition to the lines listed in LB VI/2c subsect. 7.3.4.3, Table 7, p. 97 to 99.
I = relative observed intensity with *I*(Hß) = 100.

λ [Å]	Element	Transition	*I*
4738.11	C II		
4744.90	C II		0.0446
4985.9	[Fe III]	$a^5D_4–a^3H_6$	
4987.3	[Fe III]	$a^5D_3–a^3H_4$	0.0339
5146.06	O I		0.0312
5158.81	[Fe II]	$a^4F_{9/2}–a^4H_{13/2}$	0.0874
5261.61	[Fe II]	$a^4F_{7/2}–a^4H_{11/2}$	0.0540
5299.0	O I		0.0294
5333.65	[Fe II]	$a^4F_{5/2}–a^4H_{9/2}$	0.0217
5412.0	[Fe III]	$a^5D_1–a^3P_2$	0.0346
7298.05	He I	$3^3S–9^3P$	0.0414
7377.83	[Ni II]		0.112
7411.61	[Ni II]		0.0265
7442.28	N I		0.0360
7468.29	N I		0.0548
7499.82	He I	$3^3S–8^3P$	0.0598
7889.9	[Ni III]		0.0469
8094.06	He I	$3^1S–10^1P$	0.0234
8242.34	N I		0.0519
8518.04	He I	$3^1S–8^1P$	0.0220
8528.99	He I	$3^1D–15^1F$	0.0271
8531.48	He I	$3^3D–15^3F$	
8578.70	[Cl II]		0.170
8616.96	[Fe II]	$a^4F_{9/2}–a^4P_{5/2}$	0.0665
8648.26	He I	$3^3D–13^3F$	0.0322
8650.81	He I	$3^1D–13^1F$	
8680.24	N I		0.0634
8683.38	N I		
8733.43	He I	$3^3D–12^3F$	0.0335
8736.04	He I	$3^1D–12^1F$	
8750.48	H	P_{12}	1.18
8776.77	He I	$3^3P–9^3D$	0.0515
8845.38	He I	$3^3D–11^3F$	0.104
8848.05	He I	$3^1D–11^1F$	
8862.79	H	P_{11}	1.52
8891.88	[Fe II]	$a^4F_{7/2}–a^4P_{3/2}$	0.0129
8914.74	He I	$3^1S–7^1P$	0.0346
8996.99	He I	$3^3D–10^3F$	0.0477

λ [Å]	Element	Transition	*I*
8999.75	He I	$3^1D–10^1F$	
9014.91	H	P_{10}	1.49
9068.9	[S III]		38.0
9111.03	He I	$3^1P–10^1S$	0.0249
9123.60	[Cl II]		0.0454
9174.55	He I	$3^3P–8^3S$	0.0346
9210.28	He I	$3^3D–9^3F$	0.0416
9213.24	He I	$3^1D–9^1F$	
9463.57	He I	$3^3S–5^3P$	0.432
9603.50	He I	$3^1S–6^1P$	0.0579
9702.66	He I	$3^3P–7^3S$	0.0433
9824.11	[C I]		0.0115
9850.24	[C I]		0.870
10027.73	He I	$3^3D–7^3F$	0.156
10031.16	He I	$3^1D–7^1F$	
10286.66	[S II]		0.225
10311.27	He I	$3^3P–6^3D$	0.0640
10320.42	[S II]		0.280
10336.33	[S II]		0.232
10370.5	[S II]		0.0806
10830.17	He I	$2^3S–2^3P$	45.9
10912.92	He I	$3^3D–6^3F$	0.292
10916.98	He I	$3^1D–6^1F$	

Emission lines of supernova remnants

A catalogue of ultraviolet, optical, and near-infrared emission lines within the wavelength range 900 to 12000 Å identified in Galactic and Magellanic Cloud supernova remnants was compiled by Fesen and Hurford [96F].

Table 2. Far-infrared and infrared atomic lines and lines of light molecules observed in emission within or on the periphery of molecular clouds, in addition to the lines listed in LB VI/2c subsect. 7.3.4.3, Table 8, p. 100.

Species	Transition	λ [μm]	Ref.
[C I]	$2p^2$: $^3P_1–^3P_0$	609.133	91W
	$2p^2$: $^3P_2–^3P_1$	370.414	
[C II]	$2p^2$: $^2P_{3/2}–^2P_{1/2}$	157.7	91W
[O I	$2p^4$: $^3P_0–^3P_1$	145.526	84W
[N II]	$2p^2$: $^3P_1–^3P_0$	205.2	94B1
	$2p^2$: $^3P_2–^3P_1$	121.9	
[Si II]	$^2P_{3/2}–^2P_{1/2}$	34.816	91H
[S I]	$^3P_1–^3P_2$	25.245	91H

Species	Transition	λ [µm]	Ref.
[Ne III]	$2p^4$:$^3P_0$–$^3P_1$	36.04	86S
	:$^3P_1$–$^3P_2$	15.55	84E
[Ar II]	$^2P_{3/2}$–$^2P_{1/2}$	6.99	82H
[Fe II]	$a^6D_{9/2}$–$a^4D_{7/2}$	1.2567	94B2
	$a^6D_{1/2}$–$a^4D_{1/2}$	1.2703	
	$a^6D_{5/2}$–$a^4D_{5/2}$	1.2941	
	$a^6D_{3/2}$–$a^4D_{5/2}$	1.3278	
[Fe III]	^3H–^3G(4–3)	2.1457	94D
	^3H–^3G(6–5)	2.2184	
	^3H–^3G(4–4)	2.2427	
	^3H–^3G(5–5)	2.3485	
He I	4S–3P	2.1132	94D
	7^3P–4^3D	2.1853	
H	Bß	2.626	82D
	Bγ	2.166	82G
H_2	(1–0) S(5)	1.836	86D
	Q(4)	2.436	
	Q(5)	2.455	
	Q(6)	2.476	
	Q(7)	2.500	
	O(2)	2.627	
	O(3)	2.803	
	O(5)	3.235	
	O(7)	3.81	86G
	(2–0) S(7)	1.064	84M
	(2–1) S(3)	2.0729	94D
	S(2)	2.1536	
	S(1)	2.2471	
	S(0)	2.3550	
	(3–2) S(3)	2.2008	
	S(1)	2.3858	
OH	$^2\Pi_{1/2}(J = 3/2–1/2)$	163	87P
	$^2\Pi_{1/2}(J = 5/2–3/2)$	119	
	$2\Pi_{1/2}(J = 7/2–5/2)$	85	
CH	$^2\Pi_{1/2}(J = 3/2–1/2)$	149	87P
HCl	$J = 1–0$	479	87P
CO	$J = 3–2$	867.2	87P
	$J = 4–3$	650.4	
	$J = 5–4$	519.8	91W
	$J = 6–5$	433.7	87P
	$J = 7–6$	371.6	

Species	Transition	λ [µm]	Ref.
CO (continued)	J = 14–13	186.0	93S
	J = 16–15	162.8	87P
	J = 17–16	153.3	
	J = 21–20	124.194	
	J = 22–21	118.581	
	J = 26–25	100.461	
	J = 27–26	96.772	
	J = 30–29	87	
	J = 31–30	84.411	
	J = 34–33	77.059	
HCN	J = 9–8	375.944	88S
HCO^+	J = 9–8	373.593	92J
H_2O	4_{14}–3_{21}	789	87P
H_2D^+	1_{10}–1_{11}	806	87P
H_3O^+	1_1–2_1	974	87P
NH_3	$J_K = 1_0$–0_0	524	87P
	$J_K = 4_3$–3_3	125	

7.3.4.4 Molecular masers

Elitzur [92E] gives a detailed phenomenological description and modeling of galactic as well as extragalactic molecular masers of OH, H_2O, SiO, CH, HCN, CH_3OH, H_2CO, and NH_3.
A list of the most important interstellar masers for which up to 1991 at least ten sources are known is given by Cohen [91C].

7.3.5 Diffuse HII gas

Table 3. Observed resonance absorption lines with wavelengths λ > 912 Å of collisionally ionized gas with temperatures $\geq 6\cdot10^4$ K [87S], including the lines given in LB VI/2c, subsect. 7.1.5.2, p. 58.

Species	λ [Å]	Species	λ [Å]	Species	λ [Å]	Species	λ [Å]
O VI	1031.95	N V	1238.81	Si IV	1393.76	C IV	1548.19
	1037.63		1242.80		1402.77		1550.76

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7.4 Physics of interstellar dust

7.4.0 General references

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7.4.1 Optical properties of the grains

7.4.1.1 Definitions

$C_{sca}(\lambda)$	total cross-section for scattering depending on wavelength λ
$C_{ext}(\lambda)$	total cross-section for extinction
$\gamma = C_{sca}/C_{ext}$	albedo
θ	scattering angle
$g = \langle\cos\theta\rangle$	asymmetry factor giving the degree of scattering in the forward direction $\theta = 0°$.

7.4.1.2 Efficiency factors

In addition to the references given in LB VI/2c subsect. 7.4.1.2., Table 1, p. 106:

Scattering and absorption cross sections as well as extinction profiles of grains of arbitrary size (compared with the wavelength of incident light) are calculated for dust particles containing resonantly absorbing impurity atoms or molecules, e. g., by Shapiro and Holcomb [86S].

7.4.1.3 Albedo and asymmetry factor derived from observations

For a review of albedo and asymmetry factor of interstellar grains see [90M, 95D1].

For the wavelength region 912 to 1100 Å Murthy, Henry and Holberg [91M] found an albedo $\gamma < 0.1$ of the interstellar dust particles and an asymmetry factor $g > 0.95$. From far-ultraviolet observations (wavelengths 1415 to 1855 Å) Hurwitz et al. [91H] derived an albedo between 0.13 and 0.24, a value significantly lower than that of nearly all previous measurements, also lower than the numbers given in LB VI/2c subsect. 7.4.1.3, Table 2, p. 107. For the albedo and the asymmetric factor at $\lambda \approx 4400$ Å (spectral region B of the UBV system) Witt [88W2] derived $\gamma = 0.61 \pm 0.07$ and $g = 0.60 \pm 0.22$, respectively.

7.4.1.3a Observed dust-related spectral features

Table 1. Dust-related absorption features [87W, 88B2, 89D, 95D2].
For proposed identification see also [88G, 88N, 88W1, 89P].

λ [μm]	Identification	Where observed
2.41	H_2 ice ?	WL5
2.95	NH_3 ice	Molecular clouds
3.0	?	Galactic centre
3.08	H_2O ice	Molecular clouds, circumstellar shells
3.3…3.6	H_2O-NH_3 ice	Molecular clouds
3.4	Organics ?	Galactic centre
3.48	H_2CO	Galactic centre
3.53	CH_3OH	W33 A
3.9	H_2S ice ?	W33 A
4.27	CO_2	A few dense molecular clouds
4.62	X(C=N) ice	A few molecular clouds
4.67	CO ice	Several molecular clouds
4.9	OCS	W33 A
6.0	H_2O ice	Molecular clouds, circumstellar shells
6.85	CH_3OH ?	Molecular clouds
8.86	CH_3OH	Only in AFGL 2136
9.7	Silicates	Diffuse and dense clouds
9.75	CH_3OH	Only in AFGL 2136
12.5	H_2O ice	Circumstellar shells (not molecular clouds)
13.3	H_2O ice	A few dense molecular clouds
15.2	CO_2 ice	A few dense molecular clouds
18	Silicates	Diffuse and dense clouds
45	H_2O ice	Kleinman-Low nebula

Table 2. Dust-related emission features [87W, 88B2, 89A2].
PAH = polycyclic aromatic hydrocarbon; see footnote to Table 3 in subsect. 7.4.1.4.
For proposed identifications see also [89P].

λ [μm]	Identification	Where observed
3.3 3.4	PAHs PAHs	Molecular clouds near HII regions, planetary nebulae, reflection nebulae
3.43 3.53	H_2CO ? H_2CO ?	Two circumstellar shells
5.25	PAH	One planetary nebula
6.2 7.7 8.6	PAHs PAHs PAHs	Molecular clouds near HII regions, planetary nebulae, reflection nebulae

λ [µm]	Identification	Where observed
9.7	Silicates	Circumstellar shells, planetary nebulae (O>C); HII regions
11.3	PAHs	Molecular clouds near HII regions, planetary nebulae, reflection nebulae
11.5	SiC	Circumstellar shells, planetary nebulae (C>O)
18	Silicates	Circumstellar shells (O>C)
30	MgS ?	Circumstellar shells

A detailed spectroscopic discussion of observed emission bands is given by Allamandola et al. [89A1].

Dust-related visual continuous emission

The *Extended Red Emission* band, usually between about 6000 and 8000 Å, takes the form of a broad band peaking near 6700 Å with about 1200 Å FWHM [89W] and can be fitted well with the measured band-gap emission from hydrogenated amorphous carbon [90W].

7.4.1.4 Grain models

Table 3. Materials suggested as constituents of interstellar grains, in addition to the materials listed in LB VI/2c subsect. 7.4.1.4, Table 3, p. 107.

Material [1])	Optical properties	Ref.
Polycyclic aromatic hydrocarbon (PAH)	Infrared emission features	87L, 87T, 89A1
Amorphous carbon	Infrared features	81D, 87T
Hydrogenated amorphous carbon (HAC)	Infrared emission features, extended red emission	87T, 88D, 90J
Organic refractory material	Some infrared absorption features	87T
"Astronomical" silicate	9.7 µm and 18 µm feature	84D
Biological material	UV, visual, infrared absorption features	86H

[1]) PAHs: well-characterized chemical species with definite composition, spectral and physical properties
HACs: less well-defined substances, composed of hydrogen and carbon with a variable hydrogen-to-carbon ratio
"Astronomical" silicate: silicates which may be coated or mixed with a blacker material (probably carbon dominated).

Theoretical grain models

Grain models as collections of individual particles of (mostly) different composition and special size distributions constructed to reproduce the interstellar extinction curve in the visual and the ultraviolet spectral range, including the extinction bump at $\lambda \approx 2175$ Å, as well as the observed interstellar dust-related infrared features are discussed, e. g., by Buch [90B], Mathis [90M], Draine [94D], and Dorschner and Henning [95D1]. For a review about different grain populations depending on the special environment in which they are formed and/or modified as well as dust-modifying processes in interstellar space see [95D1], for the formation and evolution of interstellar icy grain mantles [96S, 96G2]. Grain fragmentation and destruction is discussed by Dwek and Arendt [92D], dust coagulation and ice accretion in dense, cold molecular clouds, resulting in a changeing size distribution of interstellar dust grains as well as the internal structure and the grain distribution, by Ossenkopf [93O], the dust opacity by Ossenkopf and Henning [94O] and Krügel and Siebenmorgen [94K].

Nature of the polarizing particles

The polarization is attributed to, e. g., silicate particles [81M], to core-organic refractory mantle particles [87G], or to particles with superparametric inclusions [86M].

Table 4. Relative abundances of the main components of ices in molecular clouds [95D1].

Component	Feature λ [μm]	Mode	Abundance (H_2O = 1)	Comments
H_2O	3.08	OH stretch	1	
	6.0	HOH bend	1	
	13.3	libration	1	Obvious only in AFGL 961
	45	transverse optical vibration	1	Only in the Kleinman-Low nebula
CO	4.67	CO stretch	0…0.5	
CO_2	4.27	CO stretch		Not accessible from the ground
	15.2	OCO bend	0…0.2	Only in AFGL 961, AFGL 989, AFGL 890
CH_3OH	3.53	CH stretch	0.05…0.10	
	6.85	CH_3 deformation?		Uncertain identification
	8.86	CH_3 rock		Only in AFGL 2136
	9.75	CO stretch		Only in AFGL 2136

A review on infrared spectroscopy of interstellar ices is given by Whittet [96W].

Corrigendum

LB VI/2c subsect. 7.4.1.4, Table 5, p. 108: The number density N_d [cm^{-3}] of core-mantle grains (core radius a_c, mantle radius a_m) should read

$$N_d(a_m) = \exp\left[-5\left(\frac{a_m - a_c}{a_i}\right)^3\right]$$

with a_i = 0.2 μm [78G].

7.4.2 Grain temperature

Table 5. Classification of dust according to its temperature [88H, 89C].

	Very cold dust	Cold dust	Warm dust	Hot dust
Temperature:	≈ 14 K	15…25 K	30…40 K	250…500 K
Regions:	Molecular clouds	HI regions	HII regions	Circumstellar regions
Heating				
Large grains:	In equilibrium with radiation field			
Very small grains:				Transiently heated

The theoretical distribution of grain temperatures for special grain compositions, heated by absorption of background starlight and cooled by emission of infrared and far-infrared radiation, has been calculated by Draine and Anderson [85D], and Guhathakurta and Draine [89G]. The temperature distribution for very small grains is considered, e. g., by Désert et al. [86D].

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7.5 Physics of the interstellar gas

7.5.1 General references

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7.5.2 Elemental abundances in the HI gas

Table 1. Elemental abundances in the cold and warm diffuse interstellar medium [86C].

All quantities are logarithmic abundances normalized to a value of 12 for hydrogen. In general cosmic abundances are averages of solar and meteoritic values, the letters M and S denote values based solely on meteoritic or solar data, respectively. Differences between solar and meteoritic values greater than 0.05 dex are shown as ± values.

In some cases the range of values observed in various lines of sight are quoted, in other cases a mean value is given with the spread between the lines of sight shown by a ± range. The lowest value may be representative of the cold clouds, the highest of the warm. Values particularly reliably are noted by an exclamation mark, relatively uncertain values are given in parentheses.

Element	Cosmic	Warm	Average	Cold
H	**12**			
D			$6.7^{+0.3}_{-0.2}$	
Li	3.33(M)		1.4; 2.2	
Be	1.45(M)		≤ 0.9; ≤ 0.7	
B	2.93(M)		≤ 1.5; $2.2^{+0.1}_{-0.3}$	
C	8.69(S))		8.4 ± 0.6; 8.28	
N	7.99(S)		7.9 ± 0.4 !	
O	8.91(S) !		8.7 ± 0.3 !	
F	(4.5)		4.4 ± 0.4; 4.1 ± 0.2	
Na	6.32 !		6.3…4.7	
Mg	7.58 !	7.31 ± 0.04 !		6.99 ± 0.02 !
Al	6.48	5.3		4.5
Si	7.55 !	6.8		6.2
P	5.51 ± 0.06	5.28 ± 0.07 !		4.87 ± 0.04 !
S	7.24 !		7.51 ± 0.1; 7.01	
Cl	(5.4) ± 0.1	5.22 ± 0.08 !		4.88 ± 0.03 !
Ar	(6.61)		6.45 ± 1; 6.25	
K	5.13		5.2…3.2	
Ca	6.35 !		5.0…2.3	
Sc	3.09		≤ 0.8	
Ti	4.98		4.6…1.8	
V	4.01		≤ 2.6; ≤ 2.7	
Cr	5.67 !		3.14	
Mn	5.49	4.68 ± 0.04 !		4.21 ± 0.03 !
Fe	7.59 ± 0.08 !	6.16 ± 0.05 !		5.54 ± 0.06 !
Co	4.92 !		3.35	
Ni	6.25 !		4.26 ± 0.11 !	

Element	Cosmic	Warm	Average	Cold
Cu	4.23		2.76 ± 0.08 !	
Zn	4.63		≥ 4.2 ± 0.2; ≤ 4.7	

Gas-phase abundances of 32 elements for the cool diffuse cloud toward ζ Ophiuchi are given by Savage and Sembach [96S].

7.5.3 Particle processes

The global heating and cooling of the interstellar gas is summarized by Black [87B], the dust-gas interaction by Dwek and Arendt [92D].

Molecular photoabsorption processes are considered , e.g., by Kirby [90K], collision processes by Bates [90B] and by Roueff [90R].

Time-dependent models of astrochemical regimes, especially in the ion-molecular gas phase, on dust grains, in interstellar shocks, and in circumstellar envelopes are compared with observations, e.g., by Turner [89T], Wagenblast and Williams [93W1], Williams [93W2], Hasegawa and Herbst [93H] and Bergin et al. [95B]. Herbst [88H] gives a table with selected gas phase models of dense interstellar clouds which can be used as a sample of references up to 1988, see also Langer and Graedel [89L]. A list of rate coefficients of 3864 gas-phase reactions involving 395 species and 12 elements are given by Millar et al. [97M], see also [92G] and [90T].

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7.6 Cosmic rays

7.6.1 Introduction

The cosmic radiation comprises all particles of high energy that are of astrophysical origin and reach the Earth. It contains many different particle types and covers a wide range of energies. In the radiation all elements of the periodic table as well as their isotopes were detected, with protons and helium nuclei being the dominant constituents. In addition small quantities of electrons, the two antiparticles positrons and antiprotons, as well as photons and neutrinos are observed. Only those particles are missing, that decay with a lifetime generally too short to be observed on Earth, like neutrons and many radioactive isotopes. The energy spectrum reaches from some MeV up to several 10^{20} eV/particle, the highest energy of any known radiation. From the lower end up to the highest energies the flux decreases by about 30 orders of magnitude. In consideration of such a large energy range, different detection techniques are necessary to explore the cosmic radiation. Methods used at medium and high energies ($< 10^{10}$ eV) require detectors carried on balloons, rockets or satellites and for studying the charged component of the cosmic radiation this technique has been extended up to several 10^{14} eV/particle. At still higher energies the observations are done with detectors located deep underground [97A2, 97B2] and air shower arrays which cover the ultra high energy (UHE)- ($> 10^{14}$ eV) and extremely high energy (EHE)-regions ($> 10^{18}$ eV). Whereas the lower energy experiments at the top of the atmosphere measure the primary nuclei directly, the ground-based arrays only detect the air showers generated by the incoming particles.

Up to now, the origin and acceleration processes are still unknown. As the main sources supernovae, quasars and active galactic nuclei are assumed. The charged particles of the cosmic radiation appear nearly isotropic on Earth, because they are deflected in the interstellar magnetic fields and so only the neutral constituents such as photons and neutrinos would provide direct information on their acceleration site. The energy content of the cosmic radiation is about 1 eV cm^{-3} [90G] and therefore comparable with other forms of energy in our galaxy, like magnetic fields ($\approx$ 1 eV cm^{-3}) [96B1] or starlight ($\approx$ 0.44 eV cm^{-3}) [90G].

In this compilation we assemble data from various cosmic ray publications, so as to provide for the non-expert as well as the expert an overview of what is known. The material is in the form of tables and figures, and extends to the highest energies. We have been helped by many in this endeavor, but are certain to have missed important data points somewhere. The compilation is arranged in several steps, first explaining the basic instrumentation, then the data available, and finally, in a short summary, some of the pertinent attempts to understand where cosmic rays come from, how the particles get their energy, their spectrum, and their chemical composition.

7.6.2 The main experiments

The major balloon and satellite experiments, which were in operation during the last 30 years for investigating the hadronic component of the cosmic radiation and provided data on the energy spectra of individual nuclei, or will do so in the near future, are summarized in Table 1. In the subsequent section they are described in more detail, where also their energy ranges, detected nuclei and observation techniques are listed.

The major characteristics of the ground-based experiments which provided data on the allparticle flux in the past, or are operating now, or will start data taking in the near future are summarized in Table 2. In addition these experiments are described in more detail in subsect. 7.6.4. An overview on the ranges where individual experiments contributed or will contribute in the near future are shown in Fig. 1.

Table 1. The major direct experiments for investigating the hadronic component of the cosmic radiation.

Experiment	Type	Observed nuclei	Operating	Ref.
ACCESS	space station	H–U	≈ 2005 – 2008	97I1
ALICE	balloon	Si – Fe	1987	92E
ATIC	balloon	H – Fe	≈ 2000	97S1
BACH	balloon	Fe	≈ 2000	95S1
BESS	balloon	H, He	1993 – 1998	97S2
Bristol Cosmic-Ray Detector	satellite	Fe – Fm	1979	87F
CAPRICE	balloon	H	1994	97B1
Cosmic-Ray Charge-Isotope Telescope	balloon	Be – Ni	1974 + 1976	78L
CRISIS	balloon	Si – Ni	1977	81Y
CRN	satellite	C – Fe	1985	g
German American High Energy Cosmic Ray Telescope	balloon	B – Fe	1976	80S
HEAO-3-C2	satellite	Be – Ni	1979 – 1980	l
HEAO-3 Heavy Nuclei Experiment	satellite	Zn – U	1979	m
HEAT	balloon	H, He	1994	95S7
HEN	balloon	Li – Ni	1971 + 1972	74J
Successor of HEN	balloon	B – Fe	1974	77C
IMAX	balloon	H, He	1992	97M1
ISOMAX	balloon	Be	1998 –	93S1
JACEE	balloon	H – Fe	1979 – 1995	o
JEM	space station	H – Fe	≈ 2005	97M3
LEAP	balloon	H, He	1987	91S
MASS	balloon	H, He	1989	93P1
MUBEE	balloon	H – Fe	1975 – 1987	q
Orth et al.	balloon	Li – Fe	1972	78O
Proton-Satellites	satellite	H – Fe	1965 – 1966	70G
RICH	balloon	He – O	1991	93B5
RUNJOB	balloon	H – Fe	since 1995	t
Ryan et al.	balloon	H, He	1970	72R
Sanriku Balloon Experiments	balloon	H – Fe	1989 + 1991	u
SMILI	balloon	H, He	1989 + 1991	v
Sokol-Experiments	satellite	H – Fe	1984 – 1986	w
TIC	balloon	H – Fe	1994	95A1
TRACER	balloon	C – Fe	≈ 2000	98S2

Table 2. The major ground-based experiments which provided data on the allparticle flux in the past, are operating now, or will do so in the near future.

Experiment	Location	Techniques	Area [km^2]	Altitude [$g\ cm^{-2}$]	Energy range [eV]	Ref.
Akeno	Japan	S, M	1	920	$3\cdot10^{14}\ldots10^{18}$	84N
AGASA		S, M	100	920	$> 10^{17}$	95Y
Andyrchy	Russia	S	0.045	800	$\approx 2\cdot10^{14}\ldots10^{16}$	97C3
ANI	Armenia	S, M, H	0.03	700	$10^{14}\ldots10^{16}$	a
Auger	Argentina, USA	W, A	6000	900	$> 10^{19}$	d
BASJE	Bolivia	S	0.008	540	$2\cdot10^{13}\ldots10^{16}$	e
Buckland Park	Australia	S	0.03	1036	$> 10^{14}$	81C
CASA-MIA	USA	S, M	0.25	870	$10^{14}\ldots10^{16}$	f
-BLANCA		C	0.2		$3\cdot10^{14}\ldots3\cdot10^{16}$	97C1
DICE	USA	C		870	$5\cdot10^{14}\ldots3\cdot10^{16}$	97B6
EAS-Top	Italy	S, M, C, R	0.1	810	$10^{14}\ldots10^{16}$	h
Fly's Eye	USA	A		860	$> 10^{17}$	j
GRAPES III	India	S, M	0.1	790	$3\cdot10^{13}\ldots3\cdot10^{16}$	97I2
Haverah Park	Great Britain	W	12	1010	$> 4\cdot10^{17}$	k
HEGRA	Spain	S, M, C	0.04	790	$3\cdot10^{13}\ldots10^{16}$	n
HiRes	USA	A		860	$> 10^{17}$	95B4
KASCADE	Germany	S, M, H	0.04	1020	$3\cdot10^{14}\ldots5\cdot10^{16}$	p
MSU	Russia	S, M	0.05	1000	$10^{15}\ldots10^{17}$	97F
Mt. Norikura	Japan	S	0.035	735	$10^{14}\ldots10^{16}$	97I3
SPASE	Antarctica	S	0.016	685	$10^{14}\ldots3\cdot10^{16}$	97D2
- VULCAN		C				
SUGAR	Australia	M	125	1005	$> 10^{17}$	x
Tibet ASγ	China	S	0.02	606	$3\cdot10^{12}\ldots2\cdot10^{16}$	y
Tien Shan	Kazakhstan	S, M, H	0.02	700	$10^{13}\ldots10^{18}$	z
TUNKA-13	Russia	C	0.05	955	$3\cdot10^{14}\ldots7\cdot10^{16}$	97G2
VEGA	Kazakhstan	C	0.04	700	$3\cdot10^{14}\ldots3\cdot10^{16}$	97Y
Yakutsk	Russia	S, M, C, R	18	1020	$> 10^{16}$	91E

Techniques: S = scintillator stations
M = muon counters
C = Cherenkov light detectors
A = air/nitrogen fluorescence light detectors
H = hadron calorimeter/detector
R = radio antennas
W = water Cherenkov tanks

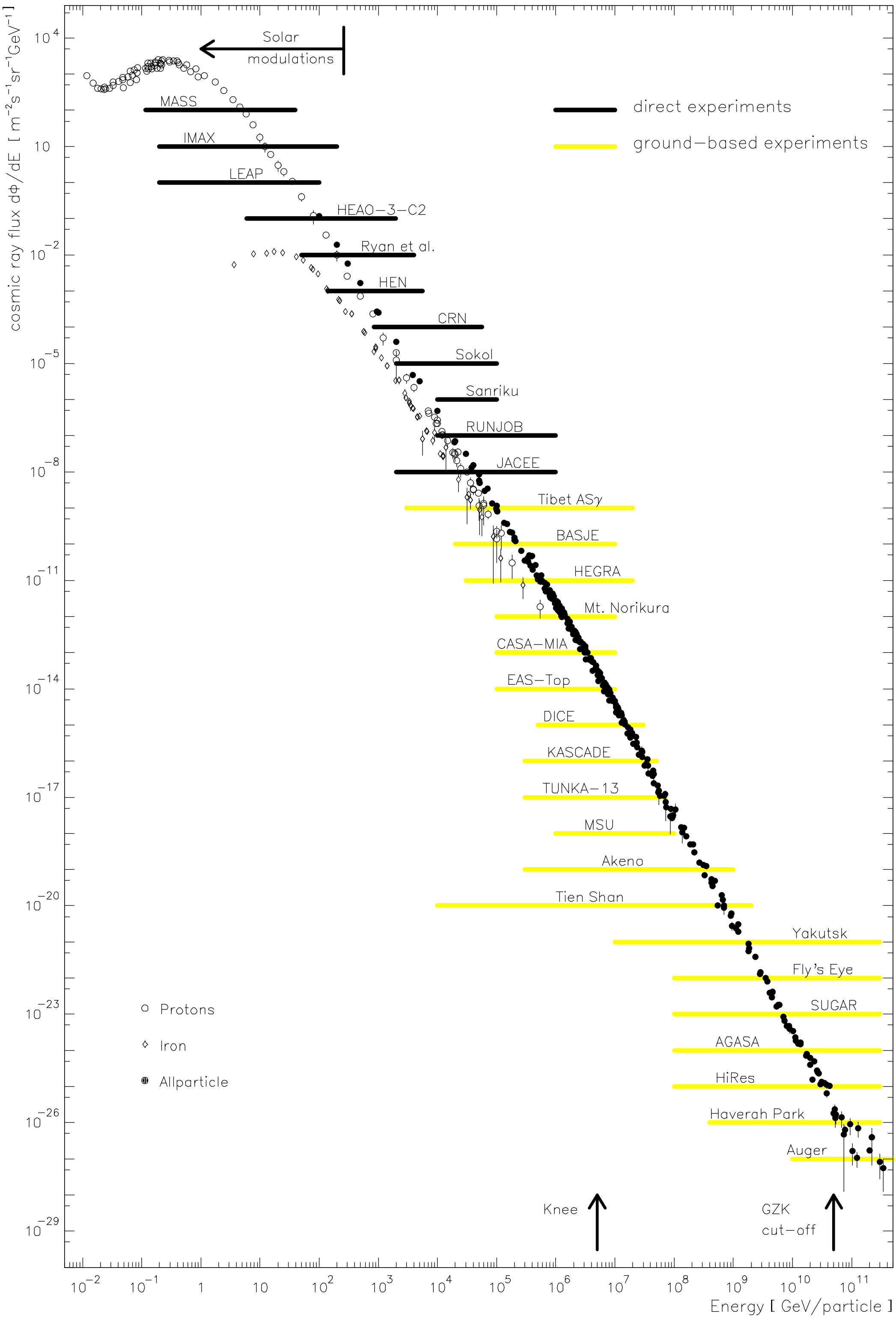

Fig. 1. The energy ranges of several direct and indirect experiments, which provided data on the cosmic ray spectrum or will provide data in the near future.

7.6.3 Direct experiments

Detectors flown on balloons high in the atmosphere or on board of satellites or even the space shuttle are capable of detecting individual cosmic ray particles and then provide a direct measurement of their spectra. The techniques are similar to those used in high energy physics experiments. Among these detectors are calorimeters, emulsion stacks, transition radiation detectors and spectrometers. Limits to the highest energies observable in such devices are given by the steeply falling cosmic ray spectra and by the detector itself. On the one hand the absorber in the detector has to be thick enough to stop the energetic particles and at least to catch the positions of the shower maxima in the calorimeter. On the other hand due to the steeply falling spectra large collecting areas are desired. So there always has to be a compromise between the size and weight of the detector and the effort to put it into flight or into orbit. The effective thickness of the absorber and the integrated exposure of the currently existing devices makes it possible to access primary energies up to several hundreds TeV. Fortunately this energy region overlaps with accelerator physics and therefore measurements are yielding clear and precise information on the spectrum and composition of the cosmic radiation. The most energetic event detected directly so far has been reported by the RUNJOB campaign and is supposed to be a proton with an energy of several PeV [97A3].

The following list summarizes the major balloon- and satellite experiments, which were in operation during the last 30 years for investigating the hadronic component of the cosmic radiation or will do so in the near future. Here observation techniques, energy ranges and detected nuclei are given. Table 3 summarizes the subdivision of single elements into groups, which are commonly used.

Table 3. The grouping of single nuclei.

Group	Elements	Z
low	H – He	1…2
medium	C – O	6…8
high	Ne – S	10…16
very high	Cl – Fe	17…26
ultra heavy	elements beyond Fe	> 26

- The Advanced Cosmic Ray Composition Experiment **ACCESS** (Isbert et al. [97I1]:

  Observed nuclei: H – U
  Scheduled for the international space station for the years 2005…2008, consisting of a hadron calorimeter for measuring protons, helium and light nuclei up to about 1 PeV, a transition radiation detector for measuring the nuclei Li – Ni beyond 100 TeV and an additional module for measuring ultra-heavy nuclei ($26 \leq Z \leq 92$) in the GeV/nucleon range.

- **ALICE** – A Large Isotopic Composition Experiment [92E]:

  Energy range: 350…800 MeV/nucleon
  Observed nuclei: Si – Fe
  Balloon-experiment, spectrometer consisting of scintillation and Cherenkov counters, flown August 1987 from Prince Albert, Canada; flight duration 14.7 hours.

- The Advanced Thin Ionization Calorimeter **ATIC** (Seo et al. [97S1]):

  Energy range: 10 GeV…100 TeV
  Observed nuclei: H – Fe
  Balloon-experiment, scheduled for the year 2000.

- The Balloon Air Cherenkov Experiment **BACH** [95S1]:

  Observed nuclei: Fe
  Energy range: > 50 TeV
  Balloon-experiment, air-Cherenkov technique.

- A Ballon-borne Experiment with a superconducting Solenoid Spectrometer **BESS** [97S2]:

  Energy range: 170 MeV/nucleon …3 GeV/nucleon
  Observed nuclei: H, He
  Balloon-experiment with a superconducting solenoid spectrometer, several flights from Lynn Lake, Manitoba, Canada during the years 1993 – 1998.

- The **Bristol Cosmic-Ray Detector** (Fowler et al. [87F]):

  Observed nuclei: $Z > 26$
  Satellite-experiment containing scintillation- and Cherenkov-counters; on board the Ariel 6 satellite, launched June 3rd, 1979; 427 days observation time with 352 complete days at 100 % efficiency.

- **CAPRICE** – The Cosmic Anti-Particle Ring Imaging Cherenkov Experiment (Barbiellini et al. [97B1]):

  Energy range: 0.15…100 GeV/nucleon
  Observed nuclei: H
  Balloon-experiment, consisting of a magnet spectrometer equipped with multiwire proportional chambers and drift chambers, a silicon-tungsten imaging calorimeter and a ring imaging Cherenkov detector; flown August 8th – 9th, 1994 from Lynn Lake, Manitoba, Canada; flight duration 18 hours at an atmospheric depth of 3.9 g cm^{-2}

- The **Cosmic-Ray Charge-Isotope Telescope** (Lezniak & Webber [87L]):

  Energy range: 0.3…50 GeV/nucleon
  Observed nuclei: Be – Ni
  Balloon-experiment containing scintillation counters, UVT Lucite and Freon gas Cherenkov detectors, flown summer and fall 1974, and fall 1976.

- The Cosmic Ray Isotope Instrument **CRISIS** [81Y]:

  Energy range: 430…560 MeV/nucleon to 650…900 MeV/nucleon
  Observed nuclei: Si – Ni
  Balloon-experiment consisting of Cherenkov counters, spark chamber, nuclear emulsion stack and scintillation detector; launched May 20th, 1977 from Aberdeen, South Dakota, USA; flight duration 56 hours, 41 minutes at an atmospheric depth of 2.6 g cm^{-2}.

- The Cosmic Ray Nuclei Experiment **CRN** (Swordy et al. [g]):

  Energy range: 70 GeV…1 TeV/nucleon
  Observed nuclei: C, N, O, Mg, Ne, Fe-group
  Satellite-experiment, consisting of gas-Cherenkov counters, scintillators and transition radiation detectors,on board the Spacelab 2 - Mission (July 29th – August 6th, 1985).

- The **German American High Energy Cosmic Ray Telescope** (Simon et al. [80S]):

  Energy range: 2…250 GeV/nucleon
  Observed nuclei: B – Fe
  Balloon-experiment, ionization calorimeter, flown October 1976.

- The French-Danish Cosmic Ray Experiment **HEAO-3-C2** (Engelmann et al. [l]):

  Energy range: 0.6…35 GeV/nucleon
  Observed nuclei: Be – Ni
  On board the NASA HEAO-3 satellite (November 17th, 1979 – June 12th, 1980), Cherenkov counters and flash tube hodoscopes.

- The **HEAO-3 Heavy Nuclei Experiment** (Binns et al. [m]):

  Energy range: > 1.5 GeV/nucleon
  Observed nuclei: $32 < Z < 92$
  On board the NASA HEAO-3 satellite, launched September 20th, 1979; containing six ionization chambers, a Cherenkov counter and four multiwire ionization hodoscopes.

- The High Energy Antimatter Telescope **HEAT** [95S7]:

  Energy range: 10…100 GeV/nucleon
  Observed nuclei: H, He
  Balloon-experiment, magnet spectrometer with a transition radiation detector and lead/scintillator electromagnetic calorimeter, flown for 29 hours in May 1994; primary goal of HEAT is the study of electrons and positrons in the cosmic radiation.

- The High Energy Nuclei Telescope **HEN** (Júliusson [74J]):

  Energy range: 20…100 GeV/nucleon
  Observed nuclei: Li – Ni
  Balloon-experiment containing a scintillation-Cherenkov counter telescope including two gas-Cherenkov counters for energy measurements above 20 GeV/nucleon, three balloon flights during 1971 and 1972.

- The **successor of the HEN - project** (Caldwell [77C]):

  Energy range: 5…90 GeV/nucleon
  Observed nuclei: B – Fe
  Balloon-experiment in analogy to (Júliusson [74J]) containing scintillators and gas Cherenkov counters, two balloon flights in 1974.

- The Isotope Matter Antimatter Experiment **IMAX** (Menn et al. [97M1]):

  Energy range: 0.2…200 GeV/nucleon
  Observed nuclei: H, He
  Balloon-experiment, superconducting magnet spectrometer with drift chambers and multiwire proportional chambers, flown July 16th, 1992 from Lynn Lake, Manitoba, Canada; flight duration 16 hours at an atmospheric depth of 5 $g\,cm^{-2}$; main goal to measure the galactic cosmic ray abundances of protons, antiprotons, deuterium, He^3 and He^4.

- The Isotope Magnet Experiment **ISOMAX** [93S1]:

  Energy range: ≈ 1 GeV/nucleon
  Observed nuclei: light isotopes, especially Be^{10}/Be^9
  Balloon-experiment, superconducting magnet spectrometer with high resolution drift chambers; first flight (duration about 24 hours) scheduled for summer 1998, Lynn Lake, Manitoba, Canada.

- The Japanese American Cooperative Emulsion Experiment **JACEE** [o]:

  Energy range: 2…800 TeV/nucleon
  Observed nuclei: H – Fe
  Balloon-experiment, fine-grained emulsion chamber containing approximately a hundred track-sensitive nuclear emulsion plates and a three-dimensional emulsion X-ray film lead plate calorimeter, 15 balloon flights between 1979 and 1995; total exposure 1436 m^2 hours, average flight altitude 3.5…5.5 g cm^{-2}.

- The Japanese Experiment Module **JEM** [97M3]:

  Energy range: 1…500 TeV/nucleon
  Observed nuclei: H – Fe
  JEM will consist of two emulsion chambers attached to the international space station for a total exposure of one year.

- The Low Energy Antiproton Experiment **LEAP** (Seo et al. [91S]):

  Energy range: 200 MeV/nucleon…100 GeV/nucleon
  Observed nuclei: H, He
  Balloon-experiment, superconducting magnetic spectrometer, flown August 21st, 1987 from Prince Albert, Saskatchewan, Canada; flight duration 20 hours at an atmospheric depth of 4.7 g cm^{-2}

- The Matter Antimatter Superconducting Spectrometer **MASS** (Papini et al. [93P1]):

  Energy range: 0.117…39 GeV/nucleon for H, 0.171…19.97 GeV/nucleon for He
  Observed nuclei: H, He
  Balloon-experiment containing a superconducting magnetic spectrometer, scintillators, a gas-Cherenkov counter and a streamer tube calorimeter, flown September 5th, 1989; flight altitude < 10 g cm^{-2}, duration of flight 5.5 hours.

- The Moscow University Balloon Emulsion Experiment **MUBEE** (Zatsepin et al. [q]):

  Energy range: > 10 GeV/particle
  Observed nuclei: H, high- and very high-group
  Balloon-experiment, emulsion chamber, 10 balloon flights during the years 1975 – 1987.

- Experiment of **Orth et al.** [78O]:

  Energy range: 2…150 GeV/nucleon
  Observed nuclei: Li – Fe
  Balloon-experiment, containing a superconducting magnetic spectrometer with scintillators and optical spark chambers, flown September 1972.

- The University of Chicago's **RICH** -Instrument (Buckley et al. [93B5]):

  Energy range: 40…320 GeV/nucleon
  Observed nuclei: He, Be, B, C, O
  Balloon-experiment containing a ring imaging Cherenkov counter, 30 hours observation time, flown September 1991.

- The **Proton-Satellites** (Grigorov et al. [70G]):

  Energy range: $10^{10}\ldots10^{14}$ eV
  Observed nuclei: H and allparticle spectrum
  Detectors on board the satellites Proton-1 (July 16th, 1965 – October 11th, 1965), Proton-2 (November 2nd, 1965 – February 6th, 1966) and Proton-3 (July 6th, 1966 – September 16th, 1966); each detector consisted of 2 plastic scintillators and 4 Cherenkov counters.

- The Russian Nippon Joint Balloon Experiment **RUNJOB** [t]:

  Energy range: 10…1000 TeV/particle
  Observed nuclei: H – Fe
  Balloon-experiment, emulsion chamber, 4 balloon flights since 1995.

- Experiment of **Ryan et al.** [72R]:

  Energy range: 50…1000 GeV/nucleon
  Observed nuclei: H, He
  Balloon-experiment, ionization spectrometer, flown November 1970

- The **Sanriku Balloon Experiments** (Ichimura et al. [u], Kamioka et al. [97K3]):

  Energy range: 10…100 TeV/nucleus
  Observed nuclei: H – Fe
  Balloon-experiment, emulsion chamber, flown May 1989.

- The Superconducting Magnet Instrument for Light Isotopes **SMILI** [v]:

  Energy range: 30…200 MeV/nucleon
  Observed nuclei: light isotopes, H, He, deuterium, He^3
  Balloon-experiment, superconducting magnet spectrometer, SMILI-1: flight duration 19 hours at an atmospheric depth of 5 g cm^{-2} on September 1st, 1989; SMILI-2: launched 24th July, 1991, Lynn Lake, Canada, flight duration 13 hours, atmospheric depth 5 g cm^{-2}.

- The **Sokol-Experiments** (Ivanenko et al. [w]):

  Energy range: 2…100 TeV/ particle
  Observed nuclei: H, He, medium, high- and very high-group
  on board the satellites Cosmos 1543 (March 10th – April 5th, 1984) and Cosmos 1713 (December 27th, 1985 – January 22nd, 1986); energy measurement with an ionization calorimeter, charge determination by two types of Cherenkov detectors.

- The Thin Ionization Calorimeter **TIC** [95A1]:

  Energy range: 100 GeV…10 TeV
  Observed nuclei: allparticle spectrum
  Balloon-experiment, ionization calorimeter consisting of 5 steel plates, each 30×30 cm^2 thick and followed by a 1 cm thick scintillator plate, flown August 1994 over northern Canada, flight duration 76 hours.

- The **TRACER** Experiment [98S2]:

  Energy range: 1…100 TeV
  Observed nuclei: C – Fe
  Balloon-experiment with transition radiation detector.

7.6.4 Ground-based experiments

At still higher energies the much larger sensitive area of ground-based detectors allows to continue the direct measurements, by detecting the air showers generated by the incoming particles in the Earth's atmosphere. These observations are intrinsically indirect and informations on the nature and energy of the primary nuclei are strongly dependent on the knowledge of the development and propagation of the air shower through the atmosphere. In addition to a minimum observable energy imposed by the shower development itself and detector thresholds, the exposure can be as high as possible to access even the highest energy regions of the primary spectrum. The oldest technique in the field is still being utilized using large ground arrays of detector stations, mainly composed of scintillation counters or water Cherenkov tanks for measuring the charged component like electrons and muons reaching the surface of the Earth. Newer techniques are based on detecting the Cherenkov light emitted by relativistic charged particles or nitrogen fluorescence light, which is emitted by the air molecules excited by the particles of the air shower during their travel through the atmosphere. The main idea of all these techniques is to measure the approximate lateral distribution function of one of the air shower parameters, like the electron, muon or Cherenkov light distribution. From the measured distribution functions, observables are evaluated, which depend both on the nature of the primary particle and its energy. Among these observables there are the total number of electrons or muons reaching ground level and in case of Cherenkov or air fluorescence light the height of the shower maximum in the atmosphere. So far it is common practice to determine the primary energy by a single component analysis, where one air shower parameter is measured and then simply compared with the predictions of trial composition models. But the advantage of getting data samples with high statistics and an easy control of the detector response is ruled out by the difficulty of evaluating the primary energy due to limiting discrimination power and a strong dependence on the nuclear interaction mechanisms. Multi-component analyses, which are based on the simultaneous measurement of several air shower parameters, enhance the discrimination power and make the evaluation of the primary energy less dependent on the air shower propagation through the atmosphere, since cross-checks between different detector components are possible, but the disadvantages are strong cuts on the data sample imposed by several coincident requirements between the detector components and a non-trivial control of detector and inter-detector effects. After all the ground-based techniques established, that the allparticle energy spectrum reaches up to 10^{20} eV.

The following list summarizes the major ground-based experiments, which provided data on the allparticle energy spectrum during the last years, are operating now, or will start taking data in the near future. In addition to the main characteristics like, location, area, altitude, energy range also details on the experimental setup are given. The abbreviation "a.s.l." denotes "above sea level".

- **Akeno** [84N]:

  Location: Kofu, Japan
  Area: first array 1 km^2, later extended to 20 km^2
  Altitude: 920 g/cm^2, 900 m a.s.l.
  Energy range: 0.3…1000 PeV
  Operating: 1984 – 1993
  Technique: 1 km^2 array: 156 $\times$ (1 m^2) scintillator stations and 8 $\times$ (25 m^2) muon counters; 20 km^2 array: additional 19 $\times$ (2.2 m^2) and 4 $\times$ (1 m^2) scintillator stations.

- The Akeno Giant Air Shower Array **AGASA** [95Y]:

  Location: Kofu, Japan
  Area: 100 km^2
  Altitude: 920 g cm^{-2}, 900 m a.s.l.
  Energy range: > 100 PeV

- The Akeno Giant Air Shower Array **AGASA** [95Y] (continued):

  Operating: since April 1993
  Technique: The Akeno array as described above with additional $111 \times (2.2\ \mathrm{m}^2)$ scintillator stations and $14 \times (2.8\ldots10\ \mathrm{m}^2)$ muon counters.

- **Andyrchy** EAS Array [97C3]:

  Location: Prielbrusye, Caucasus, Russia
  Area: $4.5 \cdot 10^4\ \mathrm{m}^2$
  Altitude: $800\ \mathrm{g\ cm}^{-2}$, 2060 m a.s.l.
  Energy range: ≈ 200 TeV…10 PeV
  Technique: $37 \times (1\ \mathrm{m}^2)$ scintillator stations on a regular grid with 40 m spacing, up to now only a measurement of the shower size spectrum in the range $(2.5\cdot10^5 \le N_e \le 1.2\cdot10^7)$ with a knee at roughly $(2\ldots4)\cdot10^6$ present.

- **ANI**-Gamma experiment at Mt. Aragatz [a]:

  Location: Mt. Aragatz, Armenia
  Area: $3\cdot10^4\ \mathrm{m}^2$
  Altitude: $700\ \mathrm{g\ cm}^{-2}$, 3250 m a.s.l.
  Energy range: 100 TeV…10 PeV
  Technique: $24 \times (3\ \mathrm{m}^2)$ scintillator stations distributed regularly on the area and one station $(20\ \mathrm{m}^2)$ 120 m apart from the array center, $75\ \mathrm{m}^2$ muon counters and a $200\ \mathrm{m}^2$ hadron detector.

- The Pierre **Auger Project** [d]:

  Location: two sites, Patagonia, Argentina and Utah, USA
  Area: ≈ $6000\ \mathrm{km}^2$ (each site $3000\ \mathrm{km}^2$)
  Altitude: ≈ $900\ \mathrm{g\ cm}^{-2}$
  Energy range: fully efficient $> 10^{19}$ eV
  Technique: 2 sites; each site equipped with 1600 individual stations ($12\ \mathrm{m}^2$ water Cherenkov tanks for measuring the charged component of air showers) covering an area of $3000\ \mathrm{km}^2$; additionally each site will be equipped with optical telescopes for detecting nitrogen fluorescence light. Time schedule: Deployment of sites and construction of detectors planned to start at the end of 1998.

- The **BASJE** array at Mt. Chacaltaya [e]:

  Location: Mt. Chacaltaya, Bolivia
  Area: $8\cdot10^3\ \mathrm{m}^2$
  Altitude: $540\ \mathrm{g\ cm}^{-2}$, 5200 m a.s.l.
  Energy range: 20 TeV…10 PeV
  Technique: $13 \times (4\ \mathrm{m}^2)$ and $20 \times (1\ \mathrm{m}^2)$ scintillator stations.

- The **Buckland Park** Extensive Air Shower Array [81C]:

  Location: near Adelaide, Australia
  Area: $3\cdot10^4\ \mathrm{m}^2$
  Altitude: $1036\ \mathrm{g\ cm}^{-2}$, sea level
  Energy range: > 100 TeV
  Operating: since 1972
  Technique: $40 \times (1\ \mathrm{m}^2)$ scintillator stations.

- The Chicago Air Shower Array **CASA** [f] with **MIA** (Michigan Anti) [f] and **BLANCA** (Broad LAteral Non-imaging Cherenkov Array) [97C1]:

  Location: Dugway, Utah, USA
  Area: 0.25 km^2 (CASA-MIA), 0.2 km^2 (BLANCA)
  Altitude: 870 g cm^{-2}, 1460 m a.s.l.
  Energy range: 100 TeV…10 PeV (CASA-MIA), 300 TeV…30 PeV (CASA-BLANCA)
  Operating: since 1990 (CASA-MIA), since 1997 (BLANCA)
  Technique: $1089 \times (1.3\ m^2)$ scintillator stations with 15 m spacing (CASA), $16 \times (156\ m^2)$ of buried muon counters (MIA), 144 open Cherenkov detectors (BLANCA).

- The Dual Imaging Cherenkov Experiment **DICE** [97B6]:

  Location: Dugway, Utah, USA
  Altitude: 870 g cm^{-2}, 1460 m a.s.l.
  Energy range: 500 TeV…30 PeV
  Operating: since July 1994
  Technique: 2 Cherenkov telescopes (2 m diameter, spherical mirror, 256 photomultipliers each), 100 m distance.

- The **EAS-Top** array [h]:

  Location: Campo Imperatore, Gran Sasso, Italy
  Area: $10^5\ m^2$
  Altitude: 810 g cm^{-2}, 2005 m a.s.l.
  Energy range: 100 TeV…10 PeV
  Technique: $35 \times (10\ m^2)$ scintillator stations distributed regularly over the area of $10^5\ m^2$, a $12 \times 12\ m^2$ muon detector, consisting of 9 active layers of streamer tubes, separated by 13 cm iron absorber, 8 steerable Cherenkov modules, each consisting of $4 \times 0.6\ m^2$ parabolic mirrors, 3 radio antennas, 15 m high, operating in the wavebands 350…500 kHz and 1.8…5 MHz, at distances of 200, 400 and 500 m from each other.

- **Fly's Eye** [j]:

  Location: Dugway, Utah, USA
  Altitude: 860 g cm^{-2}, 1500 m a.s.l.
  Energy range: 100…10000 PeV
  Operating: Fly's Eye (FE) I 1981 – 1992, FE II since 1986
  Technique: Detection of nitrogen fluorescence light, 2 detectors (FE I, FE II). FE I: 67 spherical mirrors with 12…14 photomultipliers each, FE II: 13.4 km apart from FE I, 36 spherical mirrors.

- The **GRAPES III** large extensive air shower array [97I2]:

  Location: Ooty, India
  Altitude: 790 g cm^{-2}, 2200 m a.s.l.
  Energy range: 30 TeV…30 PeV
  Operating: Full operation ≈ 2000
  Technique: $217 \times (1\ m^2)$ scintillator stations on a hexagonal grid with 8 m spacing and a ($\approx 560\ m^2$) muon detector, consisting of 4 supermodules (140 m^2 each) built so far. The scintillator array will be extended to 721 stations within the next 3 years.

- **Haverah Park** [k]:

  Location: North Yorkshire Moors, Great Britain
  Area: 12 km^2
  Altitude: 1010 g cm^{-2}, 220 m a.s.l.
  Operating: 1962 – 1987
  Energy range: > 400 PeV
  Technique: water Cherenkov tanks for measuring the charged component of the cosmic radiation.

- **HEGRA** (High Energy Gamma Ray Astronomy) Experiment [n]:

  Location: La Palma, Canary Islands, Spain
  Area: 200×200 m^2
  Altitude: 790 g cm^{-2}, 2200 m a.s.l.
  Operating: since 1989 (scintillators), since 1992 (AIROBICC), since 1993 (Geiger towers), since 1996 (system of imaging atmospheric Cherenkov telescopes)
  Energy range: 30 TeV…10 PeV, (Cherenkov telescopes: 0.5…10 TeV)
  Technique: $243 \times (1\ m^2)$ scintillator stations [96K3], 77 open Cherenkov counters (AIROBICC) [95K1], $17 \times (18\ m^2)$ Geiger towers [96R2], 6 imaging atmospheric Cherenkov telescopes [98D1].

- The High Resolution Fly's Eye **HiRes** [95B4]:

  Location: Dugway, Utah, USA
  Altitude: 860 g cm^{-2}, 1500 m a.s.l.
  Energy range: > 100 PeV
  Technique: Detection of nitrogen fluorescence light, 2 sites 13 km apart, at each site 54 single detectors with 256 photomultipliers, a prototype detector consisting of 14 mirrors is operating since March 1993 at the old FE I site.

- The Karlsruhe Shower Core and Array Detector **KASCADE** [p]:
  Location: Karlsruhe, Germany
  Area: 200×200 m^2
  Altitude: 1020 g cm^{-2}, 110 m a.s.l.
  Operating: since 1996 with a large part of the detector
  Energy range: 300 TeV…50 PeV
  Technique: 252 scintillator stations, 620 m^2 muon detector, 20×16 m^2 hadron calorimeter.

- The Air Shower Experiment at **Mt. Norikura** [97I3]:

  Location: Mt. Norikura, Japan
  Area: 160×220 m^2
  Altitude: 735 g cm^{-2}, 2770 m a.s.l.
  Energy range: 100 TeV…10 PeV
  Technique: 192 scintillation counters.

- The Moscow State University air shower array **MSU** [97F]:

  Location: Moscow, Russia
  Area: $5 \cdot 10^4$ m^2
  Altitude: 1000 g cm^{-2}
  Technique: $110 \times (1\ m^2)$ scintillator stations, 37 m^2 muon detector.

- The South Pole Air Shower Experiment **SPASE** [97D2] with **VULCAN** [97D3]:

  Location: Geographic South Pole, Antarctica
  Area: 6200 m^2 (SPASE-1), 16000 m^2 (SPASE-2)
  Altitude: 685 g cm^{-2}, ≈ 2900 m a.s.l.
  Energy range: 100 TeV…30 PeV
  Operating: 1987 – 1997 (SPASE-1), since 1994 (SPASE-2)
  Technique: SPASE-1: $16 \times (1\ m^2)$ scintillator stations on a regular grid with 30 m spacing; SPASE-2: 120 scintillator modules spread over an area of roughly 16000 m^2, where these modules are clustered in 30 stations of 4 modules each. In addition 9 air-Cherenkov detectors (VULCAN) within and surrounding this array.

- The Sydney University Giant Air Shower Recorder **SUGAR** [x]:

  Location: Narrabri, Australia
  Area: 125 km^2
  Altitude: 1005 g cm^{-2}, 250 m a.s.l.
  Energy range: > 10^{17} eV
  Operating: January 10th, 1968 – February 5th, 1979
  Technique: 47 buried liquid scintillator stations (6 m^2 each) on a 1.6 km square grid as muon counters.

- **Tibet ASγ** [y]:

  Location: Yangbajing, Tibet, China
  Area: $2 \cdot 10^4$ m^2
  Altitude: 606 g cm^{-2}, 4300 m a.s.l.
  Operating: since 1990
  Energy range: 3 TeV…20 PeV
  Technique: $49 \times (0.5\ m^2)$ on a 7×7 matrix with 15 m grid spacing and $16 \times (0.25\ m^2)$ scintillator stations.

- **Tien Shan** [z]:

  Location: Tien Shan Mountains, near Alma-Ata, Kazakhstan
  Area: $2 \cdot 10^4$ m^2
  Altitude: 700 g cm^{-2}, 3200 m a.s.l.
  Energy range: $10^{13}…10^{18}$ eV
  Technique: $37 \times (0.75…2\ m^2)$ scintillator stations, ionization calorimeter, several gas discharge hodoscopes.

- The **TUNKA-13** EAS Cherenkov Light Array [97G2]:

  Location: Tunka Valley, near Lake Baikal, Russia
  Area: 240×240 m^2
  Altitude: 955 g cm^{-2}, 680 m a.s.l.
  Energy range: 300 TeV…70 PeV
  Operating: since 1996
  Technique: 13 Cherenkov counters.

- The **VEGA** Array at Tien Shan [97Y]:

  Location: Tien Shan Mountains, near Alma-Ata, Kazakhstan
  Area: 200×200 m^2
  Altitude: 700 g cm^{-2}, 3200 m a.s.l.
  Energy range: 300 TeV…30 PeV
  Technique: 13 open Cherenkov counters.

- The **Yakutsk** EAS Array [91E]:

  Location: Yakutsk, Russia
  Area: 18 km^2
  Altitude: 1020 g cm^{-2}, 100 m a.s.l.
  Energy range: > 10 PeV
  Technique: $69 \times (4$ m$^2)$ and $15 \times (0.25$ m$^2)$ scintillator stations, $6 \times (20$ m$^2)$ muon detectors, 53 Cherenkov detectors, 7 Cherenkov pulse form detectors, 10 radio antennas (32 MHz).

7.6.5 The main elements in the TeV range

Plotting the data of individual nuclei as provided by the direct experiments so far, without using further adjustments, shows in general a fair correspondence in overlapping energy ranges. For instance, the all particle spectrum combined with spectra of protons, helium, iron, electrons, positrons, antiprotons, and photons is plotted in Fig. 2.

At higher energies the spectra can be described by simple power laws in energy

$$\frac{\mathrm{d}\Phi}{\mathrm{d}E} = \Phi_0 \cdot E^{-\gamma}$$

where $\mathrm{d}\Phi/\mathrm{d}E$ denotes the differential flux in particles/(m^2 s sr TeV/nucleus), Φ_0 the absolute flux normalization at 1 TeV, E the energy/particle measured in TeV and γ the spectral index. The spectrum of each nucleus has been fitted using the MINUIT-Package from CERN [92M]. To minimize the effect of solar modulation, for the fits no data with energies below $Z{\cdot}10$ GeV/particle were used, with Z being the nuclear charge number.

We note that there is an inherent difficulty in fitting data from different experiments, with different systematics (see also Table 9). If the systematics are very different, and not included in the error bars published, and at the same time the energy range covered is different as well, then a fit to several data sets simultaneously will lead to erroneous results. There is some discussion of these problems in [93S2, 95B2, 98W2]. The graphs in any of these papers illustrate the difficulties that can arise, and also to what degree one can deal with them.

The single spectra of nuclei are presented in Fig. 3-10. The fit parameters are listed in Table 4. In the upper part of this table the results from experiments where single nuclei can be separated are listed. The second part shows the results for the case, that experiments measured groups of elements directly. Finally in the lower part, the data of groups of elements were added together both based on individual measurements as well as from grouped measurements.

In Fig. 11 the abundances of the various nuclei at 1 TeV as determined by the fit, for the elements up to Fe as well as the lower energy data for the ultra-heavy nuclei beyond the iron group are compared to the solar system abundances. Additionally Table 5 contains the references of the single experiments which provided the data presented in these figures (Figs. 3-11).

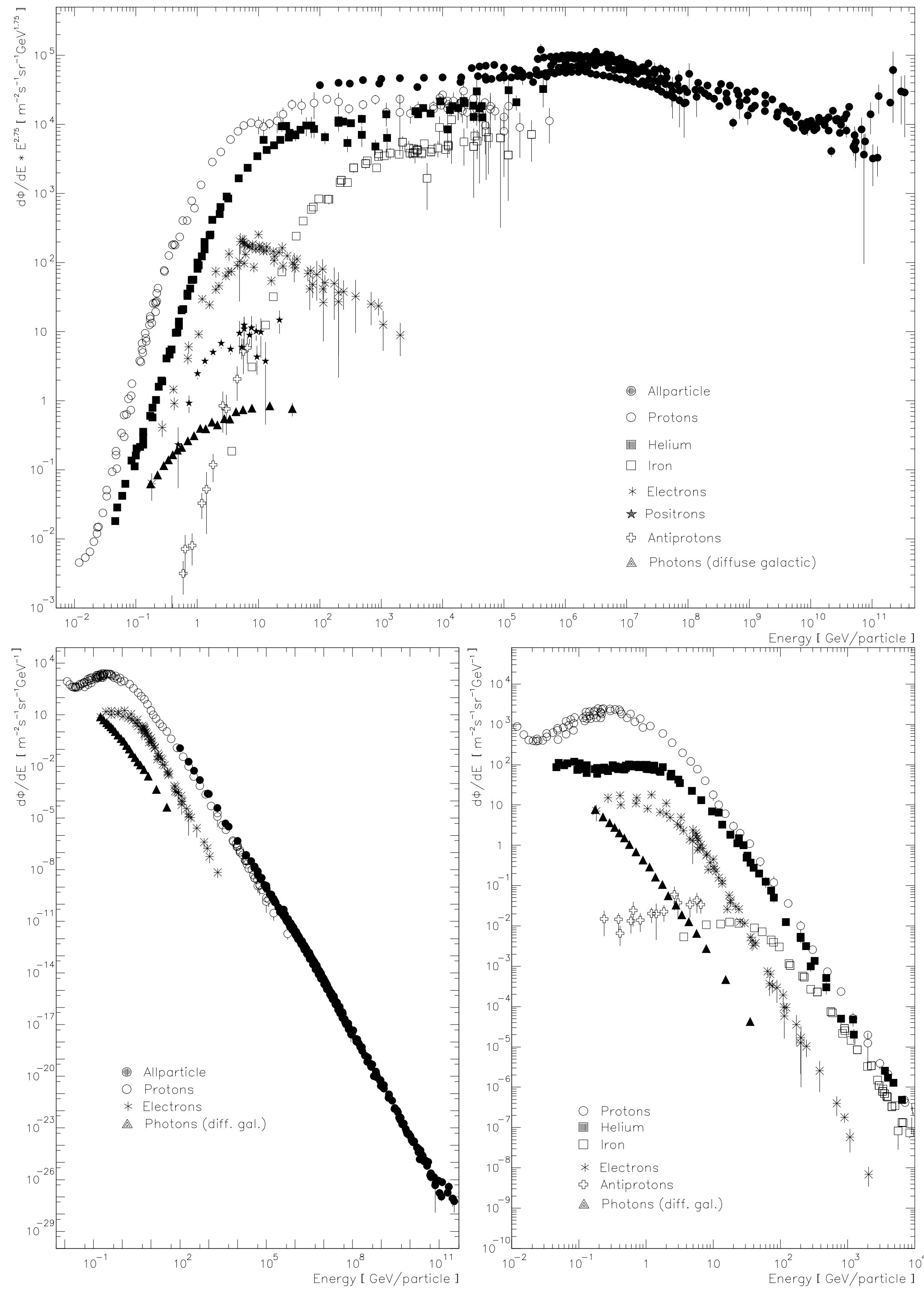

Fig. 2. Overview of the population of cosmic rays observed on Earth as measured by direct and ground-based experiments. The all particle spectrum combined with spectra of protons, helium, iron, electrons, positrons, antiprotons, and photons are shown, where in the upper graph all spectra are multiplied with $E^{2.75}$ to emphasize features in the spectra.

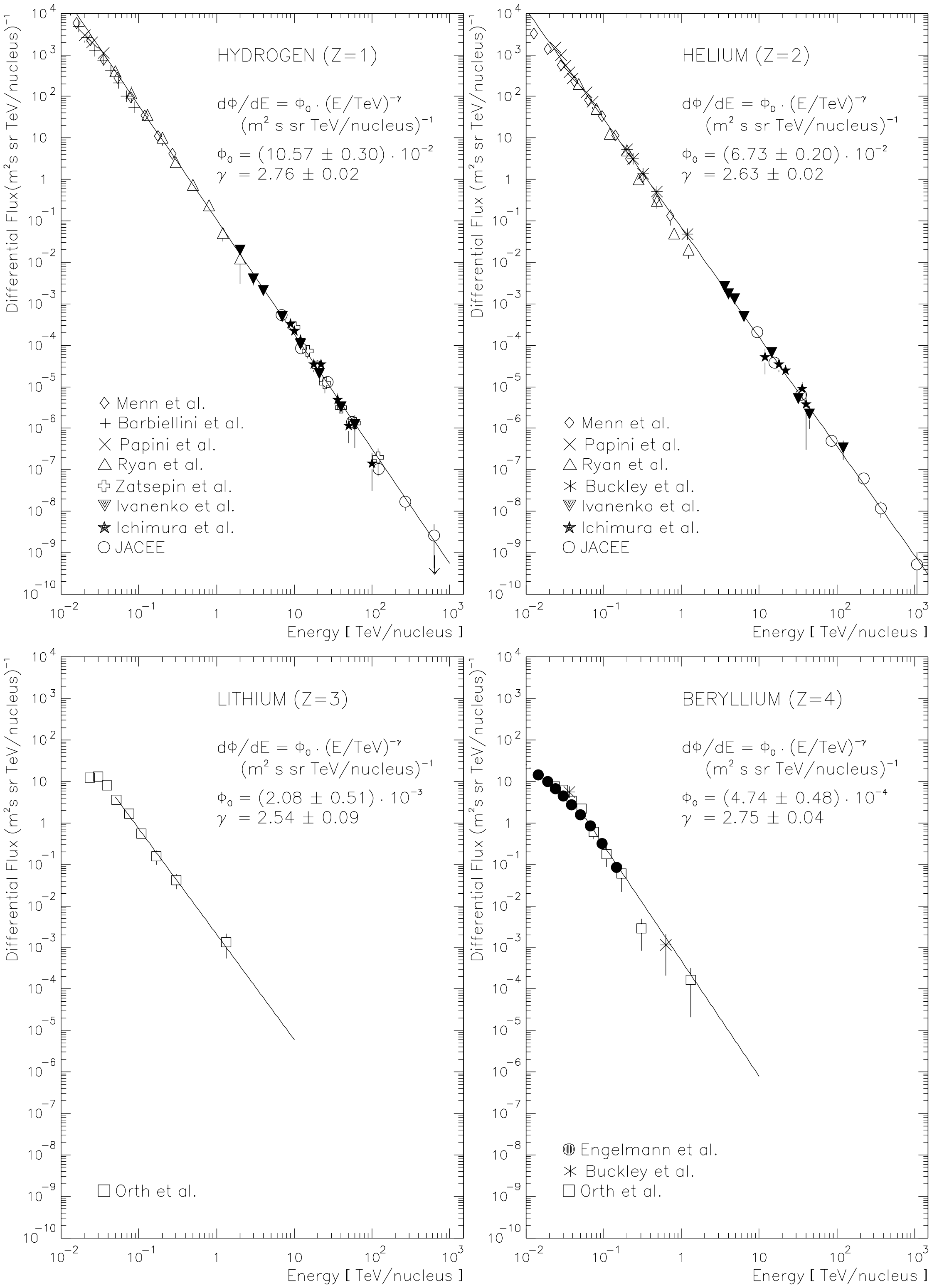

Fig. 3. Differential energy spectra of the elements H, He, Li and Be.

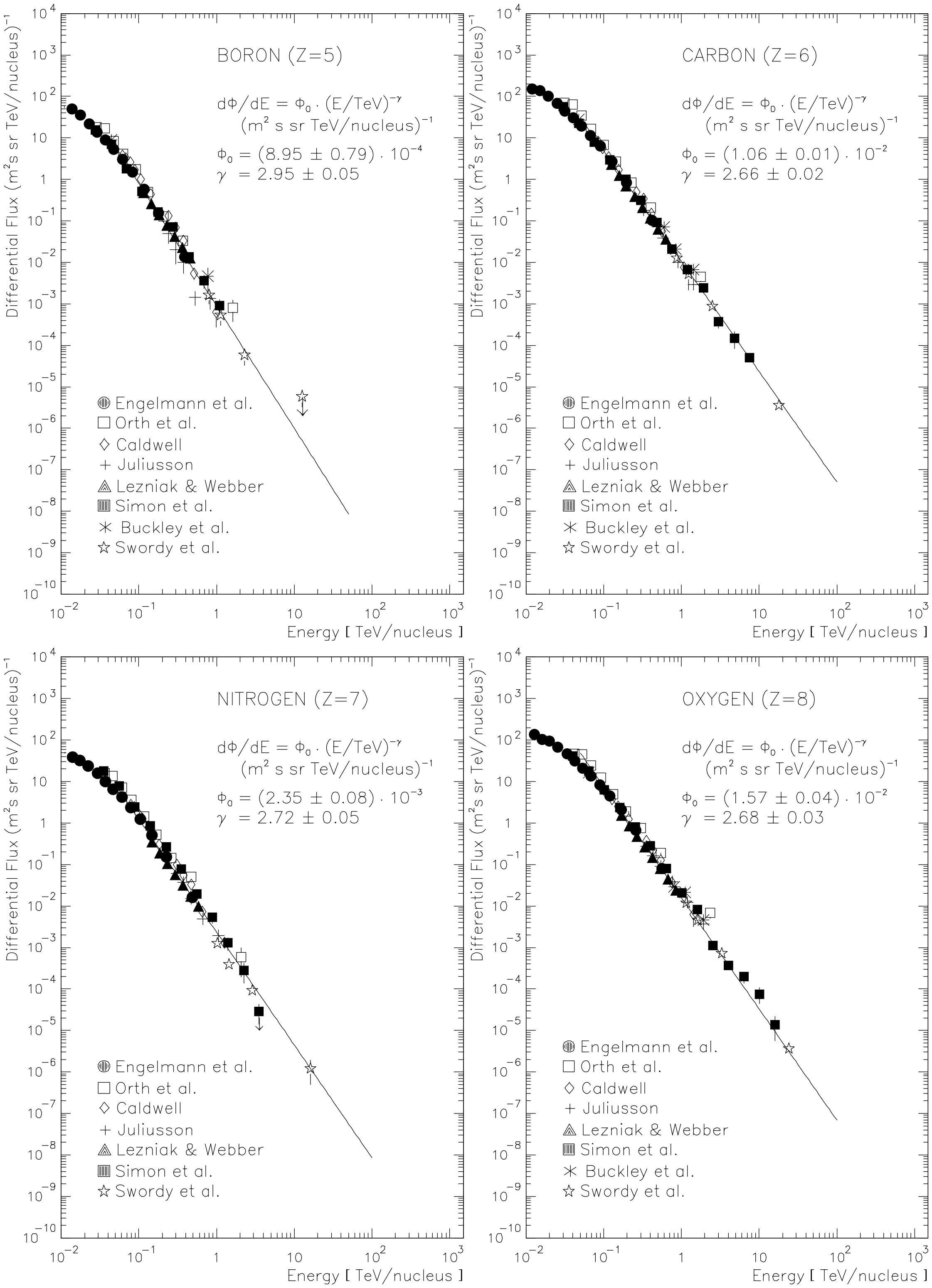

Fig. 4. Differential energy spectra of the elements B, C, N and O.

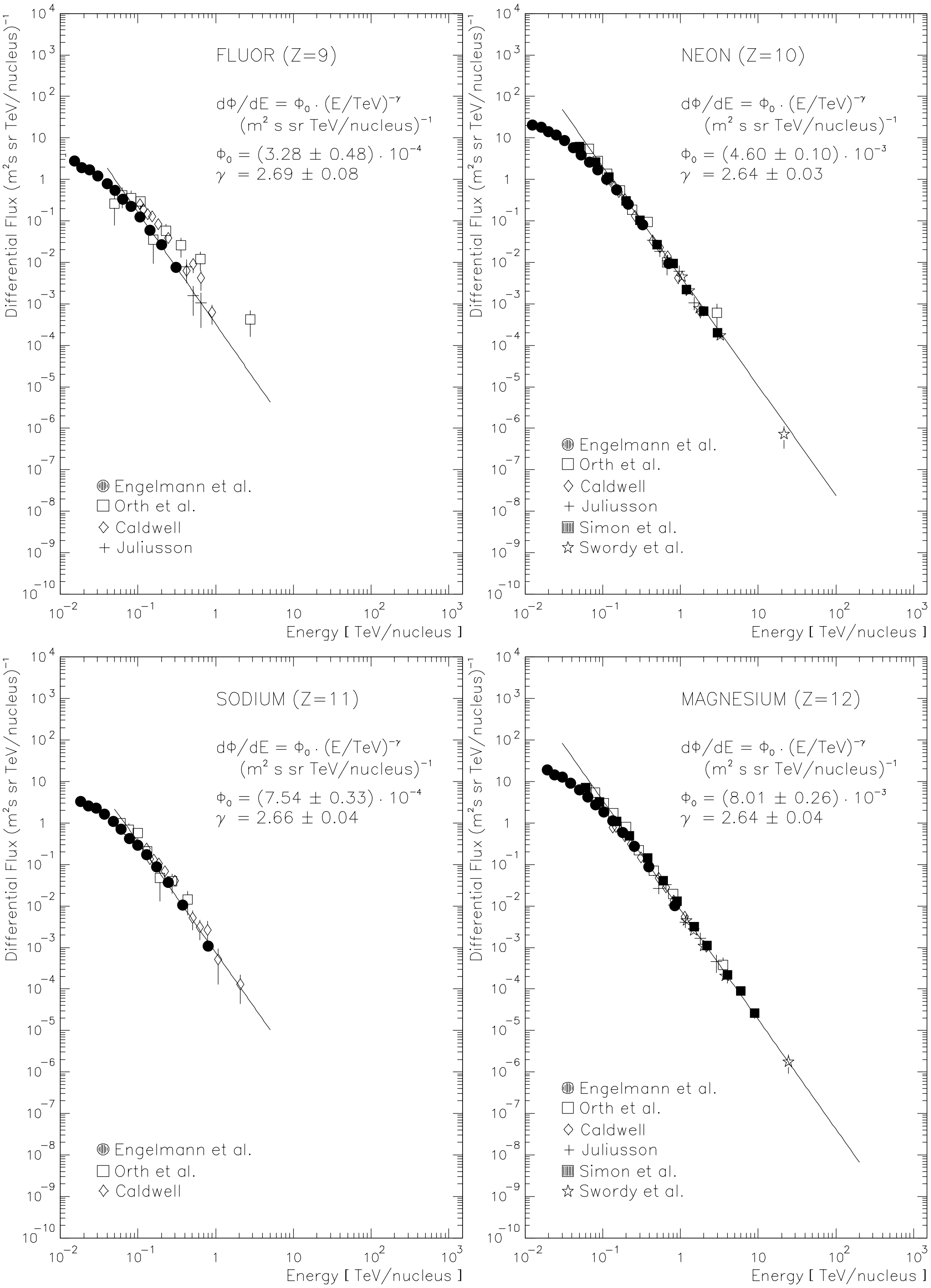

Fig. 5. Differential energy spectra of the elements F, Ne, Na and Mg.

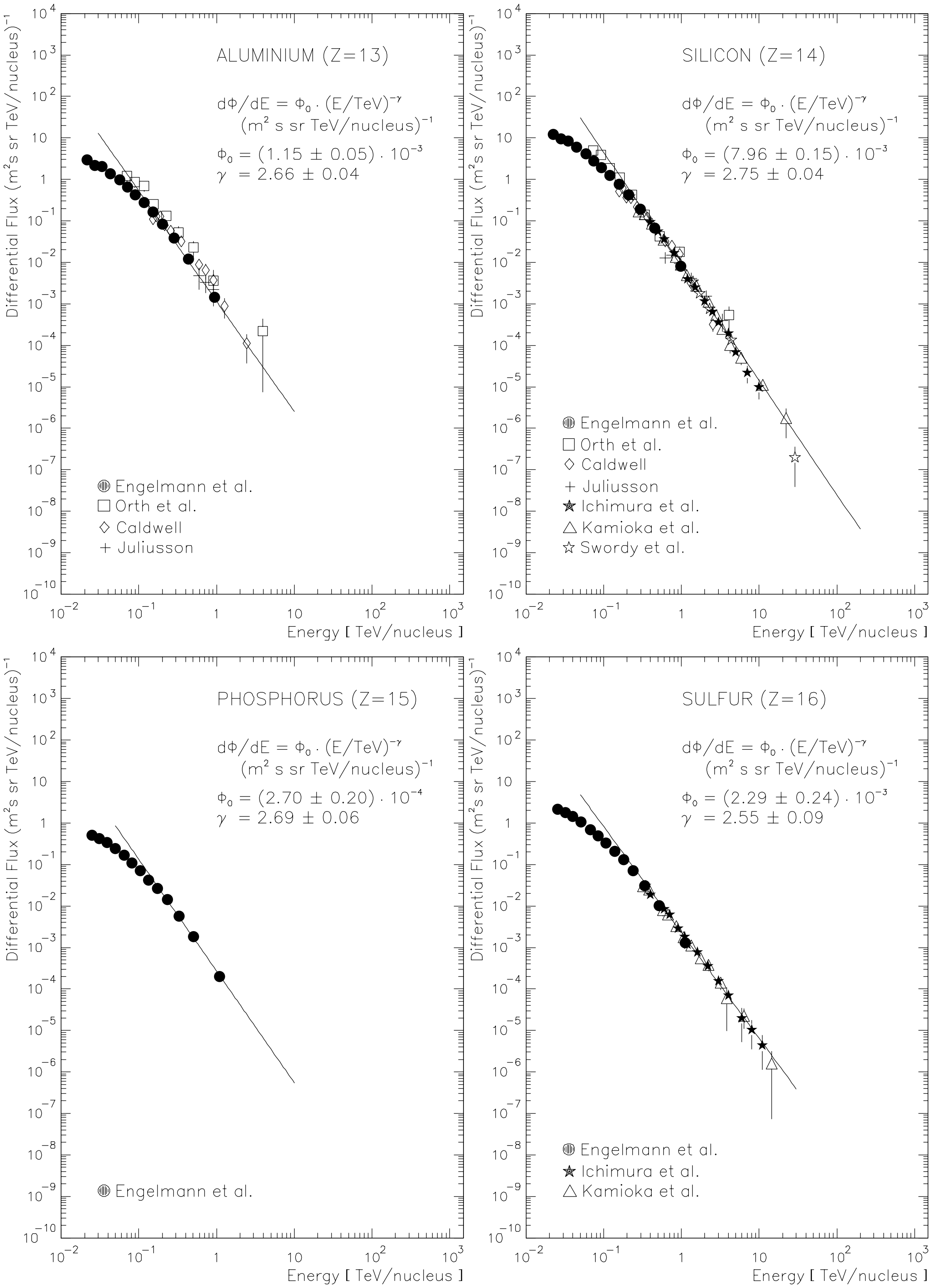

Fig. 6. Differential energy spectra of the elements Al, Si, P and S.

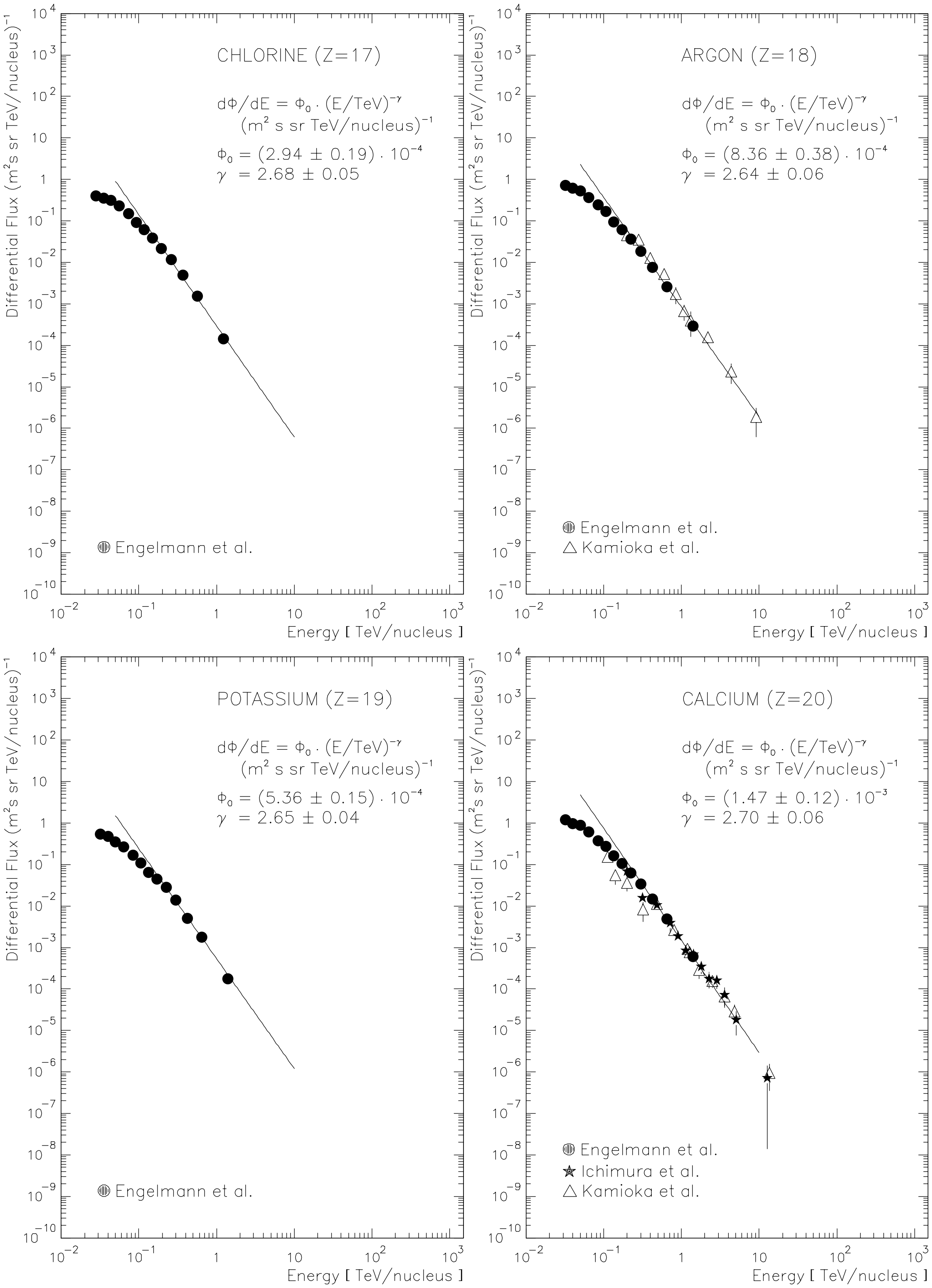

Fig. 7. Differential energy spectra of the elements Cl, Ar, K and Ca.

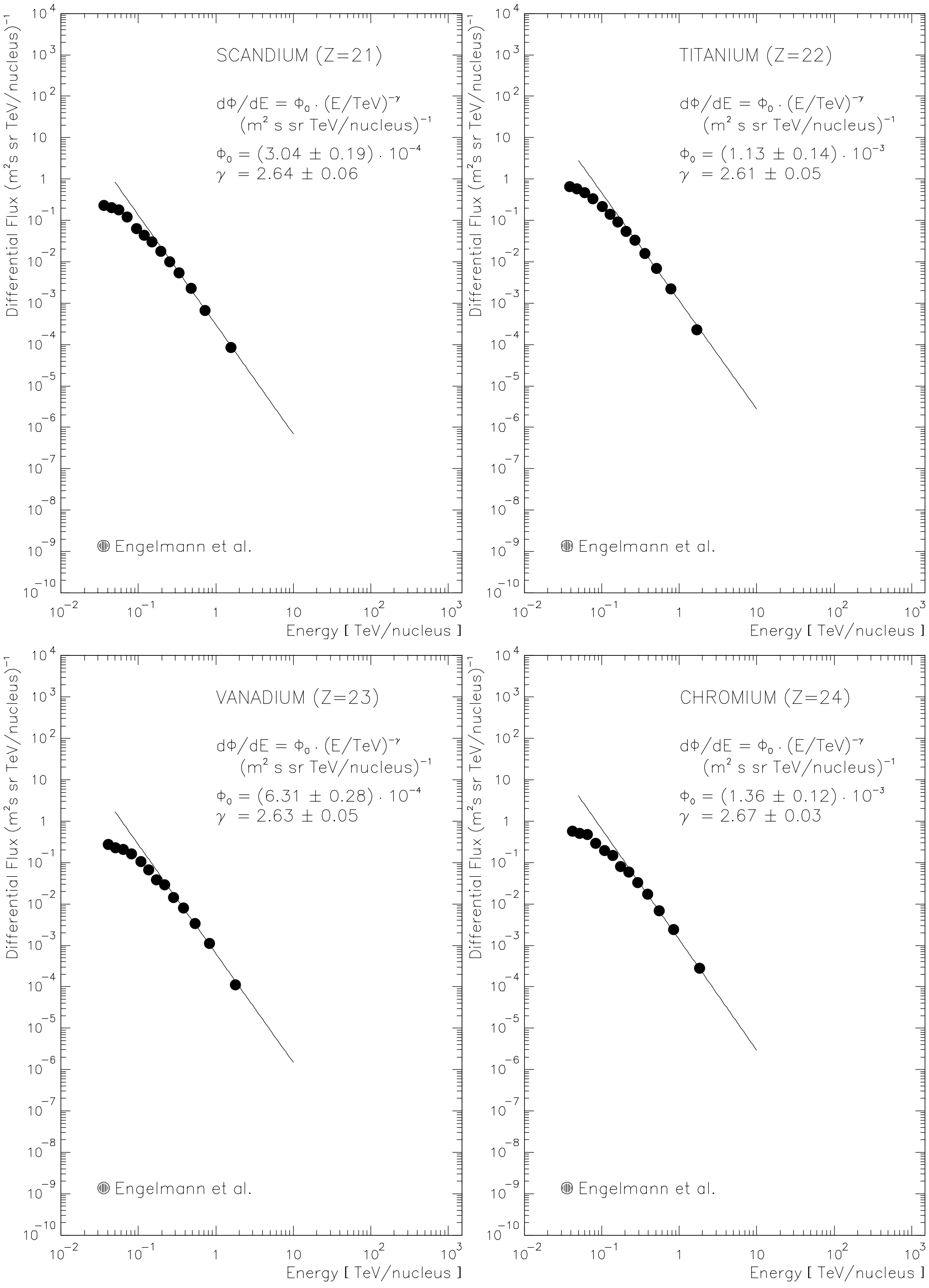

Fig. 8. Differential energy spectra of the elements Sc, Ti, V and Cr.

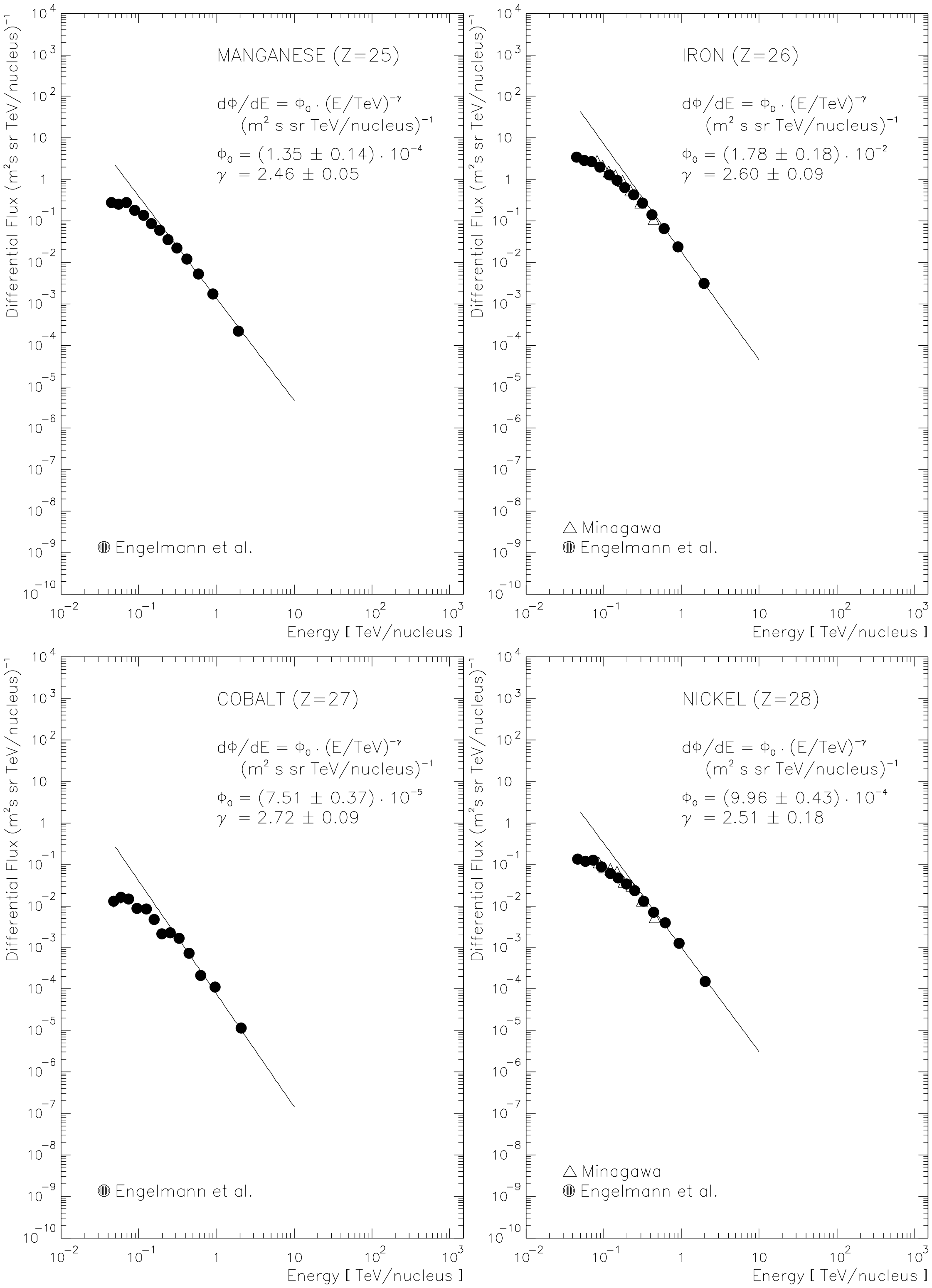

Fig. 9. Differential energy spectra of the elements Mn, Fe, Co and Ni.

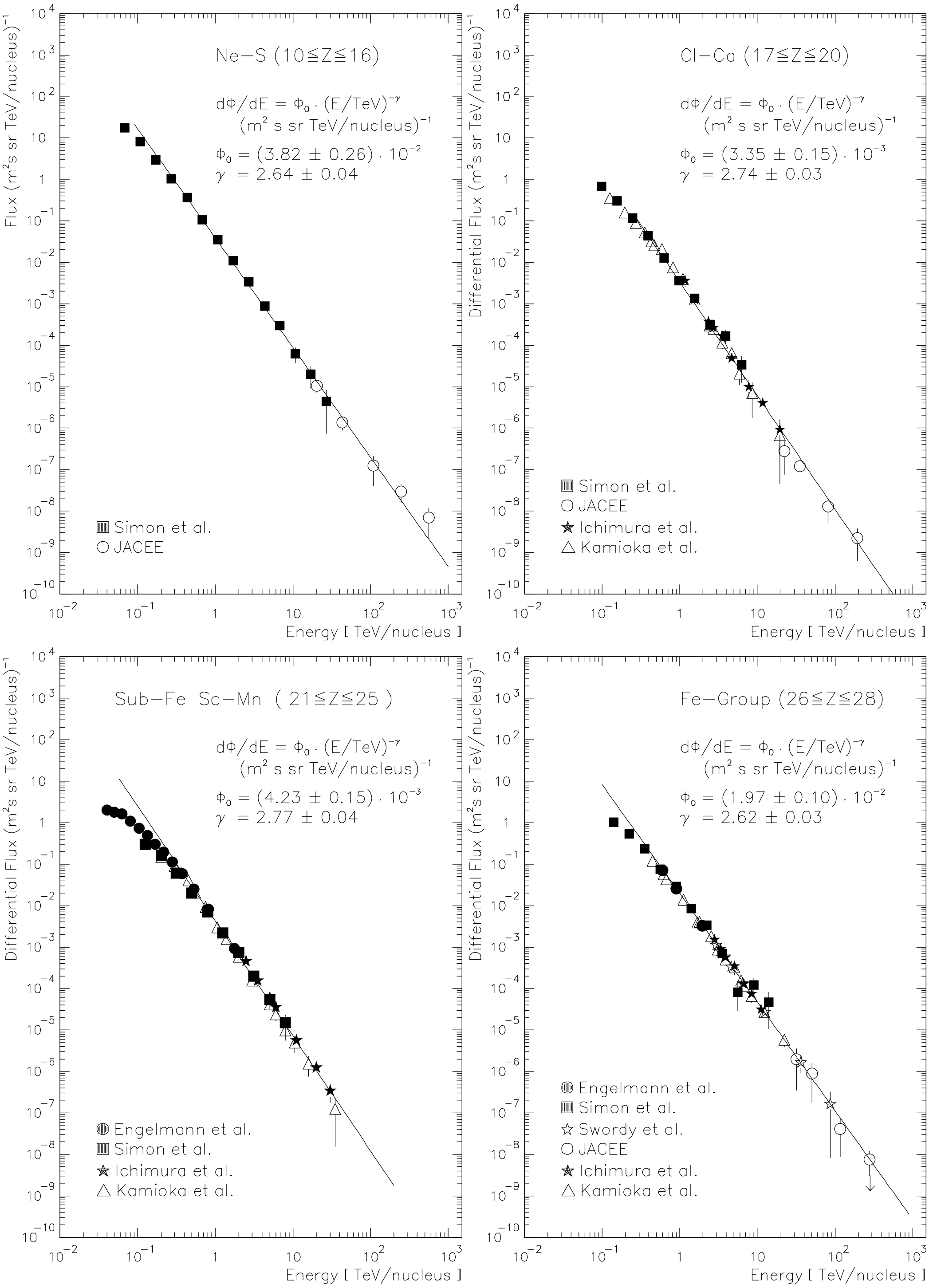

Fig. 10. Differential energy spectra of the element groups Ne – S, Cl – Ca, Sc – Mn and Fe – Ni.

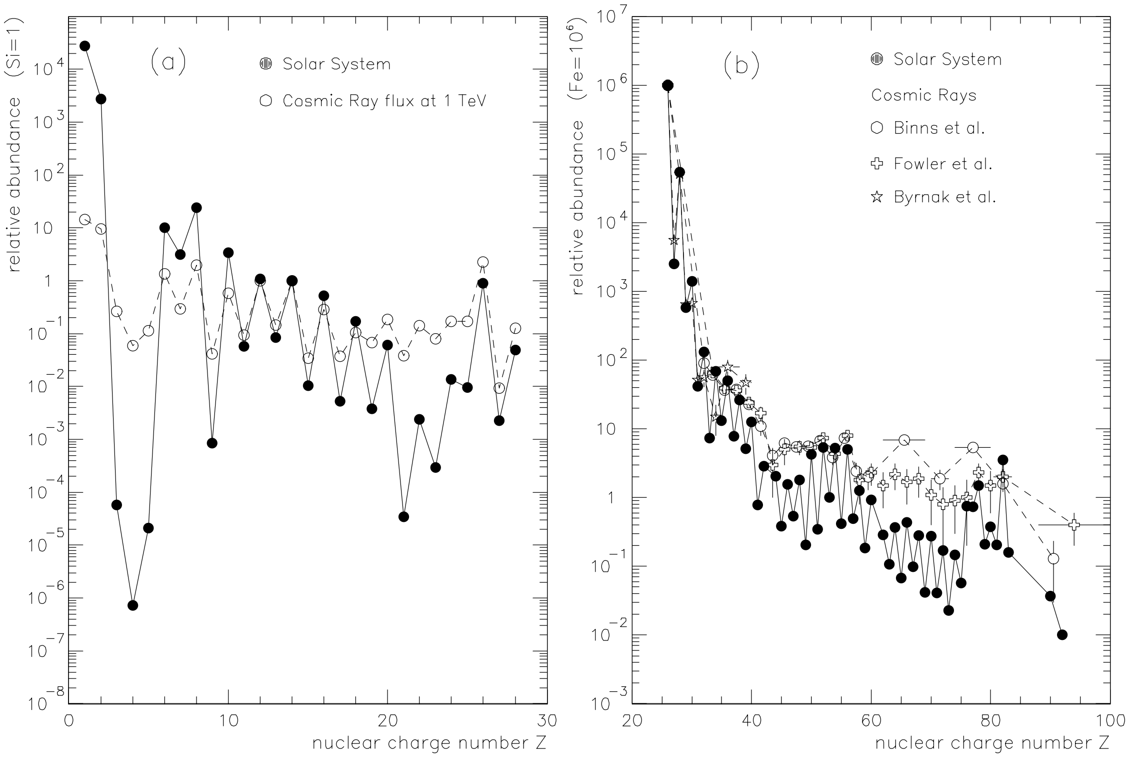

Fig. 11. The abundances of the various nuclei in the cosmic radiation compared to the abundances of the elements in the solar system. **a** The elements H – Ni (normalized to Si = 1, cosmic ray flux at 1 TeV per nucleus). **b** The elements Fe – Fm (normalized to Fe = 10^6, cosmic ray flux > 1.5 GeV/nucleon). The solar system abundances were taken from Grevesse & Anders [89G].

Table 4. The spectral indices γ and absolute flux normalizations Φ_0 for the various elements with nuclear charge number Z.

Element	Z	Φ_0 [m^2 s sr TeV/nucleus]$^{-1}$	γ	χ^2/df
Single elements				
H	1	$(10.57 \pm 0.30)\cdot 10^{-2}$	2.76 ± 0.02	0.70
He	2	$(6.73 \pm 0.20)\cdot 10^{-2}$	2.63 ± 0.02	2.10
Li	3	$(2.08 \pm 0.51)\cdot 10^{-3}$	2.54 ± 0.09	0.90
Be	4	$(4.74 \pm 0.48)\cdot 10^{-4}$	2.75 ± 0.04	0.37
B	5	$(8.95 \pm 0.79)\cdot 10^{-4}$	2.95 ± 0.05	0.45
C	6	$(1.06 \pm 0.01)\cdot 10^{-2}$	2.66 ± 0.02	1.42
N	7	$(2.35 \pm 0.08)\cdot 10^{-3}$	2.72 ± 0.05	1.91
O	8	$(1.57 \pm 0.04)\cdot 10^{-2}$	2.68 ± 0.03	1.70
F	9	$(3.28 \pm 0.48)\cdot 10^{-4}$	2.69 ± 0.08	0.47
Ne	10	$(4.60 \pm 0.10)\cdot 10^{-3}$	2.64 ± 0.03	3.14
Na	11	$(7.54 \pm 0.33)\cdot 10^{-4}$	2.66 ± 0.04	0.36
Mg	12	$(8.01 \pm 0.26)\cdot 10^{-3}$	2.64 ± 0.04	0.10
Al	13	$(1.15 \pm 0.15)\cdot 10^{-3}$	2.66 ± 0.04	1.24
Si	14	$(7.96 \pm 0.15)\cdot 10^{-3}$	2.75 ± 0.04	0.10

Element	Z	Φ_0 [m^2 s sr TeV/nucleus]$^{-1}$	γ	χ^2/df
Single elements (continued)				
P	15	$(2.70 \pm 0.20)\cdot 10^{-4}$	2.69 ± 0.06	0.68
S	16	$(2.29 \pm 0.24)\cdot 10^{-3}$	2.55 ± 0.09	0.44
Cl	17	$(2.94 \pm 0.19)\cdot 10^{-4}$	2.68 ± 0.05	2.36
Ar	18	$(8.36 \pm 0.38)\cdot 10^{-4}$	2.64 ± 0.06	0.45
K	19	$(5.36 \pm 0.15)\cdot 10^{-4}$	2.65 ± 0.04	4.58
Ca	20	$(1.47 \pm 0.12)\cdot 10^{-3}$	2.70 ± 0.06	0.60
Sc	21	$(3.04 \pm 0.19)\cdot 10^{-4}$	2.64 ± 0.06	0.81
Ti	22	$(1.13 \pm 0.14)\cdot 10^{-3}$	2.61 ± 0.06	5.67
V	23	$(6.31 \pm 0.28)\cdot 10^{-4}$	2.63 ± 0.05	6.83
Cr	24	$(1.36 \pm 0.12)\cdot 10^{-3}$	2.67 ± 0.06	3.41
Mn	25	$(1.35 \pm 0.14)\cdot 10^{-3}$	2.46 ± 0.22	5.38
Fe	26	$(1.78 \pm 0.18)\cdot 10^{-2}$	2.60 ± 0.09	1.81
Co	27	$(7.51 \pm 0.37)\cdot 10^{-5}$	2.72 ± 0.09	1.13
Ni	28	$(9.96 \pm 0.43)\cdot 10^{-4}$	2.51 ± 0.18	5.47
Groups of elements				
Ne – S	10…16	$(3.34 \pm 0.18)\cdot 10^{-2}$	2.69 ± 0.03	4.02
Cl – Ca	17…20	$(3.35 \pm 0.15)\cdot 10^{-3}$	2.74 ± 0.03	0.35
Sc – Mn	21…25	$(4.23 \pm 0.10)\cdot 10^{-3}$	2.77 ± 0.04	2.04
Fe – Ni	26…28	$(1.97 \pm 0.10)\cdot 10^{-2}$	2.62 ± 0.03	0.12
Groups of elements by adding up single nuclei and groups of nuclei				
low	1…2	$(17.40 \pm 0.96)\cdot 10^{-2}$	2.70 ± 0.02	
Li – B	3…5	$(3.49 \pm 0.40)\cdot 10^{-3}$	2.72 ± 0.06	
Be + B	4…5	$(1.36 \pm 0.11)\cdot 10^{-3}$	2.90 ± 0.04	
medium	6…8	$(2.86 \pm 0.06)\cdot 10^{-2}$	2.67 ± 0.02	
high	10…16	$(2.84 \pm 0.19)\cdot 10^{-2}$	2.66 ± 0.03	
very high	17…26	$(1.34 \pm 0.09)\cdot 10^{-2}$	2.63 ± 0.03	
Sc – Mn	21…25	$(4.74 \pm 0.20)\cdot 10^{-3}$	2.63 ± 0.03	
Fe – Ni	26…28	$(1.89 \pm 0.10)\cdot 10^{-2}$	2.60 ± 0.04	
He – Ni	2…28	$(14.20 \pm 0.80)\cdot 10^{-2}$	2.64 ± 0.03	
allparticle	1…28	$(25.70 \pm 1.63)\cdot 10^{-2}$	2.68 ± 0.03	

Table 5. References of the direct experiments which provided data on the composition of the primary cosmic radiation up to several 100 TeV/particle.

Elements	References		Elements	References	
H – Ni	Barbiellini et al.	[97B1]	H – Ni	Lezniak & Webber	[78L]
	Buckley et al.	[93B5]		Menn et al.	[97M1]
	Caldwell	[77C]		Minagawa	[81M]
	Engelmann et al.	[l]		Orth et al.	[78O]
	Ichimura et al.	[u]		Papini et al.	[93P1]
	Ivanenko et al.	[w]		Ryan et al.	[72R]
	JACEE	[o]		Simon et al.	[80S]
	Júliusson	[74J]		Swordy et al.	[g]
	Kamioka et al.	[97K3]		Zatsepin et al.	[q]

Elements	References	
$Z > 26$	Binns et al.	[m]
	Byrnak et al.	[83B]
	Fowler et al.	[87F]

7.6.6 The isotope ratios

For a number of cosmic ray constituents even the isotopic abundances are available. This required the development of detectors, that supply a good charge resolution and supplementary also a high sensitivity for the nuclear mass A. Currently existing detectors are operating with a mass resolution of better than 0.2 amu [97C7].

The determination of the elemental as well as the isotopic composition of the cosmic radiation is of greatest importance, since the cosmic ray nuclei are the only accessible sample of matter from outside the solar system, and therefore critical test of current ideas and models for the nucleosynthesis of elements, the evolution of stars and the interstellar medium are possible. On the one hand the isotopic abundances reflect the nucleosynthesis processes at their astrophysical source sites, and on the other hand the radioactive nuclides reveal the history of their propagation through the interstellar medium. Detailed knowledge of the cosmic ray source composition combined with the mean confinement time of cosmic rays in the galaxy would have important astrophysical implications, since it constrains models of the chemical evolution of the galaxy and also directly yields the accelerator input power required to maintain the cosmic ray equilibrium in the galaxy.

Of special interest are those isotopes, that are radioactive and are only produced as secondaries in collisions of the cosmic ray primaries with the nuclei of the interstellar medium. If the production rates of different isotopes for a given element are known, from the measurement of the surviving fraction of these radioactive nuclides to the stable ones, the average density of interstellar matter traversed by the cosmic rays can be estimated and within the framework of a propagation model the typical confinement or escape time T_{esc} of spallation products in the galaxy determined. The most favorite isotopes are ^{10}Be with a lifetime of $t_{1/2} = 1.6 \cdot 10^6$ y, ^{36}Cl with $t_{1/2} = 3.08 \cdot 10^5$ y and ^{26}Al with $t_{1/2} = 8.7 \cdot 10^5$ y. From these isotopes a time scale of cosmic ray confinement of $\approx 10^7$ years was evaluated, which requires an input power of about 10^{40} erg/s to maintain the cosmic ray equilibrium in the galaxy [97C5].

The isotopic abundances of the heavier nuclei (Be – Fe) are used to perform subtle tests on the origin of the cosmic radiation as these abundances are strongly related to the composition of the sources as well as to the related nucleosynthesis processes. If the isotopic ratio of a given element is measured, a detailed propagation calculation of these nuclei through the interstellar medium is performed, including secondary and tertiary production as well as ionization losses and decay, which finally leads to the cosmic ray source composition. In general it is found, that most common isotopes of the heavier elements are nearly the same as found in the solar system, but in a number of cases, a significantly higher abundance of neutron rich isotopes is found among cosmic ray particles (e.g. ^{21}Ne, ^{22}Ne and ^{57}Fe), which would require a source, that favors the production of these isotopes.

A detailed overview of the abundances of several isotopes measured so far in the cosmic radiation as well as the evaluated escape times from the galaxy and cosmic ray source abundances is given in Table 6.

Table 6. The isotopic composition of the cosmic radiation. In some cases experimental groups performed a propagation calculation of individual nuclei through the interstellar medium and derived the ratio of cosmic ray source to solar system abundance of several isotopes. Further in case of radioactive isotopes, the mean escape or confinement time in the galaxy T_{esc} are given.

Isotope	Measured ratio [%]	Energy [MeV/nucleon]	Ref.	CR source/solar system abundance	T_{esc} [10^6 y]	Ref.
^{7}Be/Be	56.3 ± 1.3	68…135	97C4			
	52.4 ± 2.9	43…113	94L1			
	57.2 ± 4.9	43…113	97L2			
	54.6 ± 2.9	60…185	80W			
^{9}Be/Be	39.1 ± 1.3	68…135	97C4			
	43.3 ± 3.7	37…98	94L1			
	38.1 ± 4.1	37…98	97L2			
	39.0 ± 2.9	60…185	80W			
^{10}Be/Be	4.6 ± 0.6	68…135	97C4		18 ± 3	97C4
	4.3 ± 1.5	35…92	94L1		27^{+19}_{-9}	94L1
	4.7 ± 1.3	35…92	97L2			
	6.4 ± 1.5	60…185	80W		$8.4^{+4.0}_{-2.4}$	80W
^{10}B/B	$23.8^{+1.1}_{-0.8}$	85…205	88K			
	30.2 ± 1.5	45…119	97L2			
^{13}C/^{12}C	6.3 ± 0.2	129	97C7	0.8 ± 0.1 ± 0.7		97C7
	5.97 ± 0.46	48…126	94L2	0.09 ± 0.36		97L1
	6.29 ± 0.33	48…126	96W			
	7.0 ± 0.6	130…300	81W			
^{17}O/^{16}O	1.21 ± 0.06	152	97C7	–3.1 ± 1.4 ± 4.8		97C7
	1.35 ± 0.24	57…150	94L2			
	1.57 ± 0.16	57…150	96W			
^{18}O/^{16}O	1.47 ± 0.07	152	97C7	–0.2 ± 0.3 ± 1.0		97C7
	1.62 ± 0.23	55…145	94L2	1.04 ± 0.72		97L1
	1.54 ± 0.14	55…145	96W			
^{21}Ne^{20}Ne	23.0 ± 0.9	168	97C7	100 ± 20 ± 63		97C7
	19.7 ± 3.7	65…172	94L2			
	22.2 ± 1.8	65…150	97W1			
^{22}Ne/^{20}Ne	59.0 ± 1.7	168	97C7	2.97 ± 0.15 ± 0.33		97C7
	60.7 ± 6.0	63…167	94L2	4.72 ± 0.43		97L1
	53.3 ± 2.9	65…150	97W1			
^{25}Mg/^{24}Mg	20.5 ± 0.6	190	97C7	1.05 ± 0.05 ± 0.09		97C7
	16.9 ± 2.6	72…192	94L2	1.06 ± 0.12		97L1
	22.3 ± 1.3	73…169	97W1			
^{26}Mg/^{24}Mg	23.1 ± 0.7	190	98S1	1.07 ± 0.05 ± 0.08		97C7
	22.6 ± 2.4	70…187	97C8	1.15 ± 0.11		97L1
	25.7 ± 1.3	73…169	94L3			

Isotope	Measured ratio [%]	Energy [MeV/nucleon]	Ref.	CR source/solar system abundance	T_{esc} [10^6 y]	Ref.
$^{26}Al/^{27}Al$	6.1 ± 0.7	≈370	97C7		19 ± 3	98S1
	6.4 ± 0.8	≈370	97W1		16 ± 3	97C8
	8.3 ± 2.4	77…206	81W		$13.5^{+8.5}_{-4.5}$	94L3
$^{29}Si/^{28}Si$	8.2 ± 0.4	210	97C7	$1.06 \pm 0.07 \pm 0.08$		97C7
			94L2	0.80 ± 0.18		97L1
	7.8 ± 0.9	80…187	97W1			
	$10.9^{+2.4}_{-1.4}$	100…300	81W			
$^{30}Si/^{28}Si$	6.3 ± 0.3	210	97C7	$0.97 \pm 0.09 \pm 0.12$		
	8.6 ± 1.5	77…206	94L2	1.03 ± 0.16		
	6.9 ± 0.6	80…187	97W1			
	$8.4^{+2.0}_{-1.4}$	100…300	81W			
$^{33}S/^{32}S$	18.6 ± 3.8	86…230	97W1			
$^{34}S/^{32}S$	26.2 ± 3.1	86…230	97W1	1.07 ± 0.67		97L1
$^{36}Cl/Cl$	6.4 ± 2.0	240	97C5		11 ± 4	97C5
$^{54}Fe/^{56}Fe$	11.4 ± 0.6	200…420	97C8	1.5 ± 0.1		97C6
	9.04 ± 0.86	100…300	97L1	0.93 ± 0.14		97L1
$^{55}Fe/^{56}Fe$	5.4 ± 0.4	200…420	97C6			
	<6.0	100…300	97L1			
$^{57}Fe/^{56}Fe$	$3.9^{+0.35}_{-0.38}$	200…420	97C6	$1.6^{+0.14}_{-0.16}$		97C6
	<6.3	100…300	97L1			
$^{58}Fe/^{56}Fe$	$0.34^{+0.10}_{-0.14}$	200…420	97C6	$0.6^{+0.3}_{-0.4}$		97C6
	0.83 ± 0.48	100…300	97L1	1.48 ± 0.75		97L1

7.6.7 Electrons, positrons, photons and antiprotons

In this section data on the electron, positron, antiproton and diffuse galactic and extragalactic photon spectra as well as the measured ratios of positrons/electrons and antiprotons/protons are shown (Fig. 12, 13). The references of the experiments which provided data on these spectra are given in Table 7.

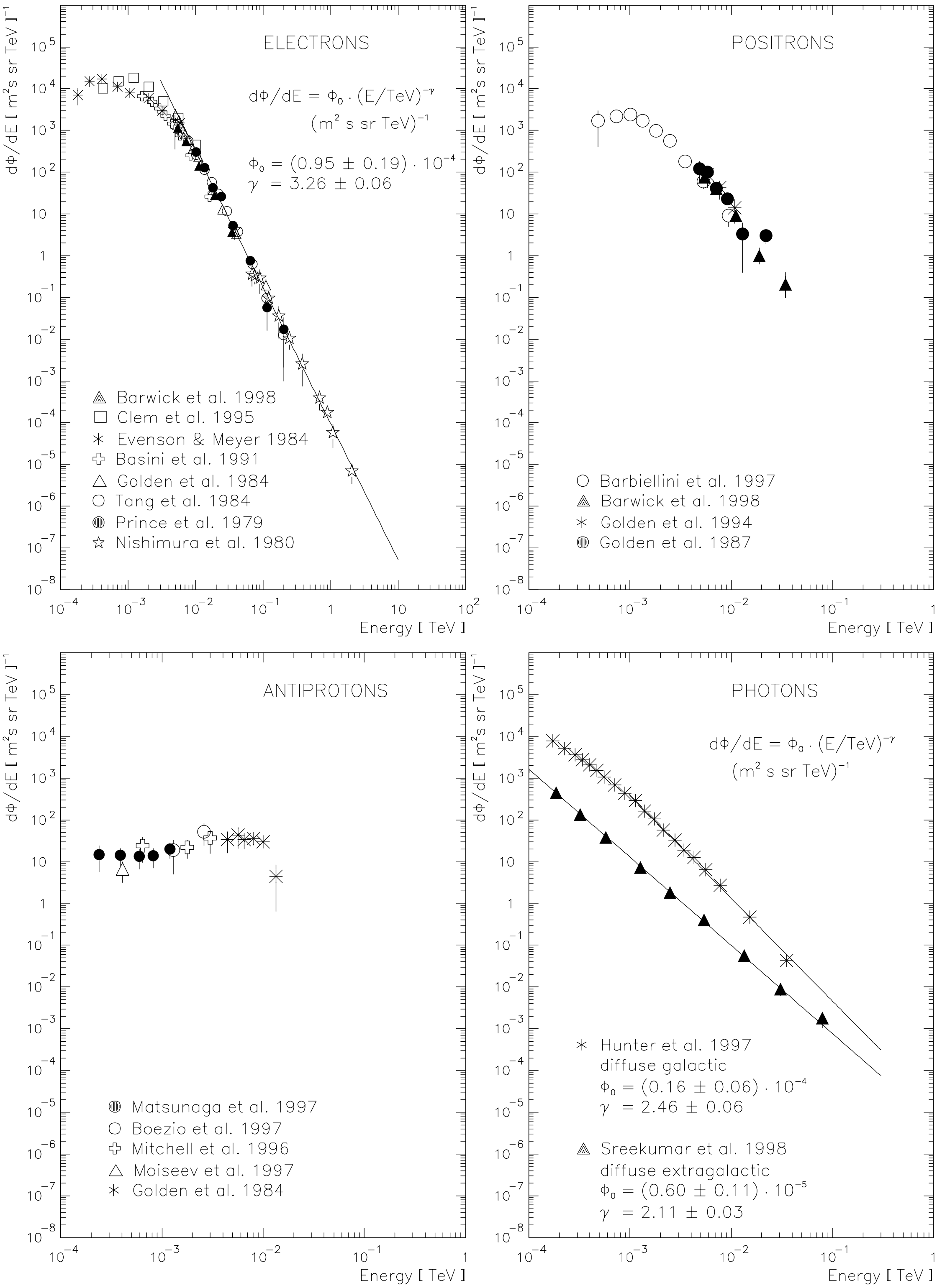

Fig. 12. Differential energy spectra of electrons, positrons, antiprotons and photons.

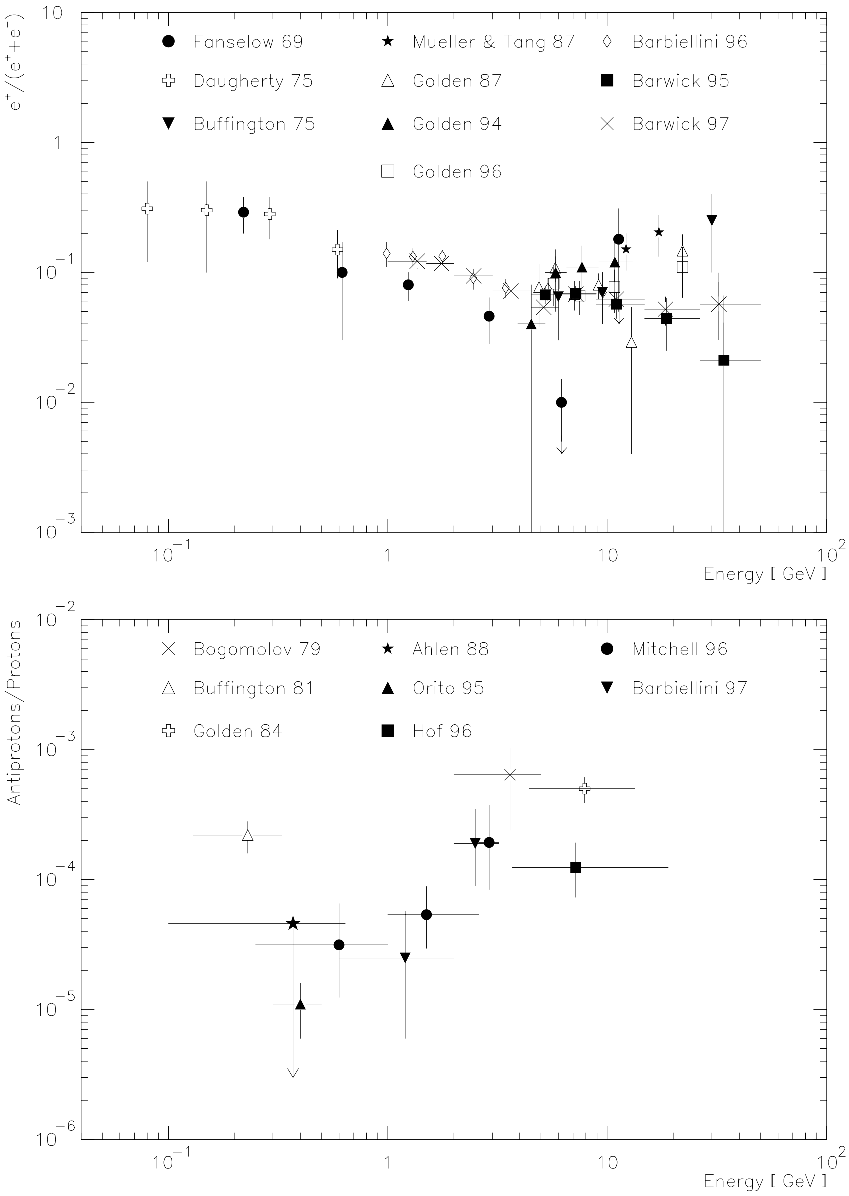

Fig. 13. The amount of positrons and antiprotons in the cosmic radiation, shown as the measured ratio of $e^+/(e^+ + e^-)$ and $\bar{p}/p$. Here only those experiments are shown, which measured the ratios directly.

Table 7. References of the direct experiments which provided data on the spectra of electrons, positrons, antiprotons and photons in primary cosmic radiation.

Particles	Reference		Particles	Reference	
e–	Electrons	[i]	$\bar{p}$	Antiprotons	[b]
e^+	Positrons	[r]	$\bar{p}/p$	Antiproton/proton-ratio	[c]
$e^+/(e^+ + e^-)$	Positron/electron-ratio	[s]	γ	Hunter et al.	[97H2]
				Sreekumar et al.	[98S3]

Antimatter

The amount of antiparticles like positrons, antiprotons and heavier anti-nuclei in the cosmic radiation is of special interest.

Antiprotons for example, are expected as a component of the cosmic radiation, which is purely produced as secondary interaction products in the collisions of cosmic ray particles with the nuclei of the interstellar medium as the primaries propagate from their sources through the turbulent galactic magnetic fields. So the observed amount of antiprotons only depends on their production rate and their subsequent diffusion in the galaxy and therefore primarily reflects the propagation history of the dominant proton component of the cosmic radiation at lower energies. In addition, since observations are made at the position of the Earth, the observed amount of antiprotons also depends strongly on solar modulation effects since the particles have to diffuse into the inner solar system.

With the known spectra of the single primary nuclei of the cosmic radiation, the knowledge of the interstellar gas composition and the relevant spallation cross sections, the expected flux of secondary antiprotons in the cosmic radiation can be estimated.

Indeed the first experiments which measured the $\overline{p}/p$-ratio reported positive evidence of antiprotons among cosmic ray particles as summarized in Table 8.

Table 8. The first measurements of antiprotons in the cosmic radiation.

Experiment	Technique	Rigidity range [GV/c]	Measured $\overline{p}/p$-ratio	Expected $\overline{p}/p$-ratio	Ref.
Golden et al. 1979	Magnetic rigidity spectrometer	5.6…12.5	$(5.2 \pm 1.5)\cdot 10^{-4}$	$1…2\cdot 10^{-4}$	79G
Bogomolov et al. 1979	Magnetic rigidity spectrometer	2…5	$(6.4 \pm 4)\cdot 10^{-4}$	$3\cdot 10^{-5}…10^{-4}$	79B
Buffington et al. 1981	Spark chamber	0.13…0.37	$(2.2 \pm 0.6)\cdot 10^{-4}$	$10^{-6}…10^{-5}$	81B

Surprisingly they reported results, which were in large excess over the expectation from a purely secondary origin, most striking at lower energies (< 400 MV/c), where the production of antiprotons in hadronic interactions is heavily suppressed by reaction kinematics and cross-sections.

Due to these experimental results, numerous suggestions were made to account for the apparent excess of antiprotons at all measured energies. In addition to the possibility that they were of extragalactic origin and provided evidence for cosmological antimatter other explanations favored exotic sources, like the evaporation of primordial black holes, the annihilation of photinos or nonstandard models for the transport of cosmic rays through the galaxy [95S6]. Fortunately recent measurements (see Fig. 13) reported $\overline{p}/p$-ratios 1…2 orders of magnitude below the former results and now up to nearly 10 GeV the antiprotons are satisfactorily explained as the secondary products of cosmic ray interactions with the interstellar medium. Fig. 14 shows the latest results on the $\overline{p}/p$-ratio together with the predictions of Gaisser and Schaefer [92G] according to the standard leaky box and diffusive halo model.

Searches for heavier anti-nuclei with $Z \geq 2$ are of far-reaching relevance, because unlike the antiprotons there is no background flux which can be produced by hadronic interaction in the interstellar medium. Therefore the discovery of just one single completely unambiguous anti-nucleus would provide conclusive evidence for cosmologically significant amounts of antimatter in the Universe. But so far no anti-nucleus with $Z \geq 2$ has been found in the cosmic radiation and currently the best upper limit of the anti-helium/helium ratio is $< 8.1\cdot 10^{-6}$ (95 % confidence level, rigidity range 1.6…16 GV/c) reported by the BESS collaboration [97O].

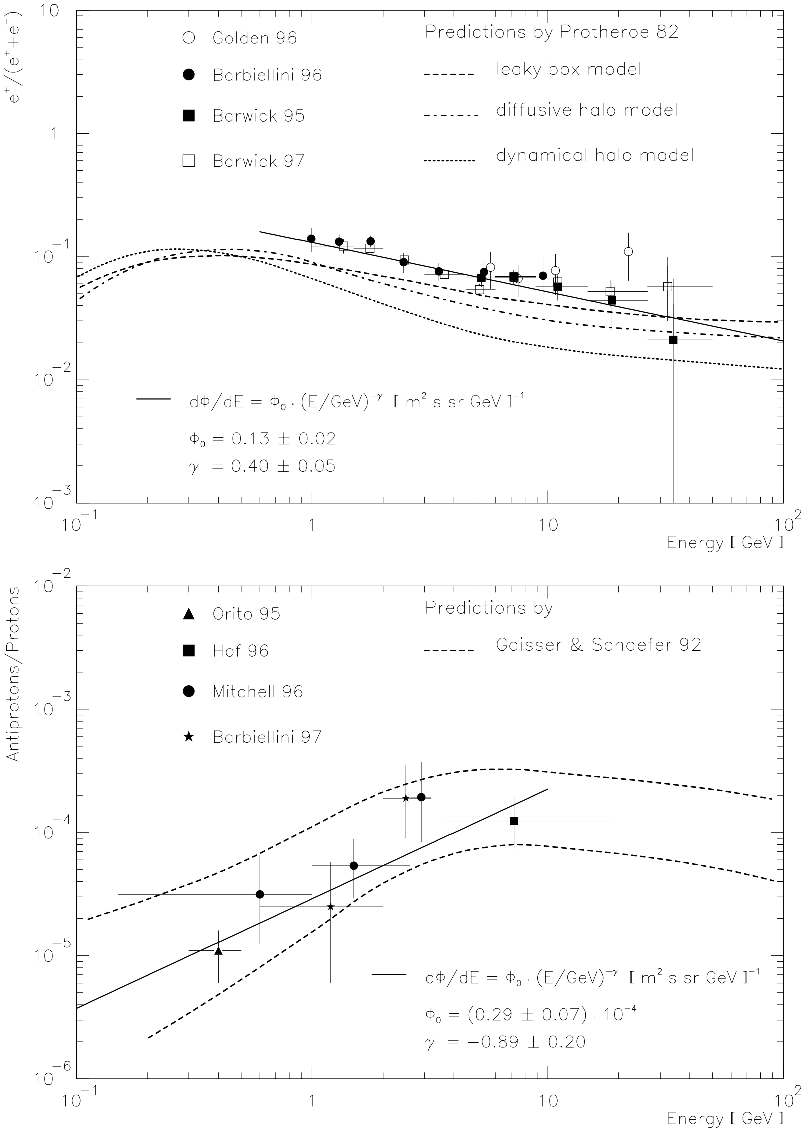

Fig. 14. The observed ratios of $e^+/(e^+/e^-)$ and $\overline{p}/p$ in the cosmic radiation. Shown are only measurements since 1995 together with recent theoretical predictions and a simple power law description of the data.

In the near future the following two missions are planned to search for anti-nuclei in the cosmic radiation:

- The Alpha Magnetic Spectrometer **AMS** [94A]:

  The AMS device is planned to be attached to the international space station in the year 2000 for three years of operation. It is designed to search for primordial anti-nuclei ($Z \geq 2$, $E > 0.5$ GeV/particle) on the level antimatter/matter $\cong 10^{-9}$ in the cosmic radiation. Furthermore it will provide data on the fluxes of antiprotons and positrons at the top of the atmosphere.

- The **PAMELA** experiment [95A2, 97A1]:

  PAMELA is planned as a permanent orbiting magnet spectrometer, which will be placed on a 700 km high polar orbit on the russian Resurs-Arktika satellite, which is scheduled to be launched in the year 2000. A long duration flight of approximately 3 years is planned. PAMELA should be able to provide high precision data on the positron and antiproton spectra from about 100 MeV up to approximately 100 GeV. Also it will search for anti-nuclei up to 30 GeV/nucleon on the level anti-helium/helium ≈ 10^{-7}.

Quite similar to the antiprotons, the bulk of cosmic ray positrons observed is also thought to be of secondary origin. Positrons should mainly originate from the decay of π^+ produced in nuclear interactions of the primary cosmic rays in the interstellar medium. In addition small amounts with energies below about 100 MeV are assumed to be produced by the decay of radioactive isotopes created by nucleosynthesis in supernovae or possibly by pair production near the surface of pulsars [82P]. Therefore the observation of high energy cosmic ray positrons combined with model predictions are a clue in understanding the propagation history of cosmic rays in the galaxy. First measurements of the e^+/e^--ratio indicated a significant increase of positrons in the 10…50 GeV range (see Fig. 13), but measurements performed during the past few years showed only a small overabundance of positrons compared with the predictions according to the standard leaky box, dynamical halo and diffusive halo model ([82P], Fig. 14). Furthermore the apparent excess seems to be consistent with uncertainties in the absolute electron flux, which directly influences the positron fraction predicted form secondary origin [97C9].

At the moment the observed amounts of antimatter in the cosmic radiation are quite consistent with a purely secondary origin, due to interactions of the cosmic ray primaries with the nuclei of the interstellar medium.

7.6.8 The allparticle spectrum

The allparticle energy spectrum provided by the different ground-based and a few direct experiments so far is shown in Fig. 15. There is quite a good agreement on the overall shape of the spectrum between the various experiments. Large differences are seen in the absolute flux normalizations, most dramatically apparent in the results of the SUGAR detector reported by Winn et al. [x]. In this experiment the primary energy was determined by analyzing the total number of muons. The use of different Monte Carlo calculations for the air shower development resulted in different conversions between muon shower size and primary energy. So finally they obtained for the allparticle flux either the upper curve in Fig. 15 or the lower one, which reflects the difficulty in evaluating the primary energy by using a single component analysis and stresses the strong dependence on the underlying Monte Carlo simulations.

Up to roughly 10^{15} eV the allparticle spectrum can also be described by a simple power law in energy with a spectral index of $\gamma \cong 2.67$ (e.g. Table 9). By adding up the single spectra of the various nuclei measured by the direct experiments, the allparticle flux as determined by the ground-based detectors is well reproduced.

Around $10^{15}…10^{16}$ eV the spectrum suddenly steepens. The detailed shape of this spectral break and its precise position are still unclear. Early investigations showed a rather sharp break at 5 PeV (e.g. Akeno [84N]), whereas some newer measurements favor a more gradual steepening starting at 1…2 PeV (e.g. Tibet ASγ [y] or Norikura [97I3]). This so-called knee was first discovered by Kulikov and Khristiansen in 1958 [58K] as a break in the shower size spectrum at $N_e \cong 8 \cdot 10^5$ corresponding to an energy of roughly 10^{16} eV. So far the knee has been found in the size spectra of electrons (e.g. [97C3, 97K1]), muons (e.g. [97G1]) and the Cherenkov light density at fixed shower core distances (e.g. [97G2]) and therefore the most natural explanation involves a corresponding break in the primary energy spectrum. The observed zenith angle dependence of the knee in the electron size spectrum reported by the KASCADE collaboration [97Gl] with a shift of the break to smaller N_e-values with increasing atmospheric depth supports the expectation for a knee at a fixed primary energy, because the shower size becomes smaller with larger zenith angle. Unfortunately the break in the electron size spectrum apparent in Tien Shan and ANI data [95D] is totally independent on the zenith angle, with a break always at a fixed N_e. Furthermore if the data from Tien Shan are selected according to young showers that have not reached their maximum yet, the break becomes even absent. This might reflect even an absence of a break in the primary spectrum and would support a totally different origin of the knee [97N].

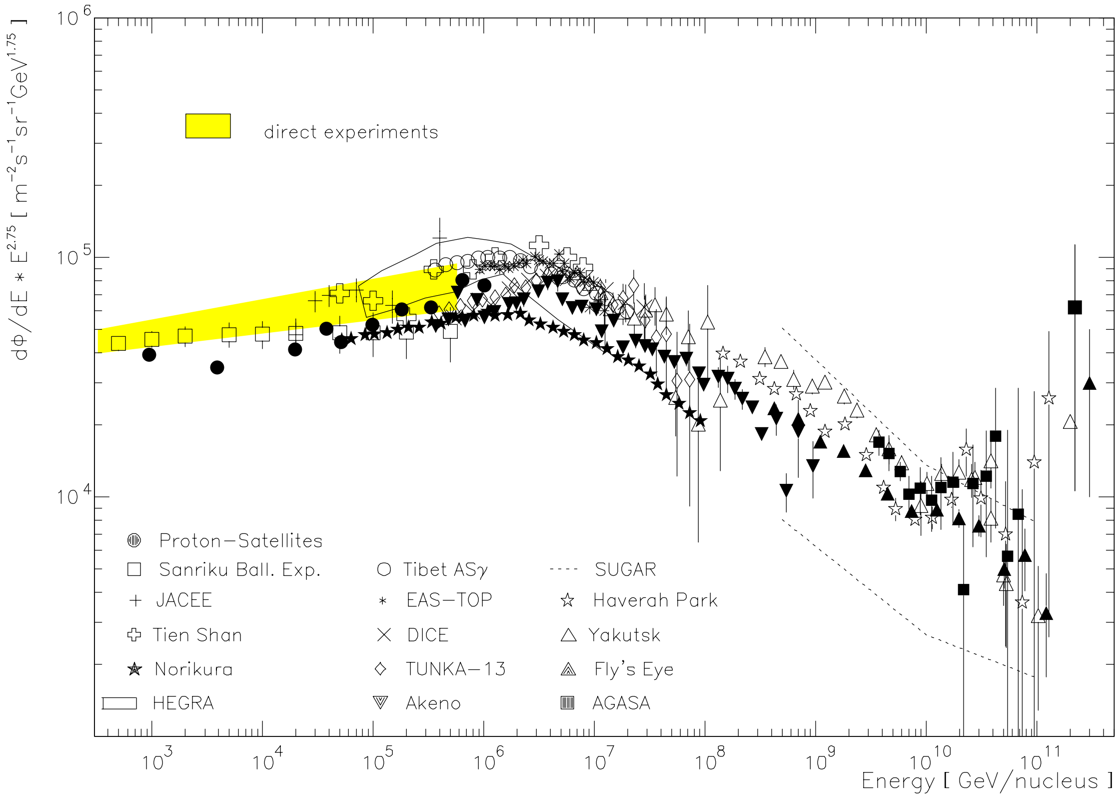

Fig. 15. The allparticle energy spectrum as measured by different ground-based experiments and three direct ones. For comparison the allparticle flux obtained by adding up the single spectra of individual nuclei as measured by the bulk of direct experiments is also given. To emphasize changes in the spectral slope, the differential flux is multiplied by $E^{2.75}$. (References see Tables 1 and 2).

Table 9. Spectral indices for hydrogen, helium and heavier nuclei as well as for the allparticle spectrum.

Experiment	Energy range	Element range	Spectral index	Ref.
predicted	below knee	H	2.75 ± 0.04	97B4
Webber	1…50 GeV	H + He	2.70 ± 0.05	87W
LEAP	10…100 GeV	H	2.74 ± 0.02	91S
Sokol	> 5 TeV	H	2.85 ± 0.14	93I
Ryan et al.	50…2000 GeV	H	2.75 ± 0.03	72R
MSU	10…200 TeV	H	3.14 ± 0.08	q
JACEE	50…200 TeV	H	2.77 ± 0.06	93A2, 93A1
Japan	8…50 TeV	H	2.82 ± 0.13	89K

Experiment	Energy range	Element range	Spectral index	Ref.
predicted	below knee	He…Fe	$2.67^{+0.04}_{-0.02}$	97B4
LEAP	10…100 GeV	He	2.68 ± 0.03	91S
RICH	100…1000 GeV	He	2.64 ± 0.09	93D
Ryan et al.	50…2000 GeV	He	2.77 ± 0.05	72R
Sokol	> 5 TeV	He	2.64 ± 0.12	93I
JACEE	50…200 TeV	He	2.67 ± 0.08	93A2, 93A1
Japan	8…50 TeV	He	2.75 ± 0.15	89K
Sokol	> 5 TeV	all	2.68 ± 0.07	93I
Akeno	$< 5{\cdot}10^{15}$ eV	all	2.62 ± 0.12	92N
Akeno	below knee	all	2.66 + syst.	93S2
Tibet ASγ	$< 10^{14.75}$ eV	all	2.60 ± 0.04	96A1
predicted	above knee	all	$3.07^{+0.14}_{-0.07}$	97B4
HP	$< 0.4{\cdot}10^{18}$ eV	all	3.01 ± 0.02	91L
HP	$0.4…4{\cdot}10^{18}$ eV	all	3.14 ± 0.06	91L
FE	$2…4{\cdot}10^{17}$ eV	all	3.07 ± 0.01	94B2
Akeno	above knee	all	3.07 + syst.	93S2
Akeno	$5{\cdot}10^{15}…6{\cdot}10^{17}$ eV	all	3.02 ± 0.03	92N
Tibet ASγ	$> 10^{15.85}$ eV	all	3.00 ± 0.05	96A1
FE	$2{\cdot}10^{17}…4{\cdot}10^{19}$ eV	all	3.18 ± 0.01	94B2
Akeno	$6{\cdot}10^{17}…7{\cdot}10^{18}$ eV	all	3.18 ± 0.08	92N

The existence of the knee is often interpreted as the consequence of a complete leakage of high energy cosmic rays out of the galaxy or the transition to other source sites [88W]. The knee can also be understood as a transition to a less efficient acceleration process in the sources, assuming that the same sources provide energies below and above the knee to about $3{\cdot}10^{18}$ eV [93B1, 95B1, 97B4]. Because in any of such models the knee is at a given rigidity, this would be accompanied by changes in the abundances of the elements, and so a thorough measurement of the chemical composition in this energy range would lead without a doubt to new conclusions on the nature of the cosmic ray sources. But so far accurate direct measurements of the composition of the primary radiation are only available up to about 100 TeV with regard to the dominant nuclei and up to about 10 TeV regarding the less abundant ones. At higher energies the results provided by ground-based detectors so far are still contradictory. For instance in Fig. 16 the measurements of four different experiments are shown. As usual the primary energy was evaluated by analyzing one of the air shower parameters, and then the mean value of another observable was compared with the Monte Carlo expectations for a pure light or pure heavy composition.

The situation below the knee looks as follows. MSU as well as DICE reported a mixed composition in good agreement with the direct measurements extrapolated to higher energies. Beyond the knee MSU reported a rapid decrease of the light elements, whereas DICE evaluated an increase of the light elements. At the upper end of the spectrum the situation looks quite similar. Fly's Eye proposes a transition from a pure heavy composition to lighter nuclei, whereas AGASA sees no dramatic change at all, but one should keep in mind that all these investigations are strongly dependent on the underlying Monte Carlo simulations of the air shower development. Indeed it is already a fact, that different models can lead to different results when applied to the same data ([x, 96K2, 97D1, 97K5] and Fig. 17). Therefore considerable systematic uncertainties remain.

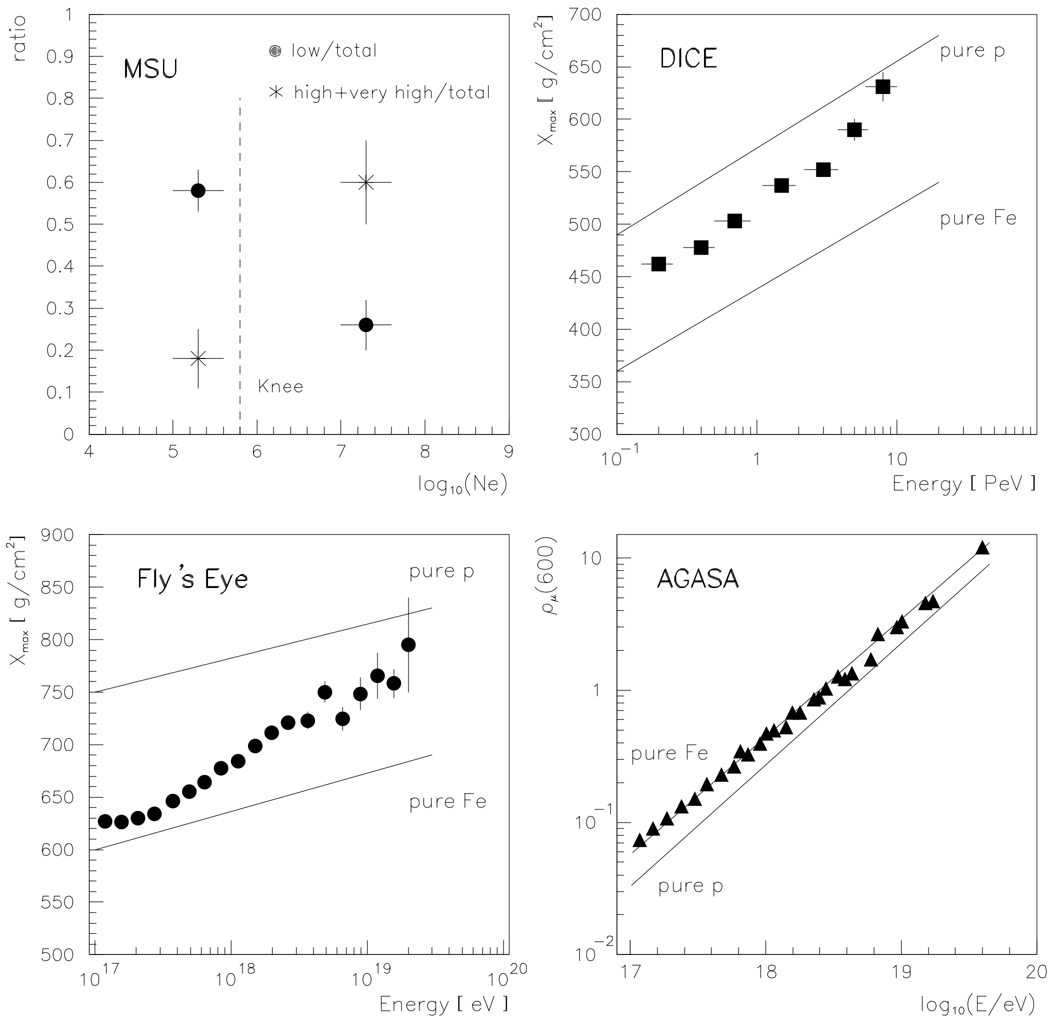

Fig. 16. The different measurements of the chemical composition by ground-based experiments yielded contradictory results so far. On the top there are two measurements which cover the knee region. The MSU results [97F] are based on the muon lateral distribution, whereas DICE [97B6] determined the height of the shower maximum by examining the Cherenkov light. In the bottom there are two measurements which cover the extremely high end of the cosmic ray spectrum. AGASA examines the muon density at a shower core distance of 600 m, Fly's Eyes calculates the height of the shower maximum by measuring the nitrogen fluorescence light. The data of both experiments were taken from [97D1]. The solid lines are the expectations for pure iron or pure protons as obtained from Monte Carlo calculations.

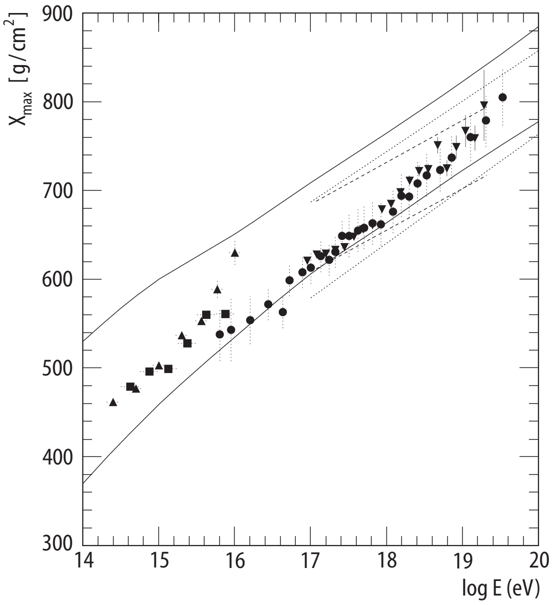

Fig. 17. The height of the shower maximum in the Earth's atmosphere measured by several experiments compared to various Monte Carlo predictions (see Fig. 16) (provided by T. Gaisser).

Beyond 10^{19} eV the detailed shape of the spectrum is of special interest. The particles are assumed to be of extragalactic origin, because at such extremely high energies the Larmor radii of charged particles exceed many times the dimension of our galaxy. Therefore they cannot be trapped within it and since they are not deflected very much by the galactic and intergalactic magnetic fields, even protons would point towards their source sites at these energies. So any kind of anisotropy in the arrival directions would provide direct information on the source sites of the extremely energetic particles of the cosmic radiation.

Unfortunately at these energies the particles will interact with the 2.7 K cosmic background radiation, detected by Penzias and Wilson in 1965 [65P]. Immediately according to the proposal by Dicke, Peebles, Roll and Wilkinson [65D] that such a radiation must exist, which uniformly permeates the whole Universe after their primeval-fireball model of the Universe and the experimental confirmation of its thermal character in 1966 [66R], Greisen [66G] and independently Zatsepin and Kuzmin [66Z] predicted a natural end of the cosmic ray spectrum, the so-called Greisen-Zatsepin-Kuzmin (GZK) cut-off. Above $3{\cdot}10^{19}$ eV the cosmic ray protons will interact with the thermal 2.7 K photons and

$$p + \gamma \rightarrow N^*(1236) \rightarrow \begin{matrix} n + \pi^+ \\ p + \pi^0 \end{matrix}$$

and therefore the contributions from distant extragalactic sources are strongly restricted. Photons are also attenuated by pair production with photons in the radio band. Calculations yielded [89S], that a sharp cut-off is expected at roughly 30 EeV, if the sources are at a distance of 150 Mpc. For a distance of 50 Mpc, the cut-off moves to ≈ 50 EeV and for a source distance of 10 Mpc, a cut-off of about 70 EeV was evaluated. Just for comparison the nearest cluster of galaxies, the Virgo cluster, is at a distance of about 20 Mpc. Up to now there is no evidence for a sharp cut-off beyond 10^{19} eV, instead it seems as if the spectrum is much flatter than expected from a pure extrapolation of the power law observed at lower energies.

Comprising the results obtained on the allparticle energy spectrum so far, reveals a lack of precise measurements above energies of approximately 100 TeV. Detailed investigations concerning energy spectrum and chemical composition beyond this energy are necessary to solve the nature of the cosmic ray sources. Especially the region of the knee has to be covered, corresponding to energies ranging from 1 PeV up to about 10 PeV. Every well determined feature in the allparticle spectrum is of greatest importance to constrain theories on the origin of the cosmic radiation. An overlap between direct and ground-based experiments would be desirable and by analyzing air shower data all the systematic effects due to changing detector performances, different simulations of the detector response and especially the different predictions of the air shower development in the atmosphere, which are based on various hadronic interaction models, have to be taken into account. To get reliable information on the primary particle, as many air shower parameters as possible should be measured, leading to cross-checks between different observables and maybe to a rejection of wrong theoretical predictions of the air shower development. On the whole this would give more confidence on the precise shape of the allparticle spectrum and on the nature of the cosmic ray sources.

7.6.9 The highest energy events

The situation with respect to the highest energies has been reviewed recently in [97B5, 98B1]. The observational situation is summarized in a special section by A.A. Watson included below, and the three highest energy events from Yakutsk are included separately.

Attached here (Table 10) is a list of all 3 events above 50 EeV, zenith angles below 45 degrees, axes within the array area, detected in Yakutsk [98I].

Table 10. Three events from Yakutsk with energies above 50 EeV (kindly provided by A. Ivanov).
δ = declination b = galactic latitude
α = right ascension l = galactic longitude

Date	UT	log (E/eV)	dE/E	δ	α	b	l	Angle error
$85^y10^m26^d$	09^h16^m	19.72	0.25	51°.0	335°.2	−5°.1	100°.6	3°
88 10 16	18 20	19.84	0.25	56.9	118.1	31.2	160.8	3
95 01 13	08 34	19.74	0.25	57.8	314.8	7.7	96.0	3

The observational situation (by A.A. Watson)

The detection of cosmic rays above 10^{14} eV is only practical because the primaries produce showers of secondary particles through electromagnetic and strong interactions within the atmosphere. The particles in these showers can be studied directly with detectors laid out over a relatively large area on the ground or indirectly by studying electromagnetic radiation created as the cascades propagate through the atmosphere. In the latter case radio emission, Cherenkov radiation and fluorescence radiation have all been used to some extent.

At energies above 10^{17} eV the generic method of particle detection has been used at Volcano Ranch, USA [93L], Haverah Park, UK [91L], Yakutsk, Russia [91E] and AGASA, Japan [92C]. In all cases, except the Haverah Park experiment where water-Cherenkov detectors were employed, the showers were measured with arrays of plastic scintillators. The particle footprint of a shower from a primary of 10^{18} eV is about 1 km^2. This sets the scale of the arrays of which that at AGASA (100 km^2) is the largest yet operated. The direction of the incoming primary is measured to within 1…3 degrees by measuring the relative arrival times of particles at the widely spaced detectors.

The only implementation of the fluorescence method has been by the Fly's Eye group at the University of Utah [j]. This technique exploits the emission of fluorescence radiation from the 2^+ band of nitrogen which is mainly in the 350…450 nm range. The direction of the shower can be measured to a few degrees from the light which is picked up by an array of photomultipliers and, most significantly, the profile of the shower cascade in the atmosphere can be traced out. A stereo pair of detectors gives the most accurate measurements.

To derive the primary energy from the pattern of densities recorded with an array of particle detectors it is necessary to model the development of the cascade in the atmosphere. This is done using Monte Carlo calculations in which assumptions are made about properties of particle interactions such as cross-sections, x-distributions and multiplicities at energies well above those accessible with man-made accelerators. As the mass of the primary cosmic rays at the highest energies is also unknown it follows that there are systematic uncertainties in the energies deduced for the primaries. By contrast the fluorescence technique allows the energy of the primary cosmic ray to be found, without recourse to model calculations, to a precision of around 20…25 %. There are, of course, systematic errors in both types of measurements, but it is found that the differential intensities at 10^{19} eV measured in the AGASA, Haverah Park, Fly's Eye and Yakutsk experiments agree to a very considerable extent. A summary compilation is shown in Table 11. The pioneering Volcano Ranch data have not been included as they are of significantly lower statistical weight but they are entirely consistent with what is shown. It is impressive that such diverse techniques are in such good agreement.

Table 11. Differential intensities at 10^{19} eV (updated version of table in [92W]).

Array	Φ_0 [m^{-2} s^{-1} sr^{-1} eV^{-1}]
AGASA	$2.91 \cdot 10^{-33}$
Fly's Eye	$2.38 \cdot 10^{-33}$
Haverah Park	$2.22 \cdot 10^{-33}$
Yakutsk	$3.39 \cdot 10^{-33}$

At higher energies the situation is less satisfactory, mainly because the statistics are small and the Fly's Eye stereo technique runs out of exposure above $4 \cdot 10^{19}$ eV. Also the Yakutsk spectrum is in sharp disagreement with those from the AGASA scintillator array and the Haverah Park water-Cherenkov array. A maximum likelihood synthesis of data from AGASA, Haverah Park and Fly's Eye by [95S3] is shown in Fig. 18. It is suggested by this plot that the spectrum continues unattenuated to the highest energies observed as represented by the single events at $2 \cdot 10^{20}$ eV [94H] and $3 \cdot 10^{20}$ eV [93B4]. This composite spectrum appears to be smooth and featureless above 10^{19} eV.

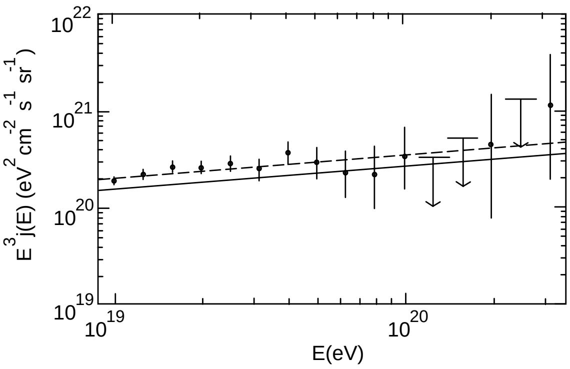

Fig. 18. Maximum likelihood fit to AGASA, Fly's Eye and Haverah Park after normalization (from Sigl et al. 1995 [95S3]).

Details of 8 events claimed to have energies above 10^{20} eV are listed in Table 12 [95W]. The AGASA group have recorded a small number of additional events of similar energy but these have not yet been described in detail.

Table 12. Details of 8 events claimed to have energies above 10^{20} eV (from Watson 1995 [95W]).
θ = zenith angle b = galactic latitude
α= right ascension l = galactic longitude
δ = declination

Detector	Date	Reference No.	Energy [10^{20} eV]	θ	α	δ	b	l
Volcano Ranch	22.04.62	4472	1.4	11°.7	306°.7	46°.8	4°.8	84°.3
Haverah Park	31.12.70	8185175	1.2 ± 0.3	35	353	19	–40	99
	05.12.71	9160073	1.05 ± 0.3	30	199	44	73	107
	18.04.75	12701723	1.2 ± 0.1	29	379	27	78	212
	12.01.80	17684312	1.05 ± 0.08	37	201	71	46	119
Yakutsk	07.05.89	890507133	1.1 ± 0.4	58.9	75.2	45.5	2.6	162.2
Fly's Eye	15.10.91		$3^{+0.36}_{-0.54}$	$43.9^{+1.4}_{-0.6}$	85.2	48	9.6	163.4
AGASA	03.12.93	25400-0296	1.7…2.6	22.9	18.9	21.1	–41	131

The spectrum of cosmic rays had been expected to be sharply attenuated above about $5\cdot10^{19}$ eV because of interactions of protons and/or nuclei with the 2.7 K cosmic microwave background (the Greisen-Zatsepin-Kuzmin (GZK) cut-off). Photons are also attenuated by pair production with photons in the radio band. There are suggestions in the AGASA data that the spectrum dips above $5\cdot10^{19}$ eV and then recovers but, as with other issues at these energies, the question is not resolved. It seems certain that events do exist well above the GZK cut-off and this implies that the sources must be relatively nearby. The $3\cdot10^{20}$ eV event must have come, with a probability > 0.9, from within 30 Mpc. A proton of this energy would be deflected by about one degree while travelling through the magnetic fields between its birthplace and the Earth. However there is no evidence of any convincing anisotropy although there are weak claims of associations with the supergalactic plane and clustering [95S5, 96H, 97U].

Our knowledge of the sources of the highest energy cosmic rays is limited by the small number of events so far detected. At 10^{20} eV the rate is only about 1 per km^2 per century so that large apertures and long exposures are necessary. An extension of the Fly's Eye detector known as HiRes [95B4] is being developed and will take data in 1999. It will have a time-averaged aperture of 340 km^2 sr at 10^{19} eV and 1000 km^2 sr at 10^{20} eV. At an advanced stage of planning, but as yet unfunded, is the Pierre Auger Project [d] which aims to combine the fluorescence and particle array techniques at locations in Argentina and the USA. The aperture of each detector of the Auger observatory is 7000 km^2 sr above 10^{19} eV and the combination of fluorescence and surface detectors will allow characterization of showers with greater precision than with either technique alone. It is hoped that construction of the Auger observatory will start in 2000. In a 10 year period around 5 events would be seen at 10^{21} eV should the spectrum extend so far, with 600…1000 events expected above 10^{20} eV. For the more distant future a space project is planned in which fluorescent light will be observed from two satellites: in this way 10^6 km^2 can be monitored.

7.6.10 Theoretical attempts

The origin of cosmic rays is still not understood and so is a question in active research [12H, 13K, 49F, 54F, 69G, 69H, 90B, 95K2]. The debate has reached a consensus, that most are produced in the shock waves of supernova explosions [34B, 53G1, 53G2, 53S, 83D, 83L, 87B2, 88B, 91J, 93G2, 96G], be it into the interstellar medium, or into a stellar wind [88V, 90S, 93B1]. Many of the relevant issues here have been dealt with in the excellent review by Hillas [84H] and in the books by Hayakawa [69H], Berezinsky et al. [90B] and Gaisser [90G]. A very recent attempt to emphasize the critical issues has been published by Webber [97W2]. The basic concept is almost always diffusive Fermi-acceleration at a shock wave. Additionally there is one rather speculative attempt to interpret all hadronic cosmic rays to be of extragalactic origin [98P]. However, when we go to quantitative models for the origin of galactic cosmic rays, there are two main approaches nowadays, with a third variant:

- 1997 Ellison et al. [97E1, 97M2] have proposed that the origin of the various chemical elements in Cosmic Rays can be traced to the injection from dust grains in shock waves in the interstellar medium. With this approach energies to about $Z \cdot 10^{14}$ eV can be understood, where Z is the charge of the nucleus under consideration. One might argue that we can push this energy up to the *knee*, that energy where the cosmic ray spectrum turns down, near a total particle energy of $5 \cdot 10^{15}$ eV. If then more distributed acceleration takes over, a different mechanism, as argued by I. Axford, then we might interpret the steeper spectrum of cosmic rays beyond the knee as a result of the less efficient acceleration. This then gives, taken as a whole, a complete possible picture of energies, spectra and chemical composition of galactic cosmic rays (see Fig. 19).

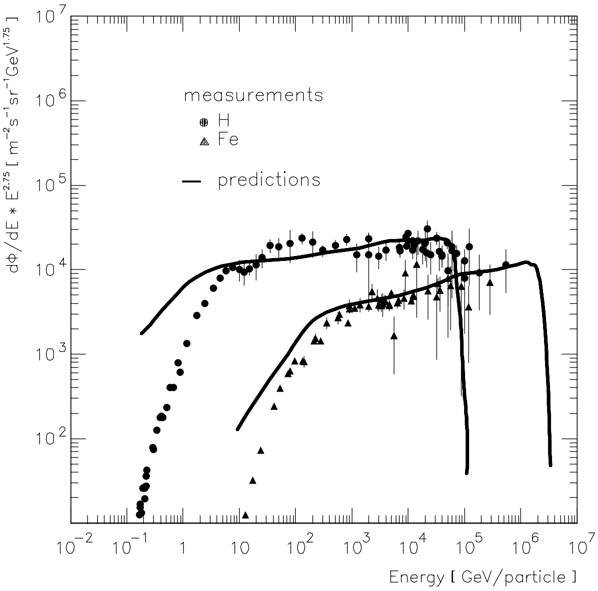

Fig. 19. The predicted spectra of H and Fe due to shock acceleration of gas and dust grains in the interstellar medium compared with the measured ones (Ellison's model).

- Biermann has proposed in a series of papers starting in 1993 ([93B1, 93B2, 93B3, 93R1, 93R2, 93S2, 95B3, 98W2], reviews in [94B1, 97B4, 97B5, 98B1, 98B2]) to produce energetic protons mainly in supernova explosion shocks in the interstellar medium, but the heavier elements all through shock waves running through a stellar wind of the predecessor star. Here one obtains the *knee* directly as a consequence of decreasing acceleration efficiency, and reaches energies up to $3 \cdot 10^{18}$ eV. The chemical composition in this picture derives directly from the composition of stellar winds of massive stars, dominated by the heavy elements for stars of zero-age-main-sequence mass of larger than about 30 solar masses. The resulting allparticle spectrum from this approach is shown in Fig. 20.

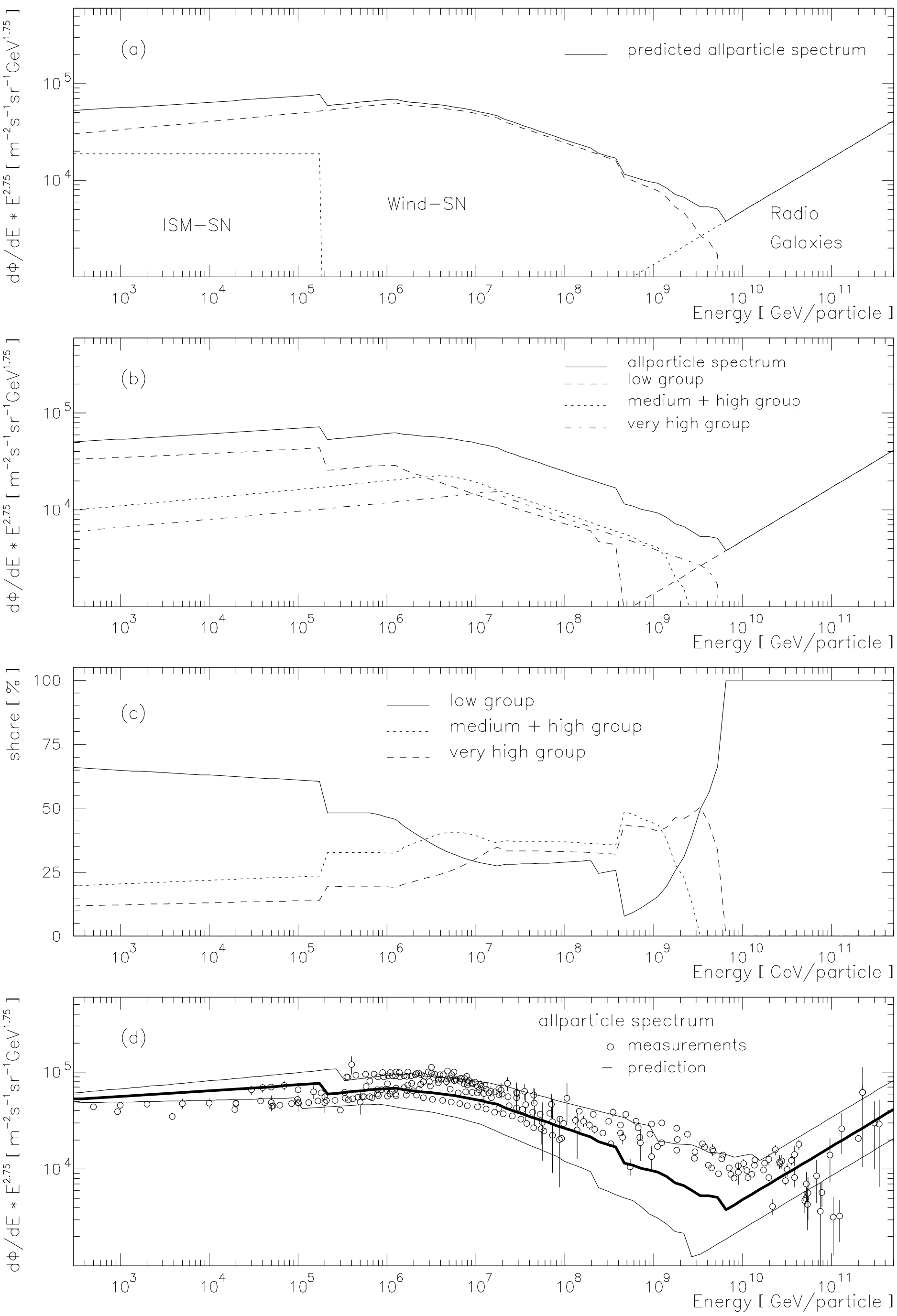

Fig. 20. a The predicted allparticle energy spectrum (Biermann's model) with the contributions of supernovae exploding into the interstellar medium (ISM-SN), supernovae exploding into their former stellar wind (wind-SN) and radio galaxy hot spots. **b** The predicted allparticle spectrum with the contributions of several element groups. **c** The percentages of the different element groups in the allparticle flux. **d** The allparticle energy spectrum measured by the different experiments so far, with the predicted allparticle spectrum shown in **a** (thick solid line) and the error range including errors inherent in the theory (thin solid lines). Concerning the extragalactic component (radio galaxy hot spots) losses coming from interactions with the microwave background above roughly $3 \cdot 10^{10}$ GeV have been ignored here.

- 1998 Ramaty proposed to use grains from the ejecta of supernova explosions of massive stars, and can match the chemical abundances and the isotopic abundances quite well [97R, 98L, 98R2].

When we move to extragalactic cosmic rays, the situation is even less clear [56C, 87B1, 91I, 94B1, 97B5, 98B1].

In the following we compare these different models briefly, and then suggest what may turn out to be decisive tests. The models have been worked out to different detail, and so a comparison is not always possible. We will refer to these models as Ellison's, Biermann's, and Ramaty's models.

- The sources for the injection are different in all models, in Ellison's model it is from grains in the interstellar medium, in Biermann's it is the stellar winds of massive stars, and in Ramaty's model it is the supernova ejecta. Since massive stars rotate, there is some mixing, the inner mass shells might well mix before the explosion and so the difference between Biermann's and Ramaty's model might be small. The difference between Ellison's model and the Biermann/Ramaty model might be the isotopic abundances, such as Fe^{57}.

- The origin of the knee is traced to a change in the acceleration efficiency in both Ellison's and Biermann's model, although the detailed physical model is very different. In either model it is difficult to understand, that the *knee* is as sharp as it is. Since in all conceivable models the knee is at a given rigidity [59P], there is considerable smearing already due to the various chemical elements. The real sharpness of the *knee*, as well as the chemical abundances through the *knee* may well exclude all presently available models. For the *knee* there are some specialized arguments by Erlykin & Wolfendale recently, proposing a local source to contribute there [97E2].

- Similarly, the possible change in chemical abundances as one moves through the *ankle* from Galactic to extragalactic sources [56C], near $3 \cdot 10^{18}$ eV is a key feature, and also a consistency check for the results closer to the *knee*. Also, the sharpness of the ultimate cut-off and any possible anisotropy there of the cosmic rays coming in will be telltale signs for their origin.

- The interstellar transport (e.g. [95S2]) is very different in Ellison's and Biermann's model: In Ellison's model the interstellar transport has an energy dependence of $E^{-0.6}$, as suggested by a stationary leaky box model and the B/C ratio at moderate energies. Light elements, odd-Z elements, as well as the sub-Fe elements derive all from spallation of heavier nuclei [74R, 94R]. In Biermann's model the interstellar transport is done with a Kolmogorov spectrum, and so has an energy dependence of $E^{-1/3}$. Therefore, in Ellison's model the B/C ratio is automatically explained, while in Biermann's model one needs to invoke the environment of young stars [98B2] or the temporal evolution of interstellar clouds [96B2].

- The abundances in cosmic rays are known to be different for elements of low first ionization potential, an effect also seen in energetic particles in the solar wind, as well as in some other stars. In Ellison's and Ramaty's model this can be explained as due to grain formation, with the solar wind properties being explained in some other way; in Biermann's model grains are not invoked, but the same physics is used for the solar wind and cosmic ray injection, namely injection from the same rigidity, i.e., different energy for ions of different degrees of ionization, given by the pre-shock gas, an idea that has been around for a long time.

Theoretically, many aspects of shock acceleration remain ununderstood, and progress is slow; recent progress has been made in some papers by H. Völk and associates [96M, 97B3], by D. Ellison, T. Jones, H. Kang, D. Ryu, and many others.

Key tests can be expected from the gamma-ray spectrum of the Galaxy, and its spatial distribution, the energetic electron spectrum, the positron and antiproton spectrum, as well as from the isotopic abundances both in cosmic rays, as well as in the interstellar medium.

- The gamma-ray spectrum of the Galaxy is posing a key problem for any model; it is normally traced to a combination of Bremsstrahlung, inverse Compton radiation, and π^0 decay from proton-proton collisions [71S]: the observed gamma-spectrum is rather flat [97H2, 97M4] suggesting that at photon energies above a GeV, the primary proton spectrum responsible for the interaction is rather flat, close to $E^{-2.1}$ to $E^{-2.4}$, not at all compatible with the average proton spectrum seen at Earth of $E^{-2.75}$; since we see the radio synchrotron emission from electrons at similar energies, we are assured that the typical proton spectrum in the Galaxy is really this steep. Therefore we need a model where the interaction to produce the gamma emission is flat, and where the spectrum which gives rise to secondaries, such as the element B from spallation, is steep. Biermann has proposed such a model, using the differences of massive stars along the main sequence [98B2]. There is also the proposal to deny that protons have anything to do with the gamma-ray-spectrum and trace it all to inverse Compton or specific sources (see, e.g., Pohl et al. [97P]). In the Ellison model there is no explanation for the gamma-ray spectrum yet.

- The gamma-ray emission from the Galaxy is extended in latitude, and that may suggest that inverse Compton is one dominant process [98H2].

- The energetic electron spectrum can be derived from the gamma emission of young supernova remnants, and such data suggest that the spectrum is close to $E^{-2.4}$ near the source [98G], posing a difficulty for Ellison's model, if generally true, and if the same spectrum holds for electrons and protons at the relevant energies.

- The positron fraction and spectrum as well as the antiproton fraction and spectrum are beginning to be available with good statistics, and those data will enable us in the future to test all models proposed.

- Certain isotopes such as Fe^{57} [97C6] pose special problems, and may need a contribution from the interior of massive stars, such as suggested by Ramaty's model. With mixing due to rotation in massive stars Biermann's model may also be able to accomodate such abundances.

- Finally, the light elements in the interstellar medium also derive to a large degree from spallation [74R, 94R], and so the abundances of light elements in old stars can be used as a key argument [97R, 98L, 98R2]. The argument is really quite simple: If the spallation derives from the heavy element abundance in the interstellar medium, then in the early days of our Galaxy there were few heavy elements, and so spallation in the interstellar medium cannot produce much of the light elements, but they are there; in the calculations of Ramaty and colleagues the difference is more than an order of magnitude. Therefore, the spallation responsible for the light element production in the early epoch of our Galaxy must have happened already at the beginning in an enriched environment, such as massive star winds (Biermann) or supernova ejecta (Ramaty). If this argument can be verified, then Ellison's model is in difficulty.

Further problems related to energetic particles are the recurrent activity at the center of our Galaxy, since we now know that most galaxies have a massive black hole at the center, including our own, and also the possibility to have occasional powerful gamma ray bursts in our Galaxy, e.g., [98H1, 98K, 98R1, 98W3]. There has been some speculation that gamma ray bursts also add to the energetic particle population from the *knee*, and so that would be a model where the source population switches near the *knee*.

The origin of the highest energy cosmic rays

This topic has been hotly debated for some time, with a recent review in [98B1]. The key problem is that the interaction with the microwave background should cut off the spectrum near about 50 EeV, and there is little sign of a cut-off, see the section 7.6.9.1 by A.A. Watson.

The proposals fall into several classes:

- A massive particle such as topological defect decays into neutrinos, gammas, and energetic protons [94S, 95S4, 96K1]. Here the key advantage is that protons are produced near 10^{24} eV and so large losses can be overcome. On the other hand, in the cascading of the gammas such a large gamma ray background is produced, that we may soon be able to decide for or against this proposal.

- Now, that there is evidence for Neutrino-oscillations from Super-Kamiokande, the proposal by T. Weiler [82W] becomes of interest: Ultra high energy cosmic rays may be the result of cosmic ray induced high energy neutrinos interacting with relic neutrinos in the halo of our Galaxy.

- Gamma ray bursts may also accelerate protons to high energy, although the cosmologically local frequency may be too small.

- Cosmological shock waves from large scale structure formation, cluster accretion shocks [97K4], galaxy collisions and galactic wind termination shocks [87J] all appear to fall a little short of producing particles of sufficiently high energy.

- Compact objects such as pulsars should correlate with the Galactic disk, and there is no such correlation for events beyond 50 EeV.

- Proton acceleration in radio galaxy hot spots does work, but there is no certain radio galaxy in sight, with the only reasonable candidates 3C134 (with a small but unknown redshift) and NGC315 [87B1, 93R1, 93R2, 97B5, 98B1, 98S4]. Fe acceleration allows larger distances, but whether we have enough flux and sufficiently high particle energies at the source is open to question.

- Finally, one speculative possibility is to convert an energetic proton in the source region into a supersymmetric partner with little interaction with the microwave background, and so get to us from large distances (Farrar, at the Maryland meeting November 97 [96F, 98C]). This requires powerful sources exactly in the line of sight of these events, and so will be testable with more accurate positioning of the high energy events.

This opens the window to new physics, and the future of this work will be exciting to follow.

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98S1 Simpson J.A., Connell J.J.: Astrophys. J. **497** (1998) L85.
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98S3 Sreekumar P., Bertsch D.L., Dingus B.L., et al.: Astrophys. J. **494** (1998) 523.
98S4 Stecker F.W.: Phys. Rev. Lett. **80** (1998) 1816.
98W2 Wiebel-Sooth B., Biermann P.L., Meyer H.: Astron. Astrophys. **330** (1998) 389.
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7.7 Interstellar magnetic field

7.7.1 General references

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Sofue, Y., Fujimoto, M., Wielebinski, R.: Global Structure of Magnetic Fields in Spiral Galaxies. Annu. Rev. Astron. Astrophys. **24** (1986) 459.
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7.7.2 Methods of determination

In addition to the methods listed in LB VI/2c subsect. 7.7.2, p. 143:

Information on the galactic magnetic field is, or can be, obtained from:

- linear polarized infrared, submillimetre, and millimetre continuum radiation emitted by magnetically aligned dust grains [88H];
- linear polarization of radio-wavelength spectral lines (polarization should be parallel to $B_\perp$, the magnetic field perpendicular to the line-of-sight) [87H];
- Zeeman splitting in the HI 21-cm emission line [87H];
- Zeeman splitting in H and C recombination lines [87H].

7.7.3 Observational results

Table 1. Some derived values of galactic magnetic field strengths *B*, in addition to the data listed in LB VI/2c subsect. 7.7.3, Table 3, p. 144.
N = number density of particles

Field region	*B* [μG]	*N* [cm^{-3}]	Methods of determination	Ref.
Molecular clouds (mean values)				
Warm clouds (associated with OB star formation)	75		OH Zeeman splitting	90T

Field region	B [μG]	N [cm^{-3}]	Methods of determination	Ref.
Molecular clouds (mean values) (continued)				
Cold clouds (without OB star formation)	9		OH Zeeman splitting	90T
Individual clouds				
Orion A	≤ 100		21-cm Zeeman splitting	89T1
	125		OH Zeeman splitting	90T
W3	≈ 100		21-cm Zeeman splitting	89T2
	73		OH Zeeman splitting	90T
Orion B	38		OH Zeeman splitting	87H
Barnard I	27		OH Zeeman splitting	89G
North Polar Spur	5.5		21-cm Zeeman splitting	89V
OH maser sources	a few μG	$\leq 10^7 \ldots 10^8$	OH Zeeman splitting	90G
H_2O maser sources	50…80	$\approx 10^9 \ldots 10^{11}$	H_2O Zeeman splitting	89F

Galactic magnetic field

Using rotation measures of 116 pulsars nearer than 3 kpc Rand and Kulkarni [89R] found a strength of the local magnetic field of B = (1.6 ± 0.2) μG toward longitude l = 96° ± 4°, with a reversal of the field at a distance of (600 ± 80) pc toward the galactic centre and stated that a concentric-ring model fits the data better than a bisymmetric spiral model (see also [87H, 90L]). Studies of Faraday rotation measures and dispersion measures of 185 pulsars by Lyne and Smith [89L] suggested that the local magnetic field is directed towards l = 90° with B = 2…3 μG. Han and Qiao [94H] found the vertical component of the local magnetic field to have a strength of 0.2…0.3 μG and a direction from the south galactic pole to the north galactic pole. Davies [94D] derived from the local volume emissivity of the synchrotron emission and the observed energy density of cosmic ray electrons near the sun values for the strength of the total local magnetic field of 4 to 8 μG.

A survey of linear polarization at ν = 2695 MHz (λ = 11.1 cm) along the galactic equator (4.9° ≤ l ≤ 76°; – 1.5° ≤ b ≤ 1.5°) with an angular resolution of 6' is presented by Junkes et al. [87J] in the form of contour maps with superposed polarisation bars.

References for 7.7

87H Heiles, C., in: Interstellar Processes, Proceed. Symp. on Interstellar Processes (Hollenbach, D.J. Thronson Jr., H.A., eds.), Astrophys. Space Sci. Libr. Vol. **134**. Dordrecht: Reidel (1987), p. 171.

87J Junkes, N., Fürst, E., Reich, W.: Astron. Astrophys. Suppl. **69** (1987) 451.

88H Hildebrand, R.H.: Quart. J. R. Astron. Soc. **29** (1989) 327.

89F Fiebig, D., Güsten, R.: Astron. Astrophys. **214** (1989) 333.

89G Goodman, A.A., Crutcher, R.M., Heiles, C., Myers, P.C., Troland, T.H.: Astrophys. J. **338** (1989) L61.

89L Lyne, A.G., Smith, F.G.: Mon. Not. R. Astron. Soc. **237** (1989) 533.

89R Rand, R.J., Kulkarni, S.R.: Astrophys. J. **343** (1989) 760.

89T1 Troland, T.H., Heiles, C., Goss, W.M.: Astrophys. J. **337** (1989) 342.

89T2 Troland, T.H., Crutcher, R.M., Goss, W.M., Heiles, C.: Astrophys. J. **347** (1989) L89.

89V Verschuur, G.L.: Astrophys. J. **339** (1989) 163.

90B Beck, R., Kronberg, P.P., Wielebinski, R. (eds.): Galactic and Intergalactic Magnetic Fields. IAU Symp. **140**. Dordrecht: Kluwer (1990).

90G Güsten, R., Fiebig, D.: in [90B], p. 305.

90L Lyne, A.G.: in [90B], p. 41.

90T Troland, T.H.: in [90B], p. 293.

94D Davies, R.D., in: Cosmical Magnetism (Lynden-Bell, D., ed.), NATO Advanced Sci. Inst. Series Vol. **422**. Dordrecht: Kluwer (1994), p. 131.

94H Han, J.L., Qiao, G.J.: Astron. Astrophys. **288** (1994) 759.

8 Our Galaxy

8.1 Positions, motions, parallaxes of stars

8.1.1 Star positions

8.1.1.1 Introduction

An extremely increasing number of highly accurate astrometric data has been obtained in the past decade resulting from improved modern techniques such as the use of automated meridian circles (La Palma, Bordeaux, Tokyo, Washington), the development of more sensitive detectors (photo-electric devices or CCD techniques) shifting the magnitude limit to fainter magnitudes, the improvement of measuring machines for the digitisation of photographic plates, the development of more sophisticated reduction techniques including also the astrometric reduction of plates taken with Schmidt telescopes (see e.g. [f, n]), the extension of astrometry to other wavelengths, in particular to radio wavelengths, the use of Very Long Baseline Interferometry (VLBI) which allows one to measure positions with milli-arcsecond accuracy, the development of optical interferometry, or the application of space techniques using ESA's Hipparcos satellite (see [i, j, k, o, v, 97ESA]) or the Hubble Space Telescope (see Chaisson and Villard [90C1]). Recent progress in measuring and evaluating astronomical data is given in the proceedings of various meetings [p, q, r]) and, with more emphasis on future developments, in [s, t, u].

Major changes in positional astrometry are also the introduction of the IAU(1976) system of astronomical constants, the adoption of the FK5 system as the primary celestial coordinate system in optical wavelengths, and the resolution that the future International Celestial Reference System (ICRS) shall be defined by the radio positions of a selected number of compact extragalactic radio sources having optical counterparts (see [h, l] for general information, and [w], p. 48ff, and [t], p. 415ff). From 1 January 1998 onwards the stellar positions and proper motions given in the Hipparcos catalogue will replace the FKS as the primary realization of the ICRS at optical wavelengths (see [y]). For the practical treatment of reference systems and the IAU(1976) system in astrometrical work and, in particular, for the computation of ephemerides reference is made to the new edition of the Explanatory Supplement to the Astronomical Almanac ([x], Chapter 3).

Astrometry has been surveyed by van Altena [83A] and advances in optical astrometry have been reviewed by Monet [88M]. A few textbooks on modern astrometry have appeared: [a, b, c, d]. Technics and reduction procedures used in modern astrometry can be found in [d]. For an introduction to radio astrometry reference is made to Counselman [76C] and to [c], pp. 362-414.

General information concerning the following tables is given by Gliese (LB VI/2c, p. 147ff). Not included in the following tables are positions and proper motions for special groups or types of stars such as high-velocity stars, high-luminosity stars, double stars, Cepheids, RR Lyraes, open or globular clusters, and so on. A complete documentation of stellar positions and proper motions can be found in the half-annually published volumes of "Astronomy and Astrophysics Abstracts" (published by Astronomisches Rechen-Institut, Heidelberg, Springer-Verlag).

8.1.1.2 Constellations

See LB VI/2c, subsect. 8.1.1.2

8.1.1.3 Star lists and nomenclature of stars

Digital designations of catalogues and surveys of star positions have been proposed by Teleki and Sevarlic [78T], and were partly used by Teleki and Pakvor [89T, 91T1]. For nomenclature of celestial objects in general reference is made to Fernandez et al. [83F2] and to Lortet and Spite [86L].

Table 1. The most important star lists (used for nomenclature).
$m_{\rm lim}$ = limiting magnitude, N = number of stars

No.	Abbr.	Name	Ref.	$m_{\rm lim}$	N	Equinox	Declination
1	BS Suppl	A Supplement to the Bright Star Catalogue	83H	7.1	2603	1900 2000	+90°...–90°
2	BS	Bright Star Catalogue (5th revised edition; preliminary version; on CD-ROM)	91H	complete to 6.5	9096	1900 2000	+90°...–90°
3		Lowell Proper Motion Survey, Southern Hemisphere	78G1	17	174	1950	one plate at $0^{\rm h}12^{\rm m}\!.4$ –9°51'
	GD + GR	Lowell Proper Motion Survey, Summary Catalogue of GD and GR Stars	80G	17	2216	1950	–40°...+90°
4	HDEC	The Henry Draper Catalogue Charts: A catalogue of accurate positions, proper motions, magnitudes and sepctral types of 86,933 stars	95N	11	86,933	2000	7 special fields having sizes between 100 and 1000 squ.deg.

8.1.1.4 Sky charts and atlases

Concerning the various sky surveys (Cat. Nos. 8-18) general reference is made to [f, n], and in particular to West [84W], Cannon [84C], Reid et al. [91R1] and Morgan et al. [92M2, 95M].

Future dates (in brackets) for the production of plates, film and glass copies are only estimates.

Table 2. Sky charts and atlases (n = number of maps).

No.	Name and remarks	Ref.	n	Scale 1 deg =	m_{lim}	Equinox	Declination
1	Norton's 2000.0. Star Atlas and Reference Handbook	89R	18	3.2 mm	6.5	2000	–90°…+90°
2	Cambridge Star Atlas 2000.0	91T2	12 maps 20 charts	3.3	6.5	2000	–90°…+90°
3	Atlas of the night sky	84D	14+88	2.95	6.0	2000	–90°…+90°
4	Color Star Atlas, Epoch 2000. (Remark: The atlas is concerned mainly with spectral types)	91C2	20	4.4	6.75	2000	–90°…+90°
5	Atlas Zvednogo Neba (The Star Sky Atlas); Poyasnenie i Katalog (Expl. and Catalogue)	91A	20	4.0	6.5	2000	–90°…+90°
6	Uranometria 2000.0 (two volumes)	87T	473	18.5	9.5	2000	–90°…+90°
7	Sonneberger Himmelsüberwachung	91W2	133	15.9	14(B)		–31°…+90°
8	POSS I (IR) obs.: 1975-79; on paper (1982)	79H	80	53.6	19(IR)		$\delta > -3°$ and limited to $\|b\| < 10°$
9	ESO-B obs.: 1973-78; on film and glass (1972-75)	82W2	606	53.4	21.5(B)		–17°…–90°
10	ESO-R;*) obs.: 1978-90, on film and glass (1978-91)	84W	606	53.4	22(R)		–17°…–90°
11	SERC-J; *) obs.: 1974-87; on film and glass (1975-88)	84C	606	53.6	23(B)		–17°…–90°
12	SERC-EJ obs.: 1979 - ; on film and glass (1984-93)	84C	288	53.6	23(B)		+3°…–18°
13	SERC-ER obs.: 1984- ; on film and glass (1992-96)	84C	288	53.6	22(R)		+3°…–18°

No.	Name and remarks	Ref.	*n*	Scale 1 deg =	m_{lim}	Equinox	Declination
14	SERC-I/SR obs.: 1978-85; on film and glass (1982-85)	81H	163	53.6	19(IR)		$\delta < +3°$ and limited to $\|b\| < 10°$; includes Magellanic clouds
15	SERC-I obs.: 1980 -; on film	92M2	731	53.6	19(IR)		$\delta < +3°$ and limited to $\|b\| > 10°$; includes Magellanic clouds
16	AAO-R obs. 1990 -	92M2	606	53.6	22(R)		–17°…–90°
17	POSS II -B, -R, -IR obs.: 1987 -; on film and glass (1991-97)	91R1 94R1	3x894 in 1993 finished: 70% of blue & red, 28% of IR plates	53.6	22.5(B) 20.8(R) 19.5(IR)		–3°…+90°
18	POSS QV; **)	90L	583	53.6	19(V)		+3°…+90°

*) The SERC-J and ESO-R Atlases are produced by ESO and are issued as the single publication "The ESO/SERC Southern Sky Atlas".

**)The POSS QV Survey has been produced by Mt. Palomar Observatory and Hubble Space Telescope Science Institute (HST ScI, Baltimore, USA) for generating the HST Guide Star Catalogue (see Table 4, Cat. No. 10) to operate the Hubble Space Telescope. Limited access may be obtained to POSS QV on special request (see Lasker et al., [90L], p. 2023).

8.1.1.5 Catalogues of star positions

From 1984 onward catalogues of star positions have to be referred to the new IAU standards (see [77IAU] and [83IAU]). The comparison of various star positions (or proper motions) requires their transformation to the same reference frame and the same system of astronomical constants. Procedures are described in [x], Section 3, page 147ff.

Comprehensive bibliographies of catalogues of star positions

ARI: Astronomisches Rechen-Institut, Heidelberg (Manuscript): about 350 catalogues published since 1963

Wyatt, N.J.: Star catalogues: their importance, bibliographic control, and a catalogue of the Royal Greenwich Observatory Library Collection. Thesis, City of Birmingham Polytechnic Department of Librarianship, Birmingham, England. 4 + 172 pp (1984) (includes many references to other bibliographies of star catalogues)

Teleki, G., Sevarlic, B.: Bibliography of stellar atlases, maps and charts. Publ. Astron. Obs. Beograd, No. 29, p. 71, 1982; (140 references of photographic catalogues).

Observational catalogues

A few larger observational catalogues obtained with (automated) meridian circles deserve being mentioned since they are more frequently used because of their large content of stars with special astrometrical or astrophysical interest.

Positions (and proper motions) derived in astrometric standard fields have a high degree of relative accuracy. They are therefore used for the calibration of telescopes and investigating their quality, for the determination of precise plate scales, for developing the best plate reduction models, for testing new observational techniques, and so on.

ESA's astrometry satellite Hipparcos provides primarily angular distances between observed stars. The resulting catalogues (Table 6, Cat. Nos. 1 and 2) define therefore their own system except for three free rotations in positions and proper motions, respectively, which have to be determined by an external link. For general information on the Hipparcos and Tycho project see [i, j, k, o, v] and [97ESA].

Table 3. Major meridian circle catalogues. N = Number of stars

No.	Abbr.	Ref.	Catalogue	N	Zone	Epoch
1	CMC	89C, 91C1, 92C2, 93C , 94C	Carlsberg Meridian Catalogues La Palma, Nos. 4-8 $m_{\mathrm{lim}} \approx 14.5$ (V)	≈120,000 star positions	–45°…+90°	1984-93
2	PMC	87Y, 89Y, 91Y, 92Y3	Tokyo PMC Catalogues 1985-88 $m_{\mathrm{lim}} \approx 12$ (V)	≈14,500	–35°…+90°	1985-88
3	Wash 5/50	82H2	Results of observations made with the six-inch transit circle	≈15,000	–30°…+90°	1963-71
4	Perth 70	76H	A catalogue of positions of 24,900 stars	24,900	–90°…+40°	1967-72

A pole-to-pole program with the Washington 6-inch and Washington 7-inch transit circles (operated at Black Birch, New Zealand) is underway.

Table 4a. Zone Catalogues: meridian circle programs, astrometric programs with photography, and digitised sky surveys. N = Number of stars

No.	Ref.	Catalogue	N	Zone	Epoch
Meridian circle programs					
1	90S1	SRS: The SRS Catalog of 20,488 Star Positions: Culmination of an International Cooperative Effort	20,488	+5°…–90°	1961-73
Astrometric programs with photography					
2	83F1	Yale Zone Catalogue Program	14,597	–60°…–70°	1941-42
3	83K	SSSC: Sydney Southern Star Catalogue	26,926 plates have been taken from –36°…–90°	–51°…–63.5°	1967-83

No.	Ref.	Catalogue	N	Zone	Epoch
Astrometric programs with photography (continued)					
4	83E	Catalogue of 20,457 star positions obtained by Photography in the declination zone –48° to –54° (1950)	20,457	–48°…–54°	1964
5	83F3	Survey of the Astrographic Catalogue from +1° to +31° Northern Declination	1,025,208	+1°…+31°	≈1906
6	86M	A survey of trigonometric parallaxes and proper motions with the UK Schmidt Telescope. Part II: Astrometric and photometric data for a complete sample of 6125 stars brighter than B=17$^{m}_{.}$5, V=17$^{m}_{.}$0 in the South Galactic Cap	6,125	South Gal. Pole 20 squ.deg.	1975-81
7	90D	USNO ZOD: The US Naval Observatory Zodiacal Zone Catalog	44,428	within 16° of ecliptic, $\delta > -30°$	1978-82
8	93V 92Z	CPC-2: The Second Cape Photographic Catalogue	276,131	+2°…–90°	1962-72
9	94B	The final FOCAT-S star catalogue for southern hemisphere	≈203,600	0°…–90°	1982-88
Digitised sky surveys					
10	90L 90R 90J	GSC I = GSC 1.0: Guide Star Catalogue for supporting the operation of the Hubble Space Telescope (digitised from POSS QV)	≈15.2 Mio.	–90°…+90°	1975-82
11	92I	APM: Northern Sky Catalogue (digitised from POSS I)	≈100 Mio. objects	≈10,000 squ.deg $\delta > 0°$; $\|b\| > 30°$	≈1955
12	92Y2	COSMOS/UKST Catalogue of the southern sky (digitised from ESO/SERC-J, EJ, I/SR plates)	≈500 Mio. objects ≈185 Mio. stars from blue plates	–90°…+2.5°	1974-87

Table 4b. Zone Catalogues: catalogues in progress. N = Number of stars

No.	Ref.	Catalogue	N	Zone	Epoch	Magn
Catalogues in progress						
13	93D	USNO-AC Project (North)	≈1.15 Mio. 2478 fields blue & yellow plates; plate photography finished, plate measurement nearly completed. 288 additional fields from –3° to –19° have been taken and may be measured	– 9°…+90°	1978-86	6...11
		USNO-AC Project (South):	not yet started			

No.	Ref.	Catalogue	N	Zone	Epoch	Magn
Catalogues in progress (continued)						
14	90K 94I	FON: Photographic survey of the sky	7270 plates 90% of plates obtained	–6°…+90°	1982-	12...16
15	91P	EKAT: Equatorial Catalogue	1832 plates (=63.6 %) obtained in January 1991, about 1 million stars.	–20°…+20°	1987-	m_{lim}=12
16	92P1 93P	APS: The Automated Plate Scanner Catalog (digitised from POSS I and Luyten plates)	≈ 10^9 scanning completed for b>20° in 1993	+90°…–33°	1950-	m_{lim}=21
17	92P2	Yale-San Juan: Faint Secondary Reference Frame (obtained within SPM Project, see Table 12b)	≈10...15 stars/squ. deg.	–17°…–90°		15…18
18	95R	GSC I.2: Guide Star Catalogue Revisited - The Determination of Proper Motions. (New reduction of the whole GSC I (see Cat. No. 10) and proper motions for the about 4 million AC-stars in the GSC.				
19	92L1	GSC II: Guide Star Catalogue II. Will include proper motions by using Second Epoch Surveys. Fainter magnitude limit in the northern part by including POSS II (see Table 2, Cat. No. 17).				
20	95R 96R1	AC: Proper motions for the about 4 million AC stars by combining AC and GSC 1.2 positions (see Cat. No. 18). The catalogue will be named "Starnet"				
21	93U 96U	U.S. Naval Observatory AC Project: Proper motions for AC stars from new reduction of AC in combination with modern observations.				

Table 5. Astrometric standard regions.

No.	Ref.	Region	Title	Centre	N	m_{lim}
1	83S	Moscov zenith	A wide-angle astrometric standard in the Moscov zenith zone	$22^{\mathrm{h}}30^{\mathrm{m}}$; +55°42'	400	11(p)
2	90P	NGP	Establishment of an astrometric standard region in the North Galactic Pole: Star catalogue	$12^{\mathrm{h}}25^{\mathrm{m}}$; +26° Coma cluster	3197 1562 with proper motions	15.0
3	86R	Praesepe	Establishment of an astrometric standard region - a description of the method with reference to the astrometric standard region in Praesepe (M44).	$8^{\mathrm{h}}39^{\mathrm{m}}.2$; +19°45'	408	16.4(V)
4	91W1	Praesepe	J2000 positions and proper motions of 257 stars in the central part of the Praesepe astrometric standard field	$8^{\mathrm{h}}39^{\mathrm{m}}.2$; +19°45'	257	

No.	Ref.	Region	Title	Centre	N	m_{lim}
5	92K	Cygnus	Construction of an astrometric standard in region of Cygnus	21^h03^m; +52°	1429 699	11...16 15...22
6	70E	Pleiades	Accurate positions of 502 stars in the region of the Pleiades	3^h45^m; +23°57'	502	14(pv)
7	94S	Equatorial zone	Astrometric Standard Fields for CCD observations of Double Stars	8 fields in $-20° < \delta < +20°$	3…30 stars	15(pv)

Table 6. Astrometry from space.

No.	Abbr.	Ref.	Name	Contents
1	HIP	[o, v] 92L2 97ESA	Hipparcos-Catalog	Mean positions, proper motions and magnitudes for the stars in the Hipparcos Input Catalogue (see Table 8, Cat. Nr. 14) obtained from the Hipparcos satellite (measurements from 1989, December until 1993, March). Concerning the progress of the work and preliminary results see various papers in [v]. The final catalogue is published in [97ESA] (17 volumes, including 6 CD ROM).
2	TYC	92H2 [v] 97ESA	Tycho-Catalog	Mean positions, proper motions and magnitudes for the stars in the Tycho Input Catalogue (see Table 8, Cat. Nr. 15) obtained from the Hipparcos satellite (measurements from 1989, December until 1993, March). Concerning the continuation of the work and preliminary results see various papers in [v]. The final catalogue is published in [97ESA] (17 volumes, including 6 CD ROM).
3	TRC	93R3	Tycho Reference Catalogue (TRC).	Proper motions for about one million Tycho stars by combining Tycho observations with AC positions.

Compiled catalogues

The fundamental catalogue officially in use since 1984 is the "Fifth Fundamental Catalogue", FK5 (Fricke et al. [88F, 91F]). Star positions computed on the basis of the FK5 represent the primary celestial coordinate system in optical wavelengths to which other observations can be referred to differentially. A replacement of the FK5 as the primary reference frame in optical wavelengths will take place from 1 Jan 1998 onwards [y].

The yearly published volumes "Apparent Places of Fundamental Stars" are based entirely on the FK5 from the volume for the year 1988 onwards. The apparent places published for the years 1984 through 1987 can be referred to the FK5 catalogue by applying additionally the corrections FK5-FK4 as given in [87ARI].

Table 7. Fundamental catalogues.
N = number of stars, *m* = magnitude

No.	Ref.	Abbr.	Name	*N*	Equinox	*m*
1	88F	FK5 (Basic)	Fifth Fundamental Catalogue (FK5); Part I: The Basic Fundamental Stars	1535	J2000.0 B1950.0	< 7
2	91F	FK5 (Extension)	Fifth Fundamental Catalogue (FK5); Part II. The FK5 Extension - New Fundamental Stars	3117	J2000.0 B1950.0	< 9.5

Table 8. Compiled catalogues which do not represent a fundamental system

No.	Ref.	Abbr.	Name and contents
Catalogues compiled from transit observations			
1	90C2 92C3	IRS	International Reference Stars: Mean positions and proper motions for the stars in the AGK3R and SRS (see Table 4, Cat. No. 1, and LB VI/2c, p. 151, Table 3, Cat. Nos. 6 and 7). Subdivided in two parts (29,163 + 6,864 stars) depending on the precision of proper motions.
2	87Z	FKSZ	General Catalogue of Fundamental Faint stars. Positions and proper motions of 931 faint stars (7.3…8.4 mag) on both hemispheres on FK4 system.
3	85K	BS-G	General Catalogue of Geodesic stars (obtained within the International Bright Star program). Mean positions and proper motions of 4949 stars brighter than 6.1 mag on the whole sky. Precision at mean epoch (about 1986): 0.003…0.005 sec in RA, 0.10…0.12 arcsec in Decl. and 0.008…0.015 sec/cy and 0.11…0.24 arcsec/cy for the corresponding proper motions.
4	92M1	BS-C	Compiled Catalogue of Positions and Proper Motions of 5115 Bright Stars for Epoch and Equinox J2000.0. Derived from observations made within the Bright Star Program from 1960-1980. Includes stars up to 7th magnitude. Precision at mean epoch 1969: 0.06 and 0.10 arcsec in RA and Decl., respectively, and 0.22 and 0.25 arcsec/cy for the corresponding proper motions.
5	89G	KSV-2	General Catalogue of the USSR Time Services. Right ascensions and proper motions in right ascension for 1000 stars brighter than 7.1 mag. in the declination zone –15 to +75 degrees declination (in progress).
6	87U1	LS	General Catalogue of Latitude programme stars of zenith telescopes. Declinations and proper motions in declination for 2844 stars north of 15 degrees in the FK4 system.
	87U2	LS-Sup	Supplement to the general catalogue of latitude programme stars. Declinations and proper motions in declination for 63 stars north of 15 degrees in the FK4 system.
7	82Y	NPZT-74	Northern Photographic Zenith Telescopes Stars Catalog. Positions for 1719 stars in the PZT Stars List; in the FK4 system.

No.	Ref.	Abbr.	Name and contents
Catalogues compiled from photographic observations			
8	93R2	PPM	Positions and Proper Motions. The final PPM Catalogue for both hemispheres. Positions and proper motions of 181,731 stars north and of 197,179 stars south of –2.5 degrees declination.
8.1	94R2	PPM Sup	PPM Star Catalogue: the 90,000 Stars Supplement. (Positions and proper motions for about 90,000 additional stars on the southern hemisphere).
9	90C2 92C3	ACRS	Astrographic Catalogue Reference Stars. Positions and proper motions of 325,416 stars on the whole sky; subdivided in two parts depending on the precision of the proper motions.
10	92B	AGK3U	AGK3U: An updated version of the AGK3. Positions and proper motions for the stars in the AGK3 catalogue (about 183,000 stars north of –2.5 degree declination).
11	92Y1	FHST	The Fixed Head Star Tracker Catalogue. Positions and proper motions for about 219,800 stars from –90° to +90° for operating the Hubble Space Telescope; derived from various catalogues observed 1900 to 1990. Complete to $V = 9$.
12	93S 78G2	SKYMAP	Catalogue of 248,516 stars on the whole sky. Compilation of astrometrical and astrophysical data for all stars brighter than 9.0 visual magnitude.
13	82H1 85H	SKY CAT 2000.0	Vol. 1 [82H1] gives astrophysical and approximate astrometrical quantities for about 50,000 stars taken mainly from SKYMAP, Version 3.0 (comp. Cat. No. 11); Vol. 2 [85H] contains double stars, variable stars and non-stellar objects.
Catalogues compiled for ESA's astrometry satellite Hipparcos			
14	92T1 92T2 92J 92G	HIC	The Hipparcos Input catalogue. Mean positions, proper motions, and other astrometric and astrophysical data (as far as available) for about 118,200 stars brighter than 13 visual magnitude. The catalogue is complete to well-defined magnitude limits and includes a substantial sampling of the most important stellar categories in the solar neighbourhoud. Compiled from various sources. To be observed in the main experiment of the Hipparcos satellite. (Comp. also Table 6, Cat. No. 1).
15	92E	TIC	The Tycho Input Catalogue. Positions for about 3 million stars with $V < 12.1$ on the whole sky, needed for the analysis of the data obtained within the Tycho project of the astrometry satellite Hipparcos. (Comp. also Table 6, Cat. No. 2).
16	96R2	HIC-S	96800 stars of the southern hemisphere (south of –17.5 deg) proposed for the Hipparcos mission (see Cat. No. 14) and 21265 additional stars. Given are positions, magnitudes, spectral types and many cross references.
Star list of future fundamental stars			
17	92C1	IFS	Intermediate Fundamental Stars: list of about 3000 stars in the magnitude range 9.5…13.0; candidates for a future extension of the fundamental system to fainter magnitudes (in progress).

8.1.1.6 Precession tables

Precession is easily computed with electronic computers and precession tables are no longer required. Formulae for transforming positions and/or proper motions from one epoch and equinox to another epoch and equinox can be found in [x], Chapter 3.2 or in the introduction to the FK5 [88F], p. 10-11.

8.1.1.7 Radio astrometry

Radio astrometry using VLBI techniques has achieved milli-arcsecond accuracy (see e.g. [m], p. 253-296 or various contributions in [l]) and it contributes therefore essentially to the determination of Earth Rotation Parameters (ERP), the detection of plate motions, the improvement of the constants of precession and nutation and the establishment of highly accurate reference frames. VLBI provides absolute declinations but merely relative right ascensions since there are no appropriate radio sources in the Solar System to define the ecliptic. The zero point in right ascension may be defined statistically by adjusting the VLBI positions of a selected number of radio sources to photographically determined positions (on the FK5 system) of their optical counterparts, or by adopting the optically determined position of the quasar 3C273B according to Hazard et al. [71H], for instance. For general information on the principles of radio astrometry reference is made to [c], p. 362-414, or to Counselman [76C].

From 1 January 1998 onwards the primary celestial reference system will be defined by the radio positions of spatially compact and intense extragalactic radio sources having also optical counterparts (see [l], [w] p. 48-50, [t], p. 415ff, and [y]). The new reference system, defined statistically by the positions of so-called primary sources, shall represent as far as possible the mean equator at J2000.0 with the dynamical equinox at J2000.0 as the origin, and it will therefore coincide with the FK5 system at J2000.0 within the accuracy of its determination. The link between the optical and the radio system has been made by using objects whose positions can be determined in both systems such as extragalactic radio sources with optical counterparts or via radio stars see e.g. Walter [82W1], Kovalevsky et al. [89K], Argue [90A], de Vegt et al. [91V], [j] p. 439ff, [97ESA]). For the link of the Hipparcos catalogue to the extragalactic frame reference is also made to [95L1, 95L2] and [97ESA].

Table 9. Lists and catalogues of radio sources with importance for constructing a celestial reference frame.

No.	Ref.	Contents
1	84A	234 strong compact extragalactic radio sources displaying also optical counterparts. Accuracy of radio positions < 0.1 arcsec with the majority < 0.01".
2	90W1	Radio and optical astrometric data for about 200 radio stars.
3	91R2	Optical positions of 221 radio stars observed with Bordeaux automatic meridian circle.
4	95J	A compiled Catalog of Optical Positions of Extragalactic Radio Sources. (About 500 sources in the FK5 system for J2000, about 60 primary sources with precision 0.10 arcsec).
5	95WG	List of extragalactic objects identified as sources which define the reference frame together with candidate sources which may, at some future day, be added or replace the defining sources. (The list contains 606 objects).

Table 10. Catalogues of positions of extragalactic radio sources obtained by VLBI.
N = number of sources
σ = precision of the positions

No.	Ref.	N	Epoch	Zone	Remarks
Individual radio catalogues					
1	90M	182	1983 - 1988	$\delta > -30°$	σ < 1 mas. Tie to the optical frame (FK5) by using 28 radio sources with known positions in the FK5 system.
2	91R3	82	1987 - 1988	$\delta > -2°$	Extension of Cat. No. 1 by adding 53 new sources ($\sigma \approx$ 0.8 mas), and improving positions of 29 sources.
3	92R	39	1988 (Jan.)	$\delta < -45°$	Extension of Cat. Nos. 1 and 2 by adding 39 new sources ($\sigma \approx$ 10 mas) in $\delta < -45°$.
4	92F	72	1988+1989	$\delta > -2°$	New positions for 11 sources; improved positions for 54 sources in Cat. Nos. 1 and 2.
5	94R3	41	1988+1989	–25°...–45°	Extension of Cat. Nos. 1-4 by adding 32 new sources and improving 9 previous observations. σ < 1 mas.
6	94F	106	1990	$\delta > -2°$	Extension of Cat. Nos. 1-5 by adding 34 new sources and improving 72 previous observations. σ < 1 mas.
7	90S2	200	1978-1989	$\delta > -45°$	σ < 2 mas for 75 percent of the sources with a distribution peak below 1 mas.
8	93R1	81	≈1982-1992	+78°...–80°	σ < 0.5 mas
9	92H1	8	1986+1987	$\delta < -45°$	σ < 10 mas
10	90W2	10	1987	0°....–40°	$\sigma \approx$ 10 mas; optical positions are also given.
Compiled radio catalogues					
11	89W	210	1975-1988	+85°...–45°	σ < 0.5 mas for the basic set (≈40 sources), σ < 2 mas for the extension.
12	93K	206	1988-1991	+85°...–45°	$\sigma \approx$ 0.2 mas for primary, 0.5 mas for secondary and 5 mas for supplementary sources.
13	95Z	>500	≈1978-≈1993	whole sky	σ < 1 mas for about 280 sources.
14	95IERS	608	1978-1995	+85°...–86°	σ < 1 mas for the large majority; σ < 0.5 mas for more than 300 sources. updated regularly.

IERS: One of the responsibilities of the International Earth Rotation Service (IERS) is to define and maintain a conventional celestial reference system based on extragalactic radio sources, and relating it to other celestial reference frames. Combining individual reference frames obtained within various astrometric VLBI programs the IERS publishes in its Annual Reports averaged radio source coordinates (RSC) representing the IERS Celestial Reference Frame (IERS Annual Reports, Observatoire de Paris). The latest realiziation at present is RSC(IERS) 95 C01 as quoted above.

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8.1.2 Proper motions

8.1.2.1 Definition

See LB VI/2c, subsect. 8.1.2.1

8.1.2.2 Components

See LB VI/2c, subsect. 8.1.2.2

8.1.2.3 Determination of proper motions

See LB VI/2c, subsect. 8.1.2.3

Proper motions derived from observed positions at different epochs depend on the constants used to transform the observations to the same reference frame. Proper motions based on Newcomb's precession and in the FK4 system can be transformed to the new IAU standards as descibed in the new edition of the Explanatoy Supplement to the Astronomical Almanac (see Section 8.1.1, Reference [x], Chapter 3.5).

8.1.2.4 Numerical values and error estimates

The accuracy of the FK5 system is given in the FK5, Part I (see [88F]), p. 7 as a function of the declination and apparent visual magnitude.

Estimates of the average precision (internal errors) of proper motions in some catalogues are given in Table 11. The values are averages over both coordinates and for the whole sky. For details see the respective catalogues.

Table 11. Average mean internal errors of proper motion components in some catalogues.

Catalogue	See Ref. for 8.1.1	Error ["/a]	
FK5 (Pt. I)	88F	0.0007	
(Pt. II)	91F	0.0026	
IRS (Pt. I)	90C2	0.0042	
(Pt. II)	90C2	> 0.0042	or merely two observations
FKSZ	87Z	0.0029	
HIP	92L2, [o, v], 97ESA	< 0.002	for the large majority of HIP-stars
PPM	93R2	0.0036	
ACRS (Pt. I)	90C2	0.0046	
(Pt. II)	90C2	> 0.0046	or merely two observations
AGK3U	92B	0.0058	
TYC	97ESA	< 0.05	for the large majority of TYC-stars

8.1.2.5 Catalogues containing proper motions

1 Fundamental catalogues: see subsect. 8.1.1.5 Table 7
2 Compiled catalogues: see subsect. 8.1.1.5, most of the catalogues in Table 8, and 8.1.1.3, Table 1, Cat. No. 4
3 Zone catalogues: see subsect. 8.1.1.5, Most of the catalogues in Table 4b
4 Meridian circle catalogues: see subsect. 8.1.1.5, Table 3, Cat. Nos. 1, 4
5 Proper motion catalogues: see subsect. 8.1.1.3, Table 1, Cat. No. 3
6 Standard regions: see subsect. 8.1.1.5, Table 5
7 Astrometry from space: see subsect. 8.1.1.5, Table 6
8 Compiled catalogues: see subsect. 8.1.1.5, Table 7 and most of the catalogues in Table 8.

A comprehensive bibliography of papers and catalogues on proper motions has been compiled by Sevarlic et al. [90S]

Table 12. Further proper motion catalogues.
m_{lim} = limiting magnitude

Ref.	Contents or title	Zone	No. of fields	No. of stars	m_{lim}
a) Proper motion survey with the 48-inch Schmidt Telescope					
81L	7120 stars in the Hyades	special regions		7120	21(pg)
85L1	6065 stars in the Hyades - Pleiades region	special regions		6065	21(pg)
85L2	7698 stars in the Hyades region	special regions		7698	21(pg)
82L, 83L, 84L, 85L3, 87L1, 87L2, 87L3	Proper motions for stars in the alleged cluster near the North Galactic Pole, for Faint Stars, and for double stars with common proper motion	special regions		≈ 2200	21(pg)
Luyten [86L] has published about 200,000 proper motions from the Bruce Survey and the Palomar Survey while data for another 250,000 are ready to be sent to NASA Goddard Space Center at Greenbelt/Maryland.					
b) Proper motions with respect to galaxies					
Projects covering large regions of the sky					
87K3, 93K, 95K	Lick Northern Proper Motion Program (NPM): Part I: Non-Milky Way Sky first epoch: 1947-54; second epoch: 1969-88. Available from Astonomical Data Centre (ADC) on tape. 2 blue, 1 yellow plate per field	–23°…+90°	899	149,000	18(B)

Ref.	Contents or title	Zone	No. of fields	No. of stars	m_{lim}
Projects covering large regions of the sky (continued)					
	Lick Northern Proper Motion Program (NPM): Part II: Milky Way Sky first epoch: 1947-54; second epoch: 1969-88. Plate photography completed 2 blue, 1 yellow plate per field	–23°…+83°	347	≈150,000	18(B)
	NPM: Southern extension first epoch 1951 - 1957 no second epoch planned at present will also be covered or replaced by Yale/San Juan (SPM), see the following project	–22°…–33°	144		
90A, 93A	Yale/San Juan Southern Proper Motion Program (SPM) first epoch: 1965-74; second epoch started 1987 200 regions completed at the end of 1993	–20°…–90°	623	≈1 Mio	18.5(B), 17.5(V)
Catalogues in special regions of the sky (SA = selected area, see LB VI/1, sect. 5.2.6.1.3, p. 330)					
80C	Classification of Stellar Populations and luminosity classes from accurate proper motions	SA 51, 57, 68	3	971	21.5(V)
89E	Astrometry using the APM and Schmidt plates	≈100 squ.deg.	4	≈170,000	*B*=21
89S	A proper motion study in SA 57	SA 57 (NGP), subarea of 2.6 squ.deg.	1	?	17(V)
90R1	Proper motion survey with Schmidt plates. I. The North Galactic Pole	SA 57 (NGP) 28 squ.deg.	1	≈35,000	≈20.0
92R	Proper Motions from Schmidt plates. II: The Hyades	Hyades cluster 112 squ.deg.	1	≈450,000	≈19.5(V)
92B	A magnitude, colour, and proper motion probe of the Galaxy at an intermediate galactic latitude	*l*=3°, *b*=46° near M5	1	1180	complete to 17.4 (V)
92S	Milliarcsecond proper motion measurements with MAMA	near North Gal. Pole	1	4384	complete to 17 (V)
95S	Membership probabilities in the Pleiades field	9 squ. deg. near Alcyone	8	≈14,500	*B*=19

Ref.	Contents or title	Zone	No. of fields	No. of stars	m_{lim}
Catalogues obtained within the KSZ program (Catalogue of faint stars, CFS)					
84B	Catalogue of proper motions of stars relative to galaxies in 9 southern areas of the sky	–25°...–5°	9	3096	15.5
85B	Catalogue of proper motions of stars relative to galaxies in 41 areas of the sky	– 5°…+90°	41	4423	15.5
84U	Catalogue of proper motions relative to galaxies in 10 selected areas of southern declinations	–25°…– 5°	10	2892	15.0
89B1	Proper motions of stars relative to galaxies in 4 selected areas of southern zone of Pulkovo program	–25°…–5°	4	773	16.0
89B2	Proper motions of stars relative to galaxies in selected areas Nos. 6, 10, 150 and 153 of Pulkovo program	–5°…+90°	4	726	15.5
91S, 88S	Determination of absolute proper motions in the main meridional section of the Galaxy. (see also [89K])	2 fields completed l=166°, b=–15° l=167°, b=+47°	17	≈ 36,500 in 2 fields	18.5 (B)
78R	GOL 1: Catalogue of 15 selected areas of CFS program	–5°…+90°	15	2,885	15.0
80K	GOL 2: Catalogue in 21 selected areas of CFS program	–5°…+90°	21	5,945	15.5
89R	GOL 3: Catalogue in 51 selected areas of CFS program	–5°…+90°	51	7,475	15.0
87K1	GOL 4: On the general catalogue of proper motions in the areas of main meridian section of the Galaxy	–5°…+90°	60	14,111	15.5
Catalogues compiled from various CFS catalogues and including also AGK3 and SAO					
87K2	MMSG: On the general catalogue of proper motions in the areas of main meridian section of the Galaxy	–5°…+90°	60	14,111	15.5
89K	MEGA: On the general catalogue of astrometric and the areas of main meridian section of the Galaxy	–5°…+90°	29	26,436	16.0
90R2	SCPM: Special general catalogue of proper motions of 21,817 stars in 75 areas of the sky with galaxies	–2°…+90°	75	21,817	15.5

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8.1.3 Radial velocities

The enormous increase in speed and accuracy of radial velocity measurements achieved during recent years opened new research fields such as searches for stellar oscillations [94H], star spots [92K], extra-solar planetary systems or brown dwarfs [95M1, 96B, 96M], low-amplitude pulsating stars [89W], and internal kinematics of open and globular clusters [90M, 95G1, 95P].

8.1.3.1 Definitions

See LB VI/2c, subsect. 8.1.3.1

8.1.3.2 Methods of observation

Traditional determinations of radial velocities by individual line measurements were almost exclusively replaced by cross-correlation techniques. This technique, computing the velocity of an object relative to a template, is much faster and allows the mass-production of precise (< 1 km/s) measurements for a large number of late-type stars.

Two different approaches can be distinguished, the on-line technique (e.g. CORAVEL [85M1], using simultaneously about 1500 spectral lines), and the software technique (e.g. CfA digital stellar speedometers [85L] registering a wavelength range of 50 Å). The IRAF radial velocity analysis package for the reduction of digitized spectra is described in [93F1]. The introduction of CCDs allowed the application of numerical cross-correlation in several modifications to various resolutions and wavelenght ranges [90D, 95Q]. Recent efforts removed the restriction to late-type stars. Now also early-type stars (using synthetic spectra calculated for a grid of spectral types and rotational velocities) [91M2, 91V, 94N] and white dwarfs [93A1] are measured by cross-correlation.

Modern techniques for precision radial velocities < 50 m s^{-1} are reviewed in [92W, 94K]. The use of HF absorption cell [88C] or iodine absorption cell [92M1] provide a wavelength calibration insensitive to optical or mechanical effects within the spectrograph.

The transformation of the measured radial velocities to a heliocentric reference frame can be performed with BARVEL [80S].

8.1.3.3 Accuracy

Typical values of the precision of radial velocity measurements since 1870 are presented in Table 1 [92H, 91L3, 91M2].

Table 1. Typical precision of stellar radial velocities.

Year	Observers	Method	σ_V [km s^{-1}]
1870	Huggins, Secchi	visual	40
1892	Vogel	photographic	3.9
≈ 1910	Frost	photographic (B stars)	13
≈ 1920	Campbell, Moore, Wright, Adams, Joy, Plaskett	photographic (late spectral types)	1…4
1921	Plaskett	photographic (early spectral types)	2.5…10
1955	Fehrenbach	objective prism	4…10
1967	Griffin	photoelectric scanner	≤ 1
1980	Mayor	photoelectric scanner	0.2…0.4
1989	Campbell, B.	diode array, HF cell	0.013
1989	Latham	intensified diode array	0.25
1990	Murdoch, Hearnshaw	diode array, fibre feed	0.04
1991	Liu, Morse	CCDs: O…A-type stars	1…3
1995	Mayor, Queloz	CCD, echelle spectrograph	0.015

In [90D] it was shown empirically that the error σ_V of a cross-correlated radial velocity is inversely proportional to the product of the *S*/*N* ratio and the depth of the cross-correlation dip. This is consistent [95Q] with the approximate formula- valid on the assumption that the lines are unblended and have Gaussian profiles- in [92H]:

$$\frac{1}{\sigma_V^2} = \frac{A^2 W^2 (S/N)^2 N_{\text{lines}}}{2\sqrt{2}\sigma_{\text{line}}^2 (\Delta X)^2}$$

Here is

A the coefficient of correlation between the spectra (≈ 1 for like spectra, but < 1 for dissimilar spectra),

W the RMS equivalent width of the lines within the spectral window observed,

(S/N) the signal-to-noise ratio in the continuum,
N_{lines} the number of lines in the spectral window,
σ_{line} the 1/e half-width of the lines due to both intrinsic and instrumental broadening, and
ΔX the pixel or sampling size of the detector.

8.1.3.4 Standard-velocity stars

The system of standard stars introduced several decades ago is inadequate for modern demands due to the rapid improvement of the precision of radial velocity measurements. Systematic differences between bright ($m < 4.3$) and faint ($m > 4.3$) IAU standard stars became obvious: V_r(IAU B) – V_r(IAU F) = + 0.76 ± 0.17 km s^{-1} [85M2], and quite a number of formerly chosen standard stars show variable velocities.

In 1985 IAU Commission 30 installed a working group with the goal to provide a new set of standard stars with individual mean velocities and absolute zero point of the system good to 100 m s^{-1}. The agreement on the zero point for solar-type dwarfs, based on observations of minor planets, is close to this goal. However, for the reddest stars a significant (and hitherto unexplained) color effect of 1 km s^{-1} or more exists between different observatories [96S].

Tables of candidates for radial velocity standard stars, considering for the first time also earlier spectral types (O9.5…F2), can be found in the Report of Commission 30: Radial Velocities, in IAU Transactions XXIB, 1992. A subset of this list is also published in *The Astronomical Almanac*.

Comparison of cluster stars shows that the zero point of current measurements from early-type to late-type stars can be obtained to within 1…2 km s^{-1}. Larger discrepancies depend not seldom on the choice of the templates used, and can easily be removed.

Systematic corrections for former objective prism measurements carried out at the Observatoire de Haute Provence are published in [95D2].

8.1.3.5 Standard wavelengths

See LB VI/2c, subsect. 8.1.3.5

8.1.3.6 Catalogues of stellar radial velocities

A bibliography of catalogues and papers on radial velocities published before 1990 was compiled in [90S] with introductory articles on radial velocities [90E] and on radial velocity observations in open clusters [90M]. The principal compilations of published stellar radial velocities (usually also available in digitized form) are listed in Table 2.

Papers published from 1990 to 1995 and providing radial velocities measurements for more than 40 stars in printed and/or digitized form are listed in Table 3. For each publication object type as well as number of objects measured are indicated to illustrate current research interests. In the corresponding time interval radial velocities for altogether 14282 field stars (including 5708 objective prism measurements) and 4369 cluster stars (63 OP measurements) were published.

A large amount of radial velocity measurements obtained in recent years are still unpublished [91M1]. This is partly due to the still unsettled discussion about the correct zero points of late-type stars.

Table 2. Catalogues of stellar radial velocities.

No.	Author	Publication	*N*
1	Wilson, R.E.	General Catalogue of Stellar Radial Velocities, Carnegie Inst. Wash. Publ. No. 601 (1953)	15106
2	Evans, D.S.	General Catalogue of Stellar Radial Velocities, preprint $\alpha = 0^h \ldots 21^h$ (~1970)	7823
3	Barbier-Brossat, M.	Catalogue de vitesse radiales moyenne stellaires. [89B1]: data before 1980	6451
4	Batten, A.H., et al.	Eigth Catalogue of the Orbital Elements of Spectroscopic Binary Systems [89B2]	1469
5	Duflot, M. et al.	The Wilson-Evans-Batten Catalogue [95D2]	20793
6	Abt, H.A., Biggs, E.S.	Bibliography of stellar radial velocities. Kitt Peak National Obs.(1972): data before 1970	25000
7	Barbier-Brossat, M., et al.	Third Bibliographic Catalogue of stellar radial velocities [94B1]: data from 1970…1990	43821
8	Mermilliod, J.-C.	Bibliography of individual radial velocities in open clusters II. NGC and IC [84M]	6626

Table 3. Radial velocities published from 1990 to 1995.

N	Type	Ref.	*N*	Type	Ref.
579	K stars at the SGP [1])	89K [2])			
247	nearby K…M dwarfs	90T	116	stars in 16 open clusters	91G
1200	F…M stars	90R	71	early-type stars (Pleiades)	91L2
291	nearby F…G stars	91D	158	stars in 23 open clusters	91L2
247	stars in SA 57	91L1	159	stars in 5 globular clusters	91R1
650	NLTT stars	91R2	57	stars in NGC 3114	91S
81	Population II stars	92B1	155	giants in 24 open clusters	93F3
1044	stars from HK OP survey	92B2	1318	stars near NGC 3201	94C2
200	K giants near SGP[1])	93F2	79	stars near NGC 752	94D
332	early-type stars	93R	130	stars of the cluster M 22	94P1
146	bright F…G type stars	94A	42	stars in IC 4665	94P3
500	LPM stars	94C1	808	stars in 3 globular clusters	95G1
75	stars in multiple systems	95D3	164	giants in 12 globular clusters	95G2
1748	nearby K and M dwarfs	95R	85	giants in globular clusters	95M2
227	M giants	95S2	464	cluster giants	95M3
270	Barium stars	91L4	182	members of M 4	95P
179	carbon stars	94M	318	stars in 11 old open clusters	95S1
82	cepheids	92G			
47	cepheids	92M2	10053	field stars (obj. prism)	84S [2])
96	faint cepheids	94P2	1070	field stars (obj. prism)	92D
134	OH/IR stars	92L	2601	field stars (obj. prism)	92F
76	planetary nebulae	95K	1303	field stars (obj. prism)	92S
302	RR Lyrae stars	94L	63	stars near Cr 135 (obj. prism)	93A2
400	giants in Baade's Window	95T	734	field stars (obj. prism)	95D1

[1]) South galactic pole
[2]) Paper not included in [94B1]

8.1.3.7 Statistical results

See LB VI/2c, subsect. 8.1.3.7

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8.1.4 Parallaxes

8.1.4.1 Introduction

See LB VI/2c, subsect. 8.1.4.1

8.1.4.2 Determination of stellar parallaxes

8.1.4.2.1 Trigonometric parallaxes

The release of the Hipparcos Catalogue (= HIP [97E]) in 1997 starts a new area of trigonometric parallaxes. It will have an enormous impact on a large variety of astronomical fields [a]. A median standard error of 0.97 mas (milliarcseconds) in the parallaxes provides a 20 per cent accuracy in distance for most objects within 200 pc [95P2]. The Hipparcos parallaxes are absolute: estimates of the preliminary Hipparcos parallaxes, determined from the first 30 months of Hipparcos measurements H30, proof that a possible global zero-point error caused by a periodic thermal distortion of the payload of the satellite [92L] should be smaller than 0.1 mas [94W, 95A], and that most of the space parallaxes have external standard errors well below 2 mas [95L].

Traditional ground-based parallaxes are measured relative to reference stars whose mean parallaxes must be determined to reduce to absolute. This reduction is usually carried out by applying a galactic model of the star distribution [74v]. Problems arising herewith are reported in [88v].

The determination of trigonometric parallaxes with the aid of photographic plates is more or less terminated. Therefore, the publication of the Fourth Edition of the *General Catalogue of Trigonometric Stellar Parallaxes* YPC (= Yale Parallax Catalogue [95v], see subsect. 8.1.4.3) represents, to a certain degree, the total yield of photographic parallax work started by Frank Schlesinger early this century. Recent investigations confirm that the classical *observatory corrections* are neither statistically nor physically justified [81L, 83H]. These findings and additional results led to the precepts applied by the compilation of the YPC [94v]. Tables of parallax standard stars were proposed in [82U] for future investigation of systematic errors.

Though most of the newly added stars have a parallax accuracy of ≈ 4 mas, the median error of the complete YPC is 102 mas compared to a median parallax of 227 mas. The enormous improvement achieved by Hipparcos is demonstrated in Table 1.

Table 1. Number of stars with good parallaxes in YPC and HIP.

σ_π/π	YPC	HIP
≤ 0.10	924	20853
≤ 0.20	1881	49399

It must be emphasized that almost 50 per cent of the YPC stars with $\sigma_\pi/\pi \le 0.10$ are faint nearby stars below the magnitude limit of Hipparcos. The importance of the Hipparcos catalogue is underlined once more by a comparison of the corresponding HR diagrams (see subsect. 8.2.4).

Modern reviews of astrometry including parallax work are given in [83v, 88M]. The latter one concentrates on modern detectors and technology.

Most current earth-based parallax programmes are carried out with CCDs [92M] achieving mean errors for the relative parallaxes in the order of 1 mas. Accuracies better than 5 mas are attainable using standard CCD equipment on a common-user telescope [94T].

1 mas accuracy is also obtained by the Multichannel Astrometric Photometer (MAP) system of the Allegheny Observatory [87G] by usage of Ronchi rulings and photomultipliers. MAP-based parallaxes were determined for four of the nearest clusters [95G].

Absolute parallaxes of 1 mas accuracy can likewise be measured by long baseline optical/infrared interferometers [95P1].

VLBI astrometric observations provide absolute (relative to extragalactic radio sources) trigonometric parallaxes for radio-emitting stars [94L] or pulsars [86G, 96C]. The VLBI parallax of the radio star σ^2 CrB was determined to 44.04 ± 0.08 mas compared to the YPC parallax 47.3 ± 3.3 mas.

Relative parallaxes are determined with the *Hubble Space Telescope* Fine Guidance Sensor Number 3 to 1 mas precision or better [94B]. First parallaxes for Proxima Centauri (769.9 ± 0.4 mas) and Barnard's star (542.0 ± 0.9 mas) are presented in [95B]. Additional parallaxes are cited in [95M].

Modern measuring machines allow the determination of trigonometric parallaxes from Schmidt plates with formal errors from 12…17 mas [86M].

Finally, the Tycho experiment on-board the Hipparcos satellite yields parallaxes to a typical accuracy of 25 mas [97E].

8.1.4.2.2 Dynamical parallaxes

See LB VI/2c, subsect. 8.1.4.2.2

8.1.4.2.3 Cluster parallaxes

The distance of globular clusters can be determined by equating the proper motion and radial velocity dispersions. This method yields a distance of 11.0 ± 1.7 kpc for the globular cluster M2 [87C].

8.1.4.2.4 Statistical parallaxes

See LB VI/2c, subsect. 8.1.4.2.4

8.1.4.2.5 Spectroscopic and photometric parallaxes

The advent of the Hipparcos parallaxes in 1997 will result in major revisions for the currently available calibrations.

Users of spectroscopic and/or photometric distance moduli should be aware of the fact that these values may be biased up to 0.75 mag due to undetected binaries.

New standard spectral types in the red/near-infrared for K5 to M8 dwarfs allow luminosity determinations good to 0.6 mag [94H]. Tied to this new system the TiO bandstrength is used as distance estimate in the Palomar/MSU spectroscopic survey (covering the region from ≈ 6200…7400 Å)

[95R]. For early M dwarfs, CaOH and CaH bands are useful to identify halo subdwarfs and metal-poor disk dwarfs.

$R - I_c$, $V - R_c$, and $V - I_c$ are good luminosity indicators for red dwarfs earlier than M6, but for later dwarfs ($R - I_c$, $V - R_c$, $V - I_c > 2.1$, 1.7, 3.8 resp.) these colours *saturate* and even become bluer for some stars [91B]. Then $I - K$ or $I - J$ colours must be used to derive precise luminosities. Luminosity calibrations for Strömgren photometry were extended to G and K dwarfs in [84O] as well as to F and G halo stars [91N].

[82B] derived reddenings in the galaxy from HI and galaxy counts.

Critical reviews of Cepheid distances can be found in [87F, 91M, 95F] (see subsect. 5.1.2.1 in LB VI/3b). Recent work on absolute magnitudes for RR Lyrae stars by a variety of methods have not yet reached convergence. Not only the zero point of the RR Lyrae distance scale is uncertain, but also the slope of the absolute magnitude-metallicity relation [95W] (see subsect. 5.1.2.2 in LB VI/3b).

Recently introduced secondary extragalactic distance indicators are the luminosity functions of planetary nebulae [90J], and surface-brightness fluctuations [91T].

8.1.4.3 Parallax catalogues and lists

A bibliography of catalogues and papers on parallaxes published before 1990 was compiled in [90S] with introductory articles on parallaxes [90G].

Practically all the hitherto published trigonometric parallaxes can be found in the YPC [95v].

This catalogue contains 14448 individual measurements for altogether 8108 stars. Since then, two new lists containing altogether 50 new or improved trigonometric parallaxes were published [95T, 96I].

[86M] published trigonometric parallaxes from Schmidt plates for 6125 stars brighter than $V = 17$ mag in a 20 square degree field near the South Galactic Pole.

The Hipparcos catalogue [97E] contains 118218 stars (117955 entries with associated astrometry).

In 1997 also the Tycho catalogue [97E] becomes available. It is a survey of 1058332 stars complete to a median magnitude of $V = 10.5$ mag.

There exists no comprehensive compilation of spectroscopic and/or photometric parallaxes. Lists of such distances and/or the corresponding calibrations used are cited in the abstract services under various categories.

In Table 2 a selection of recently published photometric parallaxes of subdwarfs and red dwarf stars (mostly from NLTT) are given.

Table 2. Recently published photometric parallaxes.

N	Type	Ref.
413	class m NLTT stars	84W
≈ 1200	subdwarfs	86N
702	class m NLTT stars	86W
1125	high-proper motion stars	87S
787	class m NLTT stars	87W
524	class m NLTT stars	88W
1665	southern NLTT stars	89R
≈ 880	subdwarfs	91R
266	common proper motion pairs	91W1
≈ 420	Stephenson K and M dwarfs	91W2
688	McCormick K and M dwarfs	93W
1269	Lowell proper motion stars	94C
1850	nearby northern M dwarfs	95R

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8.2 The nearest stars

8.2.1 Introduction and data

Almost half a century ago the term *nearby stars* was defined by the limited significance of the then available trigonometric parallaxes, i.e. a distance of not more than 20 to 25 pc. Now, with the advent of the Hipparcos data [97E] this limit can be extended by a factor of ten. But, nevertheless, with present means the absolutely faint stars can only be studied in the immediate neighbourhood of the Sun.

A considerable revival in the research field of nearby stars could be realized, consisting in dedicated programmes of trigonometric parallaxes, photometric observations of high-proper motion stars (NLTT), and spectroscopic surveys of M dwarf stars [95R1]. The debate on the local missing mass along with newly developed techniques gave new impetus to the search for brown dwarfs and planetary companions. Intermediate reports are found in [86G, 92J, 93J]. The progress achieved in recent years is reflected in Table 1.

Table 1. Compilations of nearby stars 1957-1997.

Distance [pc]	1957	1969	1997	stars/pc^3
0…5	52	54	61	0.116
5…10	179	207	257	0.070
10…20	863	918	1552	0.053
20…25			1126	0.035
0…20	1094	1179	1870	0.056

The 1997 values are from an improved version of the *Third Catalogue of Nearby Stars* (CNS3) [91G], updated with Hipparcos data to CNS4 [97J]. Due to the high-precision parallaxes of Hipparcos about 20 per cent (≈ 300) of the brighter stars were removed from the 25 pc volume. On the other hand, Hipparcos added more than 150 new nearby objects. Within 25 pc of the Sun the CNS4 is statistically complete for stars with $M_V \leq 9^m$, i.e. the rapid decrease in star number density (Table 1, column 5) with increasing distance, is caused by a growing incompleteness of the absolutely fainter stars.

8.2.2 Luminosity function in the solar neighbourhood

As a function of M_V the nearby luminosity function derived from CNS4 is given in Table 2a for all stars (column 2) and for main sequence stars (column 3) [97J]. As a consequence of the Hipparcos parallaxes there is a 15 per cent decrease in star number density for the bright end of the luminosity function with respect to a former determination [83W] based on an improved version of the *Catalogue of Nearby Stars. Edition 1969* (CNS2).

Deep ($I \leq 17…18$ mag) photometric surveys [95R2] offer an alternative way to obtain a local luminosity function for red dwarfs. In recent years such surveys were carried out also in red and infrared passbands RIJHK yielding photometric distances for all stars in a small cone up to about 150 pc from the Sun. In Table 2 photometrically determined luminosity functions are compared with a luminosity function based on CNS3 stars within 5…10 pc [95J]. Leggett and Hawkins [88L] surveyed a 52 square degree area at the South Galactic Pole. Tinney's survey [93T1, 93T2, 95T] covered a 270 square degree area, and Kirkpatrick et al. [94K] surveyed a $8\overset{\circ}{.}25$ wide strip from galactic latitudes of + 90° down to – 35° with a CCD/Transit Instrument.

For luminosity functions based on magnitude limited samples it is not sufficient to apply the classical correction for Malmquist bias, another Malmquist type correction is required [89S]. Under the assumption of a constant space density it takes the form

$$\Phi_{\text{true}}(M) = \Phi(M) - \sigma_M^2/2\ [(0.6\ \ln 10)^2 - (1.2\ \ln 10)\Phi'(M)/\Phi(M) + \Phi''(M)/\Phi(M)]$$

Here σ_M is the standard error in absolute magnitude M, $\Phi'(M)$ and $\Phi''(M)$ the first and second derivative of the observed luminosity function $\Phi(M)$.

Around $M_K = 9^m$ or $M_{bol} = 12^m$ the photometric luminosity functions yield systematically smaller number densities than the CNS3 function. An increase to the lowest luminosities seems to be indicated. Whether these discrepancies between local and photometric luminosity functions are real or merely caused by selection effects is still in discussion [93K]. Possible explanations are, for example, unresolved binaries in the photometric surveys [91K, 91R], or smaller scale hight of the fainter M dwarfs [88H]. A review can be found in [93B].

Table 2. Luminosity functions in (**a**) M_V for all stars (col.2) and main-sequence stars (col. 3), (**b**) M_K and (**c**) M_{bol} for red dwarfs compared with photometric surveys.
Units: number of stars within a sphere of 10 pc radius pro magnitude interval M ± 1/2 mag.
The stellar masses in the last columns were taken from [93H].

Table 2a. Jahreiß and Wielen [97J].

M_V	Φ (M_V) all stars	Φ (M_V) main seq.	$\mathcal{M}$ [$\mathcal{M}_\odot$]
– 1	0.1	0.06	
0	0.5	0.4	
1	1.4	1.0	
2	2.0	1.8	1.79
3	5.1	4.6	1.47
4	7.1	6.6	1.22
5	12.2	12.2	1.03
6	12.5	12.5	0.88
7	12.2	12.2	0.75
8	14.0	14.0	0.66
9	17.5	17.5	0.58
10	29.4	29.4	0.51
11	37.5	34.6	0.37
12	53.4	53.4	0.25
13	42.6	32.0	0.18
14	42.6	32.0	0.14
15	53.4	53.4	0.12
16	42.6	42.6	0.10
17	21.4	21.4	0.09
18	9.4	9.4	
19	5.4	5.4	
20			
…	> 0.05	> 0.05	
23			

Table 2b. $\Phi_{L\&H}$: Leggett and Hawkins [88L].

M_K	Φ_{CNS3}	Φ_{CNS3} syst[1])	$\Phi_{L\&H}$	$\mathcal{M}$ [$\mathcal{M}_\odot$]
6	60	55	> 4	0.48
7	52	47	94	0.27
8	107	107	15	0.16
9	128	43	8	0.11
10	17	17	24	0.074

[1]) syst: joint magnitudes and colours of binaries

Table 2c. Φ_T: Tinney [93T2] (Malmquist corrected). Φ_K: Kirkpatrick et al. [94K].

M_{bol} [2])	Φ_{CNS3}	Φ_T	Φ_K	$\mathcal{M}$ [$\mathcal{M}_\odot$]
8	28			0.57
9	60	77	62	0.40
10	71	71	104	0.24
11	114	15	24	0.15
12	103	21	9	0.105
13	24	35	≥ 19	0.08

[2]) $M_{bol} = 2.0698 + 1.105137\, M_K$ [93T1]

A white dwarf luminosity function was determined in [88L], and the subdwarf luminosity function was discussed in [95D].

8.2.3 Star number density and density of matter

See LB VI/2c, subsect. 8.2.3

8.2.4 Colour-luminosity diagram of the nearest stars

In Fig. 1 the HR diagram of 943 stars with good ground-based parallaxes is compared to the corresponding diagram of 16624 single stars with good Hipparcos parallaxes [97E]. Both samples are restricted to $\sigma_\pi/\pi < 0.1$ and $\sigma_{B-V} < 0.025$. Ninety per cent of the stars having good ground-based parallaxes are located within 25 pc from the Sun, whereas a typical distance of the Hipparcos stars is 60…70 pc. Odd positions in the HR diagrams may be caused by wrong matches of astrometric and photometric values. Both HR-diagrams represent not the true distribution of nearby stars.

Again the immense importance of the Hipparcos parallaxes for the brighter stars becomes evident, whereas future progress for the low luminosity stars must rely on ground-based work.

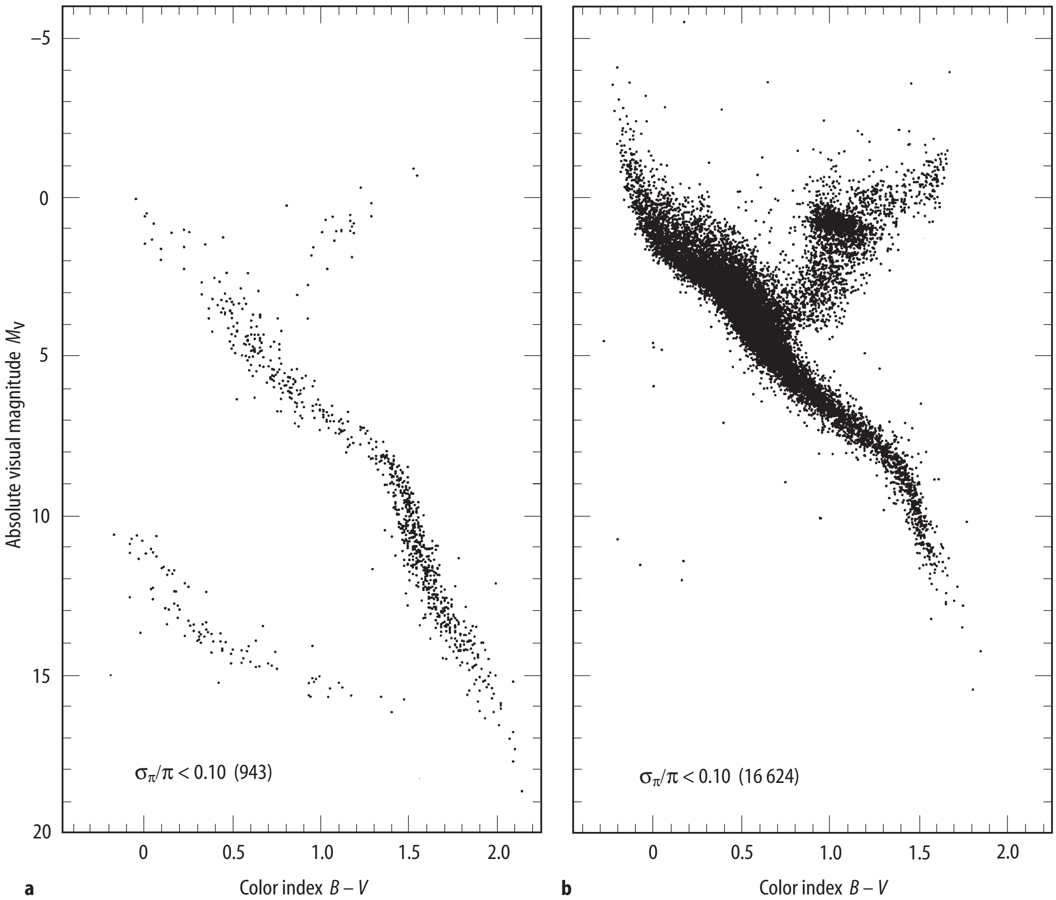

Fig. 1. HR diagram for (a) 943 stars based on ground-based parallaxes with relative parallax error better than 10 % and good *B–V* color indices, and (b) for 16624 single stars from the Hipparcos Catalogue based on Hipparcos parallaxes with σ_π/π < 0.10 and σ_{B-V} < 0.025 mag.

8.2.5 Stars within 5 pc – and beyond

Table 3 lists the principal data for all stars presently known to be within 5.5 pc from the Sun. Hipparcos parallaxes and proper motions are given for 70 % of the stars. X-ray luminosities were derived from ROSAT measurements [95S]. Most M dwarfs in this sample show flare activities; see the compilation of nearby flare stars [91P].

Table 3. Stars within 5.5 parsec of the Sun.

α, δ = coordinates (epoch 2000)
μ = proper motion
θ = position angle
V_R = radial velocity
π = trigonometric parallax
SpT = spectral type
V = apparent visual magnitude
R = apparent red magnitude
I = apparent near infrared magnitude
K = apparent infrared magnitude
M_V = absolute visual magnitude
L_X = X-ray luminosity in erg s^{-1}

No.	Name		α (2000)	δ (2000)	μ ["/a]	θ	V_R [km s^{-1}]	π [mas]	SpT	V	$V-R_c$	$R-I_c$	$V-K$	M_V	log L_X
1	Sun								G2 V	–26.75	0.38	0.34	1.50	4.82	27.30
2	Proxima Cen		$14^h29^m.7$	–62°41'	3.86	282°	–22	772±03	dM5e	11.05	1.64	2.01	6.73	15.49	27.26
	α Cen	A	14 39.6	–60 50	3.71	278	–26	742±02	G2 V	0.02	0.37	0.33	1.53	4.37	27.3
		B	14 39.6	–60 50	3.73	285	–18		K0 V	1.36	0.48	0.41	1.96	5.71	27.18
3	Barnard's star		17 57.8	+04 42	10.37	356	–111	546±01	M4 V	9.54	1.21	1.57	5.04	13.24	25.57
4	Wolf 359		10 56.5	+07 01	4.69	235	+16	419±02	M6 V	13.45	1.87	2.17	7.37	15.56	27.77
5	BD +36°2147		11 03.4	+35 58	4.80	187	–84	392±01	M2 V	7.49	1.01	1.15	4.11	10.46	26.85
6	Sirius	A	06 45.2	–16 43	1.34	204	–9	379±02	A1 V	–1.45	–0.01	–0.01	–0.14	1.44	
		B	06 45.2	–16 43	1.32	204			DA2	8.44				11.33	28.81
7	L 726-8	A	01 39.0	–17 57	3.37	81	+29	374±03	M5.5 V	12.41	1.67	2.04	6.67	15.27	27.33
	UV Cet	B	01 39.0	–17 57	3.37	81	+32		M6 V	13.25				16.11	27.33
8	Ross 154		18 49.8	–23 50	0.67	107	–12	336±02	M3.5 V	10.45	1.23	1.55	5.08	13.08	27.65
9	Ross 248		23 41.9	+44 10	1.62	177	–78	316±01	M5.5 V	12.29	1.55	1.92	6.34	14.79	27.19
10	ε Eri		03 32.9	–09 28	0.98	271	+17	311±01	K2 V	3.72	0.49	0.43	2.07	6.18	28.44
11	CD–36°15693		23 05.9	–35 51	6.90	79	+10	304±01	M2 Ve	7.35	0.97	1.05	3.96	9.76	26.69
12	Ross 128		11 47.8	+00 48	1.36	154	–31	300±02	M4 V	11.12	1.31	1.68	5.49	13.50	26.79
13	L 789-6	A	22 38.6	–15 18	3.25	47	–60	290±04	M5 V J	12.69	1.69	2.03	6.76	15.00	27.27
		B	22 38.6	–15 18	3.25	47				13.6				15.9	
14	61 Cyg	A	21 06.9	+38 45	5.28	52	–65	286±02	K5 V	5.22	0.69	0.60	2.83	7.50	27.28
		B	21 06.9	+38 45	5.17	53	–64		K7 V	6.04	0.84	0.76	3.33	8.32	27.03
15	Procyon	A	07 39.3	+05 14	1.26	215	–4	286±01	F5 IV-V	0.36	0.24	0.24	1.00	2.64	
		B	07 39.3	+05 14	1.26	215			DA	10.75				13.03	
16	BD +43°44	A	00 18.4	+44 01	2.92	82	+12	280±01	M1.5 V	8.08	0.94	1.12	4.05	10.32	27.18
		B	00 18.4	+44 02	2.92	82	+11		M3.5 V	11.05	1.23	1.57	5.10	13.29	26.70

No.	Name		α (2000)	δ (2000)	μ ["/a]	θ	V_R [km s^{-1}]	π [mas]	SpT	V	$V-R_c$	$R-I_c$	$V-K$	M_V	log L_X
17	BD +59°1915	A	$18^h42^m.8$	+59°38'	2.24	324°	–1	280±03	M3 V	8.90	1.07	1.34	4.46	11.14	26.32
		B	18 42.8	+59 38	2.27	323	+1		M3.5 V	9.69	1.11	1.43	4.71	11.93	26.32
18	ε Ind		22 03.4	–56 47	4.70	123	–40	276±01	K5 Ve	4.69	0.61	0.52	2.51	6.89	27.23
19	G 51-15		08 29.8	+26 47	1.29	243	+9	276±03	M6.5 V	14.79	1.99	2.26	7.53	16.99	26.60
20	τ Cet		01 44.1	–15 56	1.92	296	–17	274±01	G8 Vp	3.49	0.42	0.39	1.81	5.68	
21	L 372-58		03 36.0	–44 31	0.84	119	–20	270±06	M5.5	13.01	1.62	1.96	6.38	15.17	25.92
22	L 725-32		01 12.5	–17 00	1.37	62	+28	269±03	M4.5 V	12.05	1.37	1.76	5.63	14.20	26.83
23	BD +5°1668		07 27.4	+05 14	3.74	171	+18	263±02	M3.5 V	9.85	1.17	1.53	4.98	11.95	25.88
24	Kapteyn's star		05 11.7	–45 01	8.66	131	+246	255±01	M0 V	8.85	0.95	1.00	3.79	10.89	26.68
25	CD –39°14192		21 17.2	–38 52	3.45	251	+28	253±01	M0 Ve	6.68	0.90	0.86	3.59	8.70	27.08
26	Krüger 60	A	22 28.0	+57 42	0.99	242	–33	250±03	M3 V	9.79	1.15	1.47	4.88	11.78	27.39
		B	22 28.0	+57 42	0.99	242	–32		M4 V	11.46				13.45	27.39
27	Ross 614	A	06 29.4	–02 49	0.93	132	+17	243±03	M4.5 V	11.14	1.32	1.72	5.59	13.07	27.75
		B	06 29.4	–02 49	0.93	132				14.47				16.40	27.75
28	BD –12°4523		16 30.3	–12 40	1.19	184	–13	234±02	M3 V	10.08	1.16	1.52	4.98	11.93	26.48
29	Van Maanen 2		00 49.2	+05 23	2.98	156	+54	232±02	DZ7	12.39	0.26	0.25	0.95	14.22	
30	CD –37°15492		00 05.4	–37 21	6.10	112	+23	229±01	M4 V	8.55	0.97	1.15	4.03	10.35	26.73
31	Wolf 424	A	12 33.3	+09 01	1.81	278	–5	228±05	M5.5 V	13.04	1.57	1.97	6.40	14.83	27.26
		B	12 33.3	+09 01	1.81	278			M7	13.3				15.1	27.26
32	L 1159-16		02 00.2	+13 03	2.10	148	–31	225±03	M4.5 V	12.27	1.36	1.76	5.62	14.03	27.33
33	L 143-23		10 44.5	–61 12	1.66	348		222±11	m	13.87	1.59	2.04		15.61	26.21
34	BD +68°946		17 36.4	+68 20	1.31	194	–23	221±01	M3 V	9.17	1.09	1.41	4.70	10.89	26.84
35	CD –46°11540		17 28.7	–46 54	1.05	147	–10	220±02	M3	9.38	1.07	1.33	4.48	11.10	27.45
36	LP 731-58		10 48.2	–11 20	1.64	158	+0	220±04	M6.5 V	15.60	2.12	2.32	7.64	17.32	25.98
37	G 208-44	A	19 53.9	+44 25	0.74	143	+42	220±01	M5.5 V	13.48	1.62	2.01	6.52	15.19	27.18
		B	19 53.9	+44 25	0.74	143	+73		M6 V	14.01	1.67	2.06	6.56	15.72	27.18
		C	19 53.9	+44 25	0.74	143				16.66				18.37	
38	L 145-141		11 45.7	–64 50	2.69	97		216±02	DQ6	11.50	0.16	0.16	0.50	13.18	
39	G 158-27		00 06.7	–07 32	2.04	204	–31	213±04	M5.5 V	13.76	1.61	1.99	6.33	15.40	25.55
40	BD –15°6290		22 53.3	–14 16	1.17	125	–2	213±02	M3.5 V	10.16	1.18	1.55	5.12	11.80	26.50

No.	Name		α (2000)	δ (2000)	μ ["/a]	θ	V_R [km s^{-1}]	π [mas]	SpT	V	$V - R_c$	$R - I_c$	$V - K$	M_V	log L_X
41	BD +44°2051	A	$11^h05^m.5$	+43°32'	4.51	282°	+69	207±01	M1 V	8.76	0.98	1.05	4.00	10.34	25.92
		B	11 05.5	+43 31	4.51	282	+68		M5.5 V	14.42	1.73	2.11	6.55	16.00	27.48
42	BD +50°1725		10 11.4	+49 27	1.45	250	–25	205±01	K7 V	6.59	0.86	0.76	3.38	8.15	27.48
43	BD +20°2465		10 19.6	+19 52	0.50	264	+12	205±03	M3 V	9.41	1.11	1.42	4.71	10.96	28.92
44	CD –49°13515		21 33.6	–49 01	0.82	183	+4	202±01	M1 V	8.67	1.00	1.18	4.18	10.20	26.28
45	LP 944-20		03 39.6	–35 26	0.44	49		201±05	>M9V	9.58K				11.10K	
46	CD –44°11909		17 37.0	–44 19	1.18	217	–60	198±03	M3.5	10.95	1.24	1.58	5.27	12.44	25.85
47	40 Eri	A	04 15.3	–07 39	4.09	213	–43	198±01	K1 Ve	4.42	0.45	0.41	2.01	5.91	27.65
		B	04 15.4	–07 40	4.09	213	–21		DA4	9.51	0.37			11.00	
		C	04 15.4	–07 40	4.09	213	–46		M4.5 V	11.21	1.25	1.66	5.23	12.70	28.06
48	BD +43°4305		22 46.8	+44 20	0.84	237	–0	198±02	M3.5 V	10.23	1.16	1.51	4.95	11.71	29.07
49	BD +2°3482	A	18 05.5	+02 30	0.97	173	–7	197±02	K0 Ve	4.24	0.49	0.38	2.14	5.71	28.18
		B	18 05.5	+02 30	0.97	173	–10		K5 Ve	5.9		0.57		7.48	28.18
50	Altair		19 50.8	+08 52	0.66	54	–26	194±01	A7 IV-V	0.77	0.14	0.14	0.51	2.21	27.59
51	G 9-38	A	08 58.2	+19 46	0.87	268	–34	191±03	M5.5 V	14.07	1.70	2.11	6.75	15.48	27.60
	LP 426-40	B	08 58.2	+19 46	0.87	268			M5.5	14.93				16.34	27.60
52	G99-49		06 00.1	+02 42	0.24	108	+4	186±10	M3.5 V	11.34				12.69	28.03
53	AC+79°3888		11 47.7	+78 41	0.89	57	–112	186±02	M3.5 V	10.80	1.14	1.49	4.89	12.14	26.66
54	BD+15°2620		13 45.7	+14 54	2.30	129	+16	184±01	M1.5 V	8.47	0.96	1.09	4.01	9.80	26.60
55	LP 816-60		20 52.5	–16 58	0.31	276		182±04	M5.5	11.41				12.71	
56	L 722-22	A	00 15.5	–16 08	0.88	134	–20	182±07	M4 V J	11.60	1.22	1.55	5.10	12.90	25.83
		B	00 15.5	–16 08	0.88	134				14.4				15.7	25.83

The 47 stellar systems within 5 pc include 11 binaries and 3 triples resulting in a relative binary frequency of 48%. This percentage increases to 56% for stars north of $\delta = -30°$ (research programmes concentrate on northern observatories). The relative binary frequency of nearby M dwarfs amounts to 61% according to [92F].

Whether Proxima Centauri is really in orbit around α Centauri AB is still open [93M]. Component A of L 789-6 (No. 12 in Table 3) is most probably itself a spectroscopic binary with equal components.

The very low mass stars ($\leq 0.3\,\mathcal{M}_{\odot}$, $M_V \geq 11^m$) constitute the most numerous objects in our Galaxy. Their properties are reviewed in [87L]. Late M dwarfs are also discussed in [91B]. [92L] provides a critical compilation of the infrared colours. Improved mass-luminosity relations for low luminosity stars at various passbands were determined in [93H].

Only one star among the absolutely faintest red stars listed in Table 4 is nearer than 5 pc. For comparison, the faintest nearby white dwarf GJ 1276 = LP 701-29, spectral type DZ9+, at a distance of 8.1 pc has $M_K = 13\overset{m}{.}94$, or $M_V = 16\overset{m}{.}12$.

Table 4. The absolutely faintest red dwarfs.

Name	α (2000)	δ (2000)	SpT	M_K	M_V	r [pc]
ESO207-61	07^h 08^m	– 49° 01'	M9 V	11.22	20.09	15.1
RG0050-2722	00 53	– 27 06	M8: V	10.62	19.57	24.4
LHS2924	14 29	+ 33 11	M9 V	10.50	19.57	10.8
GJ2005C	00 25	– 27 08		10.46	18.7	7.4
LHS2065	08 54	– 03 30	M9 V	10.33	19.04	8.5
LHS2876B	14 12	– 00 35	M6.5 V	10.10	18.11	24.9
GJ1245C	19 54	+ 44 25		10.00	18.37	4.5
LHS2397a	11 22	– 13 13	M8 V	10.00	18.28:	14.3
Gl752B = VB10	19 17	+ 05 09	M8 V	9.97	18.65	5.8
LHS3003	14 57	– 28 10	M7 V	9.90	17.97	6.4
LHS2930	14 31	+ 59 43	M5.5 V	9.80	17.98:	9.6
Gl644C = VB8	16 56	– 08 24	M7 V	9.77	17.71	6.5

During recent years the 5 pc volume has been exhaustively explored. But really new findings could be obtained only beyond the 5 pc limit: a probable cool brown dwarf was discovered as companion to Gl 229 (5.8 pc) [95N]. Promising candidates for extra-solar planets were detected from high precision radial velocity measurements near 51 Peg = Gl 882 (17.4 pc) [95M], 47 UMa = Gl 407 (13 pc) [96B], and 70 Vir = Gl 512.1 (18.6 pc) [96M], respectively.

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8.3 Structure of the Galaxy

8.3.0 Introduction

At first we give an overview of recent proceedings on the galactic structure. Starting with a technical and observational point of view, a discussion on catalogues and surveys is given in [a], on the modern use of wide-field imaging in [b], on huge surveys in [c], and on the background radiation in [d]. Databases with regard to the galactic structure are extensively discussed in [x].

A general lecture on the Milky Way can be found in [e]. Proceedings on many aspects of the Galaxy are [f, g, h, i, j], the most recent discussion on actual topics is collected in [k], and the vertical structure is discussed in [l].

An important tool for the understanding of galactic structure is the concept of stellar populations and galactic components. General reports are given in [m, n, o], and a recent discussion on the basic concepts is contained in [p]. There are special proceedings on the outer disk [q], on the galactic center [r, s, t], and on bulges [u, v].

Lectures on the interstellar medium (ISM) are given in [e, zb], a general review on the physics and distribution of the ISM can be found in [za], and all aspects of molecular clouds are discussed in [zg, zk]. For an overview on surveys on the ISM see [c, x, zd], for the radio astronomical background see [zc, zj], and for the dust component and infrared observations see [zh, ze]. Results from extreme ultraviolet observations are presented in [zf]. Investigations on many aspects of the galactic ISM are contained in the general proceedings on the Milky Way [g, h, k]. The physics of the disk are discussed in [i, zi], and the ISM at high galactic latitude is presented in [w].

For many investigations on the galactic structure kinematical data are essential. Therefore see also sect. 8.4 for further references.

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8.3.1 Apparent distribution of galactic objects on the celestial sphere

8.3.1.1 Galactic coordinates

For the definition of the galactic coordinate system (l, b) and the orientation with respect to equatorial coordinates 1950.0 see LB VI/2c, subsect. 8.3.1.1. Here are the values referred to the J2000.0 coordinate system [93M] for the north galactic pole

$$\alpha = 12^{\mathrm{h}}51^{\mathrm{m}}26\overset{\mathrm{s}}{.}2754,\ \delta = +27°07'41\overset{''}{.}705,$$

for the zero point of the galactic system (l = 0, b = 0)

$$\alpha = 17^{\mathrm{h}}45^{\mathrm{m}}37\overset{\mathrm{s}}{.}1991,\ \delta = -28°56'10\overset{''}{.}219,$$

for the inclination of the galactic plane (J2000.0)

$$i = 62°52'18\overset{''}{.}295 = 62\overset{\circ}{.}872,$$

and for the ascending node of the galactic plane (J2000.0)

$$\alpha = 18^{\mathrm{h}}51^{\mathrm{m}}26\overset{\mathrm{s}}{.}2754 = 282\overset{\circ}{.}8595 \text{ corresponding to } l = +32\overset{\circ}{.}9319.$$

8.3.1.2 Distribution of surface brightness

Reviews on the use of surface photometry for galactic structure are given in [90T1] for optical bands and in [90F] for the near infrared range. A review on stellar UV radiation and tables of the surface brightness at λ = 1565 Å, 1965 Å, 2365 Å, 2740 Å can be found in [90G]. A list of NIR surveys of the Milky Way is presented in [93G].

A description of the Bochum super-wide-field surface photometry of the Milky Way in U, B, V, and R are given in [83S]. A collection of recent work on surface photometry is presented in Table 1.

Table 1. Surface brightness photometry of the Milky Way (MW) at visible, near infrared, and near ultraviolet wavelength λ. Update of Table 1 in LB VI/2c, subsect. 8.3.1. Field of view: area in square degree (□°), diameter in degree (°).

Spectral region	Field of view $\Delta l \times \Delta b$	Region of MW	Ref.
λ=975Å, $\Delta\lambda$=140Å	2/3 of sky	$-60° < \delta < 60°$	84O
U, B, V, R	30°×30°	Coalsack, l = 303°, b = 0°	82S
U	90°×60°	central part of MW	83P
U	170°×82°	northern MW	82W1
U	360°×80°	whole MW	84W
B	220°×80°	southern MW	93K
V	130°×40°	northern MW	85Z
I	180°×20°	southern MW	81H
H, K	1°×4°	l = 26.5°, b = 0°	82M2
K	140°×60°	central part of MW	92K
K	255 □°	northern MW	93G

8.3.1.3 Apparent distribution of the different types of galactic objects

In recent years point source catalogues in the far ultraviolet (FUV) and the far infrared (FIR) became very useful for sampling special types of stars (e.g. OH/IR stars of the bulge from the IRAS point source catalogue [85H]). In Table 2 some point source catalogues and photometric catalogues are listed. For star catalogues concerning also star positions or proper motions see subsect. 8.1.1 and 8.1.2.

Table 2. Point source catalogues in the FUV and FIR and photometric catalogues. The field of view is given by the diameter in degree (°) or the area in square degree (□°).

Instrument / photometric system	Spectral region (band)	Limiting magnitude	Field of view	Number of stars	Ref.
FAUST	1400…1800 Å	10^{-14}erg s^{-1} cm^{-2} Å^{-1}	19°×7.6°	4800	93B
GLAZAR	1640 ± 250 Å	11^m	77 □°	28	90T2
Geneva	U, B, V, B1, B2, V1, G			14633	81R
DDO	3200…5300 Å			2911	82M1
IRAS PSC	12, 25, 60, 100 μm	0.8, 1, 1.2, 2 Jy	whole sky	134000	86C

Surveys of stars with special spectral types are listed in Table 3. The apparent distribution of planetary nebulae is discussed in [89M]. A review on OH/IR stars is given in [87C1].

Table 3. Surveys and catalogues for selected spectral types, Carbon (C-)stars, and Blue horizontal branch (BHB-)stars in the Milky Way (MW). The extension of the region is given in □° and the location by the central coordinates of the fields. NGP and SGP are the North and South galactic pole, resp. Update of Table 4 in LB VI/2c, subsect. 8.3.1.

Spectral type	Region	Limiting magnitude (band)	Number of stars	Ref.
O, B	l = 335°…0°…6°	13.3 (V)	316	82D
O, B	42 □° l = 270°, b = 0°	14.5 (R)	108	82V
O, B	15 □° l = 264°, b = – 0.5°	9 (1640Å)	71	93T
O, B	21 □° l = 335°, b = 0°	14.4 (V)	103	87F
O…B5	26.6 □° l = 245°, b = 0°	12.5 (V)	108	84R
O…A0	gal. plane, 135° < l < 175°	10.5 (V)	355	82W2
B…M	20 □° l = 298°, b = 1°	13 (V)	8000	83M
B5…A5	9.6 □° l = 253°, b = – 7°	12 (V)	130	84B
B5…F8		7.2…9 (V)	686	91P
< F6	2 fields 70 □° l = 90°, 270°, b = – 45°	15 (V)	430	93R
A3…F5	6 fields 16 □° gal. plane, 256° < l < 320°	11 (pg)	540	88F1
F	100 □° SGP	16.5 (V)	5000	88L
F, G	δ < 38°	9.6 (V)	6190	94O
G	4 □° SGP	16.4 (V)	214	88C
G5…M	81 □° SGP	13.5 (V)	2228	86M
M	2 fields 28 □° SGP; l = 335°, b = – 47°	20.2 (R)	16000	88H
M	6 □° SGP	18 (R)	2600	81S

Spectral type	Region	Limiting magnitude (band)	Number of stars	Ref.
> M5	b > 10°, δ > – 25°	13 (V)	538	86S
M giants	0.12 □° – 25° < l < 25°, b = – 6°	14.5 (I)	4300	89B
M giants	0.01 □° Baade's Window	18.5 (V)	174	86B1
M giants	2 fields 400 □° l = 0°/20°, b = 0°	1 Jy (12 μm)	14000/10000	85H
M giants	l = 0°, – 12° < b < – 2.9°		400	86F
M giants	0.13 □° l = 0° b = – 8°	15 (I)	120	87B
M giants	10 fields 0.13 □° l = 0°, – 13° < b < – 2°	14.8 (I)	4000	88B
> M4 giants	l = 0°, – 12.6° < b < – 2°			86B2
C-stars	2 fields 322 □° gal. center and anticenter	13 (I)	283	81F
C-stars	115° < l < 130°, – 5° < b < 5°	16 (V)	180	87N
C-stars	130° < l < 145°, – 5° < b < 5°	16 (I)	122	88N
C-stars			215	87C2
BHB-stars		19 (V)	20	88F2
BHB-stars	NGP; l = 183°, b = 37°	16.5 (V)	72	94K

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8.3.2 The local star field

8.3.2.1 Luminosity function

See subsect. 8.2.2

8.3.2.2 Star densities in the solar neighbourhood

See LB VI/2c, subsect. 8.2.3

8.3.2.3 Distribution of common stars near the galactic plane

Star counts of selected fields remain an important tool for the investigation of galactic structure. A brief history of the use and technique of star counting is given in [93R]. A review on star counts in several bands for modelling the Galaxy including a list of the most important star count investigations is given in [94R]. A more complete list of star count investigations in at least two photometric bands is presented in Table 4.

Table 4. Recent regional studies of spatial star density distribution at low galactic latitudes |*b*| < 15°. Update of Table 9 in LB VI/2c, subsect. 8.3.2.

Field center or extension in (*l*, *b*)		Area [□°]	Number of stars	Observational data	Limiting magnitude (band)	Ref.
l	*b*					
Galactic center direction (*l* = 350°…0°…10°)						
9°.3	12°.1	0.19	1235	R, G, U	17.9 (G)	82B1
3.7	– 8.8	0.432	1603	R, G, U	16 (G)	83F1
284.9	– 0.1	0.21	2099	R, G, U	16.6 (G)	84A
4	12	0.09	1426	R, G, U	18 (G)	87R
0…1	– 3.9…– 10	4 fields 0.004		B, V, I	20.5 (V)	88T
Scutum-Aquila-Vulpecula (*l* = 10°…60°)						
26.2	– 1	0.167	2647	R, G, U	17.7 (G)	85K
Cygnus-Cepheus-Cassiopeia-Perseus (*l* = 60°…150°)						
112.8	0.0	0.28	1765	R, G, U	18.1 (G)	83F2
Galactic anticenter direction (*l* = 150°…210°)						
179	2.5	2/0.002	17000	U, B, V	17.5/21 (V)	88M
198.0	– 5.4	0.306	1882	R, G, U	18 (G)	84F1
203.2	– 0.9	0.217	1362	R, G, U	18 (G)	85F
Puppis-Vela-Carina-Crux (*l* = 210°…300°)						
211	1	1.5	12800	U, B, V	17.5 (V)	88M
239.5	0.7	0.11	1569	R, G, U	17 (G)	87F3
240	0	26.6	610	U, B, V		83R
277	0.8	0.31	2132	R, G, U	16.8 (G)	82B2
289.7	– 0.3	0.123	2001	R, G, U	16 (G)	82B3
Centaurus-Circinus-Norma-Scorpius (*l* = 300°…350°)						
307	0	0.33	2425	R, G, U	16.6 (G)	82S

8.3.2.4 Distribution of common stars perpendicular to the galactic plane

For the investigations of the vertical structure of the Galaxy star count data in high galactic latitude fields are used. Table 5 gives a list of star count investigations in at least two photometric bands of high galactic latitude fields. The fields near the galactic poles are seperately presented in Table 6.

Table 5. Recent regional studies of spatial star density distribution at high galactic latitudes 15° < |*b*| < 70°.

Field center or extension in *l*	*b*	Area [□°]	Number of stars	Observational data	Limiting magnitude (band)	Ref.
13 fields	|*b*| > 27°	1	1238	v, *b*, y	17.3 (V)	92H
0°	29°	0.54	1869	R, G, U	18.7 (G)	83S
3.3	23.1	0.93	2375	R, G, U	18.5 (G)	82W
3	47	1.78	1180	U, B, V	17.4 (V)	92B
10	– 14.3	0.2	11000	B, V	19.5 (V)	89R
	– 22.3		4500			
	– 33.0		1800			
36.5	– 51.1	0.31	603	B, V	20.0 (B)	84T
37	– 51	17	28000	B, V, I	22.5 (V)	85G
36.5	51.1	4	774	B, V	15 (V)	86F
64	– 19	0.29	1810	R, G, U	19 (G)	83B
101	60	2	1806	R, G, U	19.5 (G)	87F2
151	29	1.21	1857	R, G, U	19.5 (G)	88F1
175.3	– 49.3	4	640	B, V	15 (V)	86F
196.8	37.7	0.25	1050	U, B_J, F	23 (B_J)	86B
198	20	0.62		R, G, U	18 (G)	87F1
200	59	16	7600	U, B, V	18 (V)	92Y
205.9	32.4	3.56	1500	R, G, U	16.2 (G)	84K
210.6	32.2	1.7	759	R, G, U	16.5 (G)	84F2
340	– 15, – 25, – 35	3 fields 0.2	>25000	B, V	21.5 (V)	86R

Table 6. Recent regional studies of spatial star density distribution in the north and south galactic pole (NGP, SGP) regions with 70° < |*b*|.

Field center or extension in *l*	*b*	Area [□°]	Number of stars	Observational data	Limiting magnitude (band)	Ref.
256°	78°	3.46		R, G, U	18.5(G)	91F
65.5	85.5	2.61	1179	R, G, U	19(G)	88F2
NGP		24		U, B, V	18(V)	86S
80.8	86.5	21.46	18303	U, B, V, (I)	19(V)	87S
NGP		1.08	6563	B_J, V	23(B_J)	94I
245	– 85.8	1.92	642	R, G, U	18(G)	88F2
SGP		18.24	11000	V, R, I	17(I)	82R
SGP		18.24	12500	V, I	18(I)	83G
SGP		11.5	10000	B, V	20.5(V)	85G
73.5	– 80.1	0.55	2800	B_J, r	22.5(B_J)	86I

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For Proceedings see 8.3.0, p. 137

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8.3.3 Large-scale distribution of the stars

Detailed comparisons of Galaxy models and star count data are available now. The "standard model" of Bahcall and Soneira [80B] is often used as a reference model. The mostly referred galactic parameters of this 2-component model (disk/spheroid) were derived in [84B]. A review on the comparison of star count data and galactic models is given in [86B]. Galaxy models based also on the kinematics and chemical evolution are described in [89G], and an evolutinary model including the chemical evolution is given by [86R1, 86R2]. A Galaxy model for the UV observations is presented in [91B2], and IR models are developed in [88H, 91K].

8.3.3.1 Subsystems of the Galaxy, stellar populations

The distinct stellar components of the Galaxy, namely the thin disk, the thick disk, the bulge, and the halo are determined by their spatial and kinematical structure [e]. For a general review see [90G], and for an evolutionary model see [95G]. The galactic components should be well distinguished from the concept of stellar populations, which are characterized by age and metallicity [95K]. A detailed review on the basic features of galactic stellar populations is given in [82M]. The population concept for the understanding of the evolution of the Galaxy is reviewed in [86S]. The stellar populations of the different galactic components are discussed in [93T1]. Investigations on many aspects of stellar components in the Milky Way are collected in [n]. The most recent comprehensive work on stellar populations can be found in [p].

8.3.3.2 Distribution of stars in the galactic disk

Here we discuss the thin disk component, which is the fast rotating major body of the Galaxy and is composed of stars with ages of 0 to about 12 Gyr. The scale height increases with age from 100 pc for OB associations and young open clusters up to 1 kpc for the old disk component with a mean (standard) value of 325 pc. A review on the old disk, the bulge and halo are given in [87F]. A detailed model of disk and bulge including a young and old disk component, spiral arms, and an exponential dust component to reproduce star counts in the optical, IR, and FIR bands is presented in [93O]. Recent determinations of the radial scale length h_R are listed in Table 7.

The scale length is not well determined due to extinction in the optical range and population dependencies seen in the IR. A modern value of h_R = 3.5 ± 1 kpc seems reasonable and h_R = 4 kpc is often used as a standard value.

An overview on optical tracers of spiral arms in the second quadrant are given by [89K]. Spiral arm structure is investigated by open clusters and HII regions [89A], OB stars [93R1], early A-type stars [89S], Cepheids [87K], and pulsars [90M].

The galactic warp is now also found with OB stars [88M], and with IRAS sources [89D, 90W2].

A new feature of our Galaxy is a bar-like distortion in the inner few kpc seen in the IR [91B1, 94D], AGB stars [92W2], Mira variables [92W3], and also in the gas kinematics (see sect. 8.4). N-body simulations of the galactic bar are presented in [93S1, 96F]. A comprehensive discussion on the bar is given in [k]. For the triaxial structure of the bulge due to the nonaxisymmetric potential see subsect. 8.3.3.3.

Table 7. Recent determinations of the radial disk scale length h_R.

h_R [kpc]	Data	Model	Ref.
5.5 ± 1.0	B, V surf. photom. Pioneer 10	2 exp. disks; young and old	86K
2.5	U, B, V star counts; anticenter	exp. disk with cutoff	92R
2.5 ± 0.3/2.8± 0.8	U, B, V star counts	exp. thin (flattened)/thick disk	96R1
2.3 ± 0.6/3.0 ± 1.0	U, B, V star counts; proper motions	exp. thin/thick disk	96O
3.5…4.5	B_J, R_F star counts; gal. center	exp. disk, bulge, extinction, pop. synthesis	95N
4.0/4.25	R, G, U star counts	thin/thick disk; bulge; halo	96B
3.0 ± 0.4	V, I HST star counts; M dwarfs	$\cosh^{-2}$-thin disk; exp. thick disk	96G
2.3 ± 0.1	I, J, K_s DENIS star counts	ellipsoidal disk; extinction	96R2
3.0 ± 0.5	2.4μm surf. photom. IRT	exp. disk; bulge; dust via HI+CO distr.	91K
4/2.6	K, 12μm, 25μm IRAS star counts	exp. thin/thick disk; bulge; spiral arms, extinction	93O
4.5/6.5	12μm, 25μm IRAS star counts	thin/thick disk with cutoff	88H
3.0	K star counts	exp. disk; bulge	84E
6	12μm, 25μm, 60μm IRAS star counts	exp. disk; bulge	87R
4.5	12μm IRAS variables	exp. disk; $\cosh^{-2}$-dust comp.	92W1

8.3.3.3 Distribution of stars in the galactic halo

Here we describe the vertically extended components of the Galaxy, i.e. the thick disk, the bulge and the halo. In all star count models the assumption of reasonable colour magnitude diagrams determined by age and metallicity for the different components is important.

The thick disk component is now established, but the evolutionary connection to the thin disk and the halo is not fully understood. The thick disk corresponds to the intermediate population II [93R3]. [87N] argues against a distinct thick disk component, but [89R] found strong evidence for a thick disk from a statistical model analysis. The thick disk as the disk-halo connection is discussed in [91W]. The most extensive proof for the thick disk component is given in a series of papers [89F1…4] based on the 15 fields of the Basle Halo Program. The star count data are used to confirm the existence of a distinct thick disk component by using a scale length of 4 kpc, a scale height of 1 kpc, and a local normalisation of 2% of the thin disk density. A detailed comparison of different models for the vertical structure of the Galaxy using deep observations in the North Galactic Pole Field SA 57 is given in [93R3]. A standard model for the halo is used with a de Vaucouleurs density law with R_e = 2.7 kpc, a flattening of 0.85 and a local normalisation of 0.15% relative to the old disk density. The profile in the solar cylinder is very similar to a power law $r^{-\alpha}$ with α = 3.3 consistent with other determinations of α between 3.0 and 3.5. The result is that the standard thick disk model with a scale height of 1200 pc and a local normalisation of 2% leads to a deficiency of faint thick disk stars. A corrected model with a scale height of 1400 pc, a local normalisation of 2.5% and a slightly varied luminosity function gives a satisfactory result.

Many new insights in the structure of the galactic bulge came from IR observations due to the strongly reduced extinction compared to the optical range [93G]. Revievs on the bulge can be found in [87F, 88F, 89F5, 93K]. The bulge structure is discussed using different tracers in [u] and [v], i.e. red giant variables and carbon stars [90F, 93W], K and M giants [90W1, 93T2], OH/IR stars [90V, 90P, 93H], AGB stars [90B], planetary nebulae [90R, 93S2]. Bulge models were developed in [92W1] based on IRAS variables, in [83B] based on star count data, and in [85G] including also the metallicity distribution. The radial profile is discussed in [86M], the triaxiality in [91N]. In [94D] a detailed comparison is made of different triaxial bulge models from the literature with COBE DIRBE observations at 2.2, 3.9, 4.9 μm. They found best fits with Gaussian or exponential profiles combined with boxy shaped isodensity contours as used in [92W4] for IRAS data and [92W3] for the distribution of the Mira variables. The bulge is triaxial with axis ratios $(x_0{:}y_0{:}z_0) = (1{:}0.33 \pm 0.11{:}\ 0.23 \pm 0.08)$ with the major axis pointing to the first galactic quadrant and a viewing angle of $\alpha = 20° \pm 10°$ to the line of sight. The bar is tilted about 1° out of the galactic plane with the near end pointing to the southern hemisphere. The total luminosity in the K-band inside R = 2.4 kpc is $4.1 \cdot 10^8\ L_\odot$. The axis ratios and the orientation are strongly dependend on the radial profiles used, but it seems confirmed that the global form is prolate and the bar extends over about 2 kpc along the major axis. Gas kinematical models with $\alpha \approx 16°$ [91B3] support the Gaussian model, whereas the AGB star distribution with $\alpha \approx 36°$ [92W2] supports the exponential model also used for the Miras [92W3].

Different aspects of the bulge– halo connection are discussed in [u]. A review on the galactic halo is given in [87F]. The vertical profile of the stellar components above the galactic plane is discussed in [83G, 87S, 89Y, 93R2]. A comparison of different models for the vertical structure is given in [93R3]. The vertical distribution of planetary nebulae is described in [91Z].

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8.3.4 Large-scale distribution of interstellar matter

8.3.4.1 General remarks

A lecture on the observational properties, the large scale distribution and dynamics, and also the chemistry and physics of the interstellar medium (ISM) is given in [zb]. A recent review on these general points of view can be found in [89H], and an overview on the radio astronomical aspects of the observation of the ISM is given in [zc]. The far infrared emission of the ISM with a special view on the COBE results is reviewed in [92B1]. From the opacity in the extreme ultraviolet the distribution of the local HI and H_2 can be analysed [91F], many aspects on galactic molecular clouds are reviewed in [90F].

8.3.4.2 Interstellar dust

A review on dust properties and the large scale distribution in the Milky Way and other galaxies derived from far infrared observations is given in [83S]. Large scale variations of the extinction law are discussed in [88L1], the characteristics of dust in the far infrared from COBE DIRBE observations in [94S], and the gas mass determination from dust in [88B1]. An extensive atlas of dark clouds on the celestial sphere is given in [86F].

8.3.4.3 Interstellar gas in the galactic disk

The radial distribution of HII regions show systematic differences in the northern and southern part of the Galaxy (see Fig.1) [90L]. Similar differences were also found for the distribution of H_2 [88B2].
The distribution of diffuse ionized gas ($T_e \approx 8000$ K) is measured in the H166α line. For a survey of the southern galactic plane see [89C], and for the structure of the 3 kpc arm see [90C, 90L].

A guide for the use of the numerous HI surveys is given in [93L] presenting also a selected list of important surveys (see Table 8).
A recent review on the HI in the Galaxy is given in [90D]. The global distribution of the HI column density is shown in Fig. 2.
The radial distribution of HI and H_2 is presented in Fig. 3 showing also the uncertainties due to a slight variation of the outer rotation curve.

The HI distribution of the outer Galaxy is discussed in [86B], and more recently with special view on the differences for different number densities of HI in [91D]. An edge-on view of the spatial distribution is shown in Fig. 4.

An extended review on the distribution of CO is given in [91C] including a list of important CO surveys (see Table 9). A special discussion on CO surveys can be found in [93S]. The most important survey of the entire galactic plane is the composite Columbia and Cerro-Tololo survey [87D].

An overall map of the CO distribution is shown in Fig. 5.

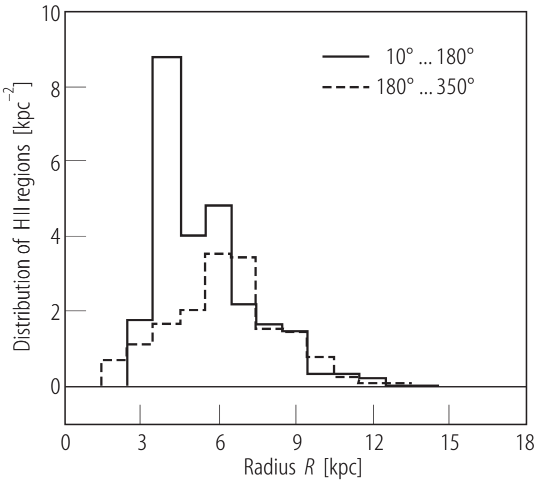


Fig. 1. Surface density of HII regions in the North (10°…180° full line) and South (180°…350° dashed line) from the combined Green Bank and Parkes Surveys. The figure does not include nebulae at R < 1.5 kpc because of the longitude limit. The relative amplitude of the distributions is a function of the sensitivity of the surveys, but the difference in shape is real [90L].

Table 8. Selected HI Surveys.

Coverage	HPBW	Δv [km/s]	Noise [K]	Ref.
10°< l < 250°; $\|b\|$ < 10°	36'	2.1	0.4	73W
all l; $\|b\|$ > 10° at δ > – 30°	36'	2.1	1.2	74H
all l; $\|b\|$ > 10° at δ < – 30°	48'	7.0	0.3	79C
11°< l < 235°; $\|b\|$ < 2°	13'	2.0	1.0	82W
all l; $\|b\|$ < 20° at δ > – 46°	21'	1.0	0.2	86B
240°< l < 350°; $\|b\|$ < 10°	48'	2.1	0.8	86K
δ > – 40°	3°×2°	5.3	0.02	92S
δ > – 30°	36'	1.0	0.08	96B

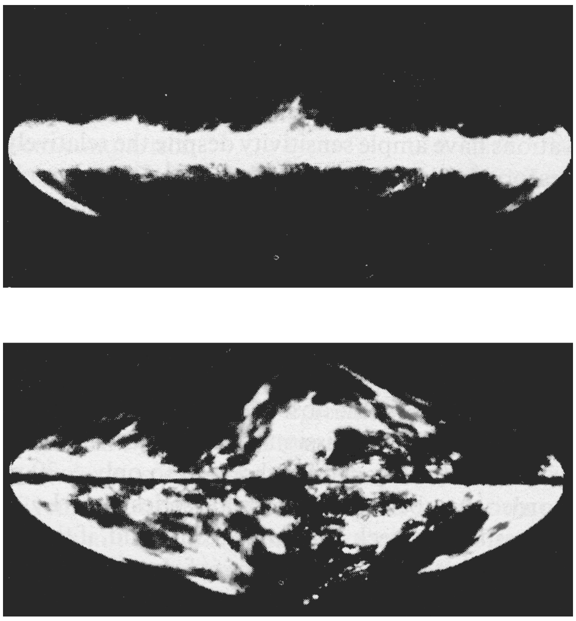


Fig. 2. Two views of the HI sky. Both maps are centered on the galactiv centre with longitude increasing to the left. Top panel: The distribution of total HI column densities. Bottom panel: The distribution of $N_H \sin|b|$. This shows the deviation of the sky from a uniform, infinite, plane-parallel layer [90D].

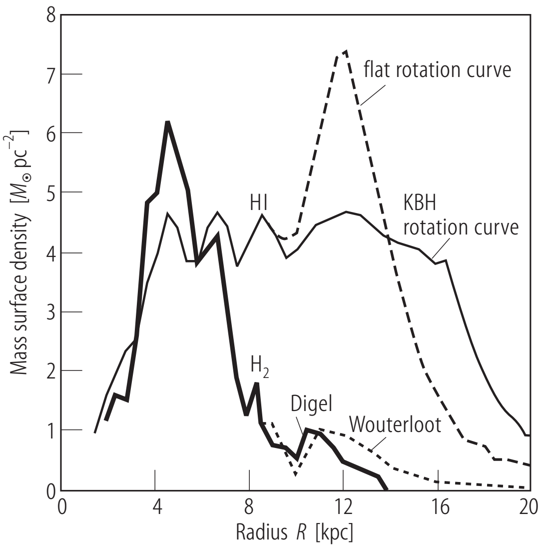


Fig. 3. Average HI and H_2 mass surface density in the Milky Way. H_2 at $R < R_\odot$ (heavy solid): [88B2, Tab. 4], scaled to X = 2.3 and $R_\odot$ = 8.5 kpc. H_2 at $R_\odot$: [87D], scaled to X = 2.3. H_2 at $R > R_\odot$ (heavy solid): [91D, Tab. VI-2] with factor 1.36 correction for helium removed. H_2 at $R > R_\odot$ (heavy dashed): [90W], renormalized to the H_2 mass surface density at $R = R_\odot$ adopted here. HI at $R < R_\odot$ (light solid): derived from midplane number densities given in [78B] and constant HI layer thickness of 220 pc (FWHM) given by [90D]; values have also been arbitrarily scaled by a factor of 2 to approximately match the value at $R = R_\odot$ (see [92L]). HI at $R = R_\odot$: [90D, Fig. 6]. HI at $R > R_\odot$ (light solid): derived by [88L2] using the rotation curve of [82K] (KBH). HI at $R > R_\odot$ (light dashed): derived by [88L2] using a flat rotation curve, which differs from the KBH curve by < 14% at any point [93D].

Table 9. CO Surveys of the Milky Way.

Survey	Line	Sampling in l	effect. resol.	# of pos.	Δl [deg]	Δb [deg]	% Sky covered	σ(K)	Ref.
N.R.A.O.	^{12}CO	60'	1'.08	100	350…90	b = 0°	0.00008	0.5	75S
N.R.A.O.	^{12}CO	12'	1.08	500	350…90	b = 0°	0.0004	0.2	78B
N.R.A.O.	^{12}CO	60'	1.08	1500	350…90	–1…+1	0.0012	0.5	79S
Columbia	^{12}CO	2.5°	8	179	15…60	–1.5…+1.5	0.008	0.3	77C
Bell Labs	^{12}CO	≈ 2°	1.7	4000	4…90	–2…+2	0.008	0.3	85K
Bell Labs	^{12}CO	3'	1.7	4000	355…122	–1…+1	0.008	0.2	89S2
Massach.-Stony Brook	^{12}CO	3'×3' 6'	0.73	40551	18…55 8…90	–1…+1	0.015	0.4	86S, 86C1
Epping	^{12}CO	9'	8	600	279…13	–0.07…+0.07	0.026	0.4	88R
Columbia	^{12}CO	0.12° 0.25°	8	3083	12…60	–0.25…+0.25 –1.25…+1.25	0.1	0.3	86C2
Columbia-Southern	^{12}CO	0.12° 0.25°	8.8	7000	300…348	–0.75…+0.75 –2…+2	0.4	0.1	89B
Columbia+ Cerro-Tololo	^{12}CO	30'	30	31000	0…360	–20…+20	20	0.3	87D
Cerro-Tololo	^{12}CO	0.25°/ 0.125°	8.8	>3600	194…270	–4…+1	≈ 0.006	0.1	93M
CAT-ESO	CO (2-1)	30'	5.5	170	270…355	b = 0°	0.0035	0.5	84I
Bordeaux	^{13}CO	5'	4.4	282	38…67.5	b = 0°	0.004	0.09	88J
NRAO	^{13}CO	3'	1.1	391	20…40	b = 0°	0.0003	0.07	84L
Bell Labs	^{13}CO	3'	1.8	73000	355…122	–1…+1	0.16	0.1	89S2
Columbia-S	^{13}CO	0.25°	9	200	300…350	b = 0°	0.01	0.08	88B3

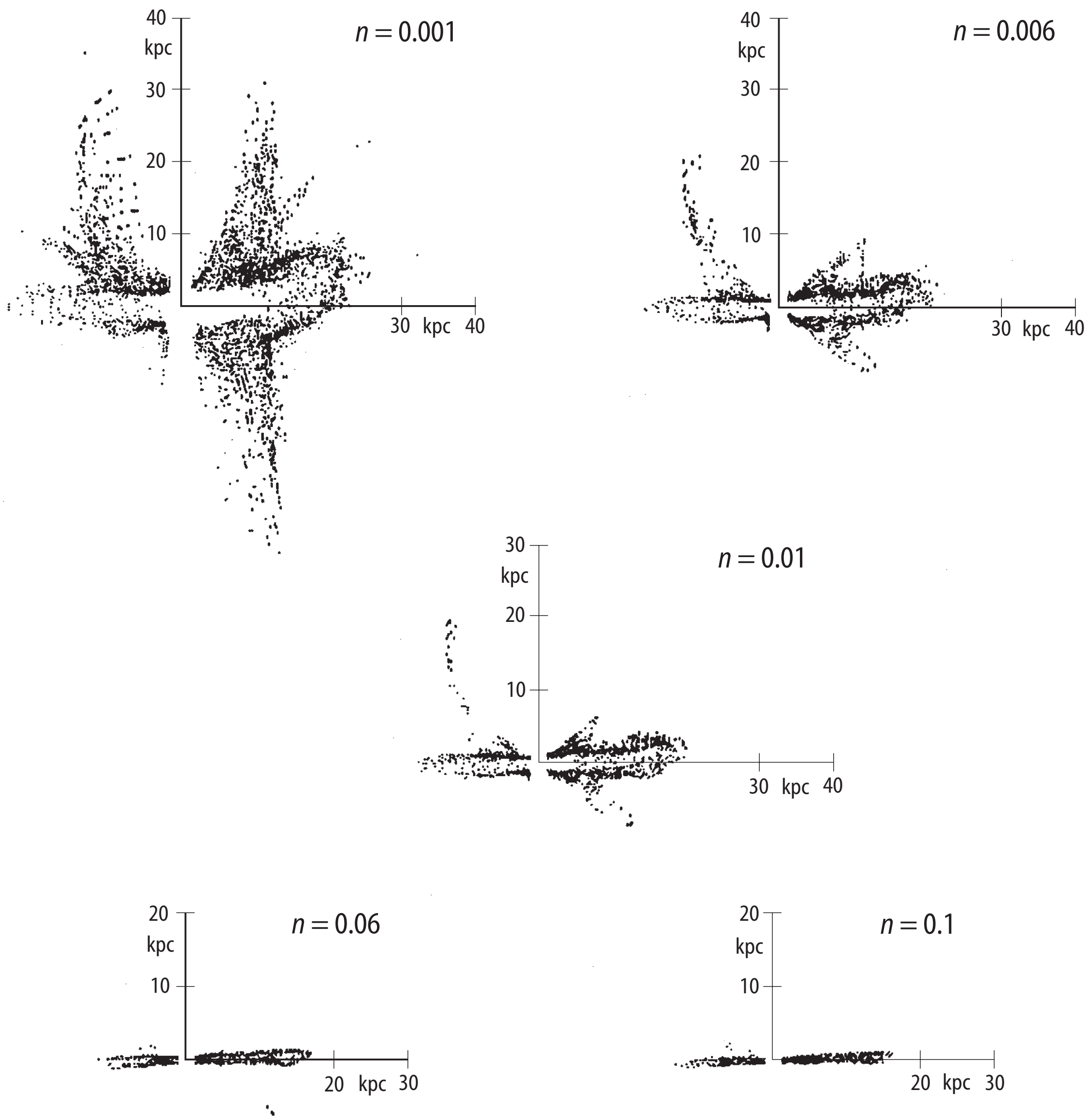


Fig. 4. Isodensity plots of the low-density gas in the Milky Way as viewed from an external location, for n_H = 0.001, 0.006, 0.01, 0.06, and 0.1 atoms cm^{-3}. All five plots wee made to repesent the view of an external observer situated on an extension of the galactic plane in the l = 0° and b = 0° direction looking toward the galactic centre and the Sun. The region $x > 0$ corresponds to galactic quadrants 1 and 2, while the region $x < 0$ corresponds to galactic quadrants 3 and 4. For high densities the data are confined close to the galactic plane. For lower densities the gas layer is significantly extended and warped for large distances from the centre of the Galaxy. For the low densities a significant number of points seem to be misloaded and in the form of spurs that extend away from the plane [91D].

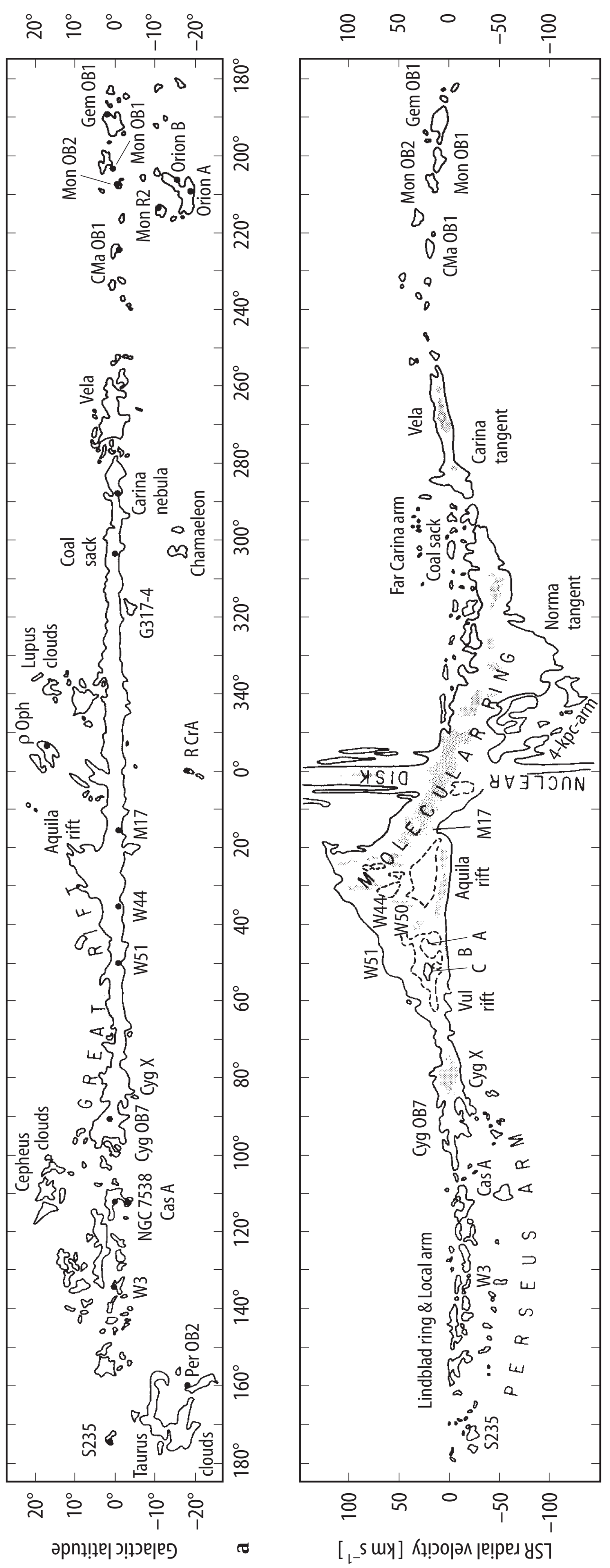


Fig. 5. Finder charts for objects and regions in the Milky Way: (a) is a velocity-integrated spatial map and (b) is a longitude-velocity map. The lowest contour is sketched schematically in both charts, and large regions with intensity greater than 4 K deg_b are shaded in (b) [87D].

The local distribution of CO is analysed in [92W], and a sketch of the distribution of nearby molecular clouds is shown in Fig. 6. The global distribution of molecular clouds is shown in Fig. 7. The different spatial distribution of warm and cool molecular clouds in the first quadrant is presented in Fig. 8. The radial distribution of warm and cold cloud cores compared to the radial distribution of HII regions is shown in Fig. 9, demonstrating that the distribution of warm cloud cores and HII regions are correlated.

Molecular clouds at galactocentric radii as large as 28 kpc are also found [94D]. The vertical distribution of CO is discussed in [95D].

The molecular cloud distribution is also measured in OH, which is mainly used as spiral arm tracer [82T, 88Y].

In a recent reanalysis of the observational data of the last 15 years on the global spiral structure of the Milky Way [95V] found strong evidence that the Galaxy shows a grand design four armed logarithmic spiral with a pitch angle of – 12°± 1°. Pulsar rotation measures lead to a mean local magnetic field 2…3 μG parallel to the spiral structure pointing to $l \approx 90°$ [89L]. It is indicated that the field direction is reversed in the interarm regions [94R].

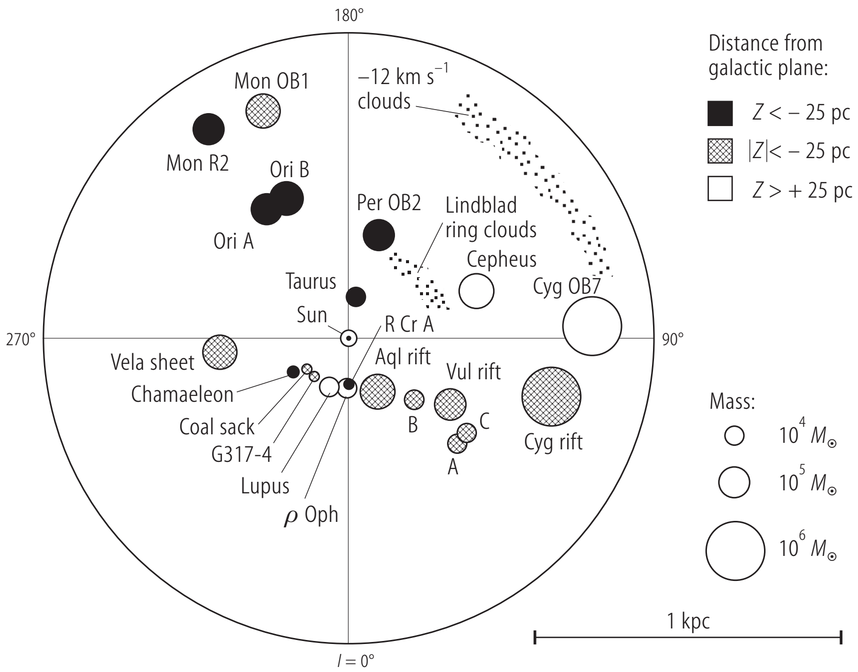


Fig. 6. The distribution in the galactic plane of molecular clouds within 1 kpc of the Sun. The circle radii are proportional to the cube roots of the cloud masses and in most cases are close to the cloud's actual radii. The circle filling indicates distance from the galactic plane. The general regions of the "– 12 km s^{-1}" and Lindblad Ring clouds are indicated but individual clouds are not shown. The width of these regions in heliocentric distance are unknown; the width shown are arbitrary [87D].

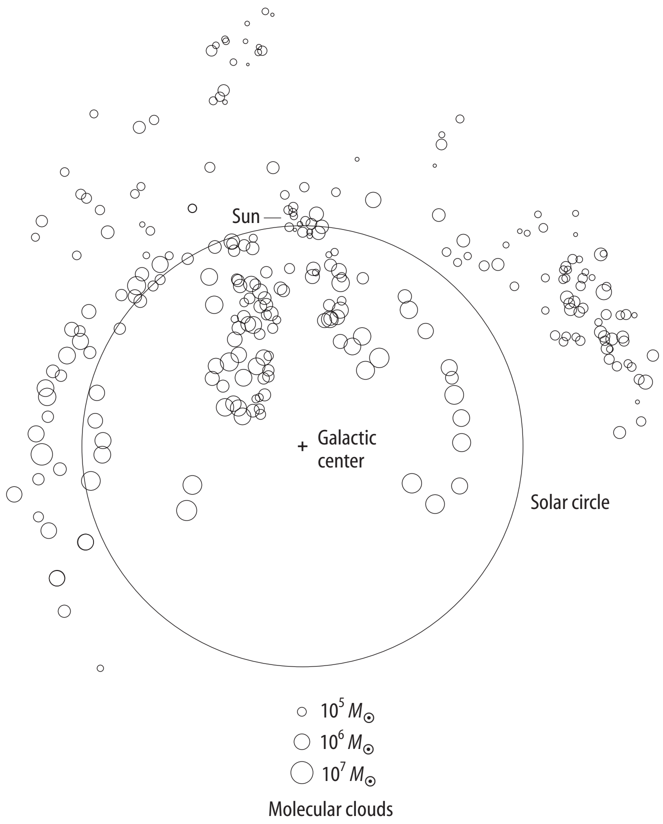


Fig. 7. Face-on view of molecular clouds in the Galaxy (open circles), including all the CO data obtained with; the Columbia 1.2-m-telescopes and analyzed to date. The size of the open circles in the figure is proportional to the logarithm of the molecular gas mass [92B2].

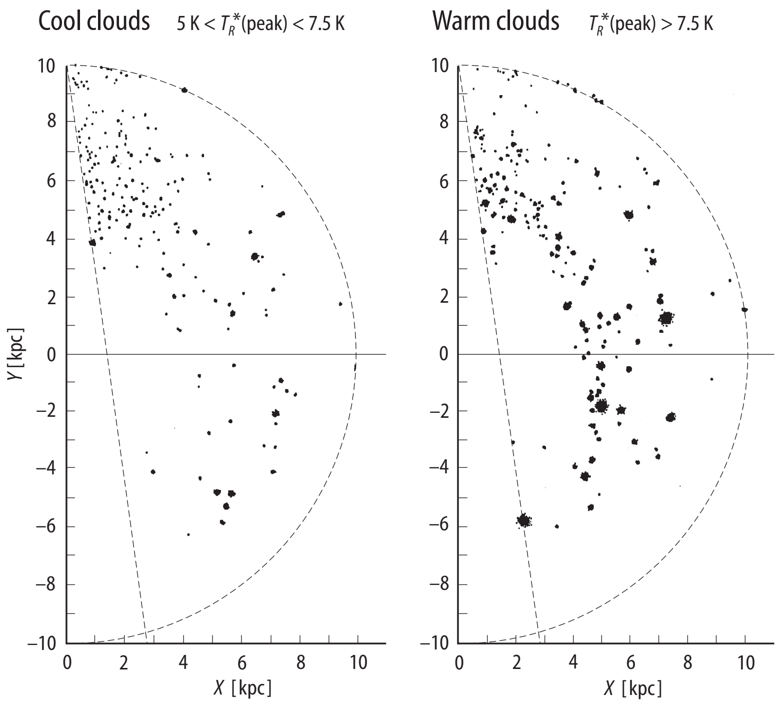
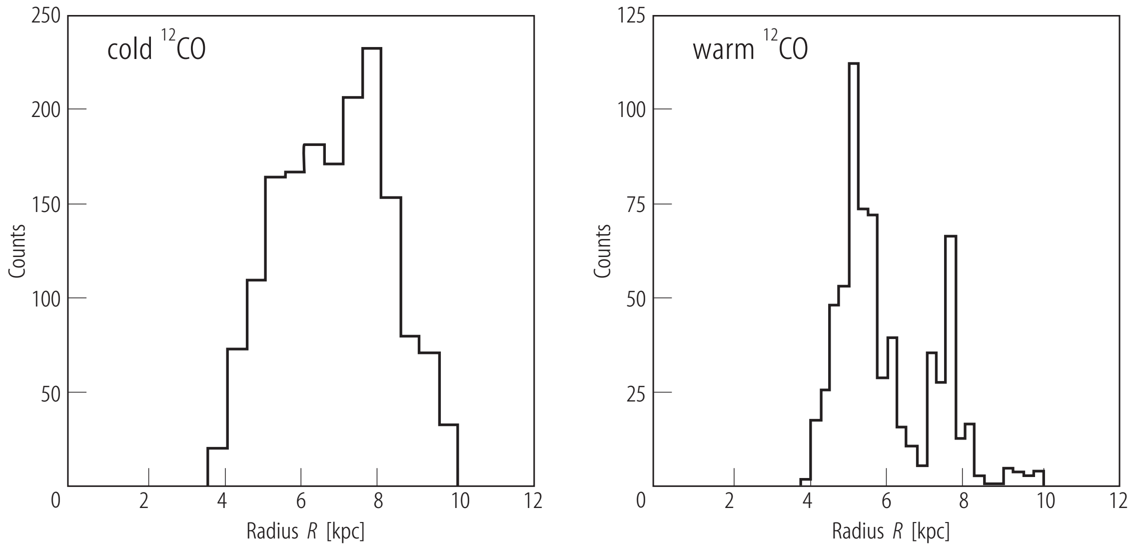


Fig. 8. Face-on maps of warm and cool molecular clouds. Each cloud is depicted as a Gaussian disk with brightness proportional to cloud mass and size dispersion proportional to the effective radius of the clouds ($\sigma \approx R_{\mathrm{eff}}$). The Sun is at (0, 10) [89S1].



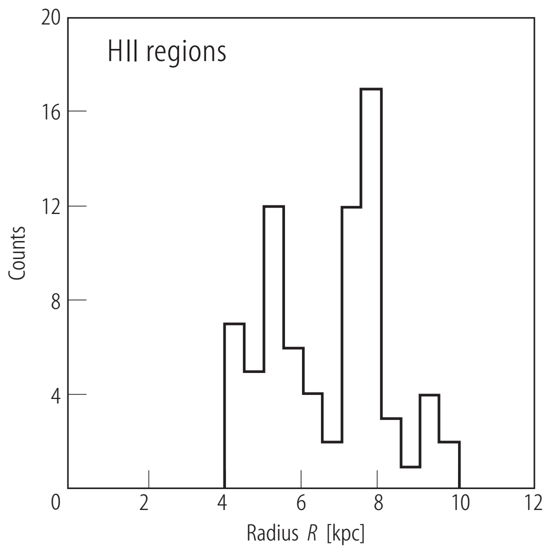


Fig. 9. Galactic radial distribution of cold molecular cloud cores, warm molecular cores, and HII regions from [80D] between longitudes 20° and 50° [87S].

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For Proceedings see 8.3.0, p. 137

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8.3.5 The galactic center

The manuscript was closed in 1992.

8.3.5.1 Distance R_0 of the galactic center from sun

Table 1. Summary of measurements [89R].

Method	R_o [kpc]	±	$(\sigma^2_{stat}$	+	$\sigma^2_{sys})^{1/2}$
H_2O maser proper motions (SgrB2, W51, W49)	7.5	±	$(0.7^2$	+	$1.0^2)^{1/2}$
Centroid of distributions of globular clusters, RR Lyrae, giants/Miras	7.9	±	$(0.6^2$	+	$1.0^2)^{1/2}$
Kinematic models of the Galaxy	8.4	±	$(0.3^2$	+	$1.2^2)^{1/2}$
Eddington luminosity of X-ray bursters	6.9	±	$(0.7^2$	+	$2.0^2)^{1/2}$
Weighted average	7.8	±	0.7	kpc	

IAU recommended distance R_o: 8.5 kpc [86K]

8.3.5.2 Phenomena in the galactic center

Figure 1 gives an overview of the many phenomena observed in the central ≈ 10^2 pc of the Galaxy [87G1, 89M4].

The central stellar cluster can be observed at wavelengths longward of about 1 µm and is concentrated along the galactic plane with a minor/major axis ratio of 0.6…0.8. Its surface brightness scales with radius R from the peak as $R^{-1.8}$ between about one and a few hundred parsecs [89M4]. Most of the stars radiating at a few µm are evolved giants of 2000 to 3000 K surface temperature that have an age of a few hundred million years or more.

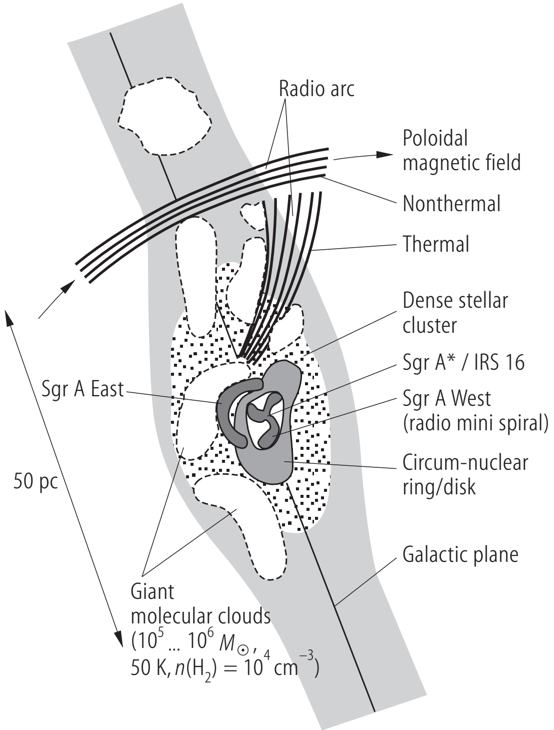

Fig. 1. Phenomena in the galactic center. For explanation see text.

A system of dense, warm, and massive giant molecular clouds (GMC's) is also concentrated toward the galactic plane. Most of these clouds (as accompanying HII regions and infrared sources) are located at positive latitudes. Their velocities require a combination of circular motions in the sense of galactic rotation, with substantial non-circular motions [91B].

The peak of the radio continuum emission (the SgrA complex) coincides with the stellar maximum. At high spatial resolution the SgrA radio source is resolved into a very compact source (SgrA*, size ≈ 1 milliarcsec), a system of free-free emitting filaments of ≈ 10^4 K photoionized gas surrounding it (the SgrA West HII region with the "minispiral"), a shell-shaped synchrotron (non-thermal) nebula of size a few arcmins east of SgrA* (SgrA East) and a ≥ 5' diameter diffuse halo with a mixture of non-thermal and free-free emission. At high resolution one finds a number of interesting thin, straight filaments in the halo ("threads"). For detailed discussions of the morphology of the radio emission the reader is referred to the various contributions in the proceeding of the 1988 IAU symposium on the galactic Center [89M4]. SgrA* is within 1" of the dynamical center of the Galaxy and a group of enigmatic blue near-infrared sources, called the "IRS16 complex" which probably represent a compact cluster of luminous blue supergiants [91K]. Because of its small size and lack of proper motion in excess of about 40 km s^{-1} SgrA* is the most likely candidate for an active central source (e.g. a massive black hole). The SgrA West HII region with its mini-spiral is a system of orbiting (most likely infalling) gas streamers that are ionized by the central radiation field [85S]. SgrA East may be the remnant bubble of (a) recently exploded supernova(e) [89M2].

North of the SgrA complex one finds a spectacular set of straight, non-thermal filaments, oriented perpendicular to the galactic plane. They and a second set of arched, thermally (free-free) emitting filaments form the so called "Radio Arc" [89M4] The straight filaments are very likely due to synchrotron emission in a large scale, poloidal magnetic field system (100 μG…1 mG). Not indicated in Fig. 1 is an even more extended Ω-shaped radio structure stretching out of the plane at positive galactic latitudes (size ≈ 50…100 pc). The Ω "lobe"' may be physically associated with the magnetic field structure of the Radio Arc and may have an explosive origin (for a review of the out-of-plane radio structures, see [89S].

SgrA West and the radio mini-spiral is surrounded by an oval-shaped distribution of dense, warm molecular gas that is orbiting the center. This circum-nuclear ring or disk has an inner radius of about 1.5 pc and can be traced out to about 5 pc. It may represent an accretion disk that is fueling interstellar gas into the central parsec [87G3].

SgrA is a fairly weak keV X-ray source and other X-ray sources in the central degree are not obviously correlated with the phenonema depicted in Fig. 1 [81W, 88S]. A remarkable source of 511 keV e^+-e^- annihilation radiation and γ-ray continuum has recently been shown to be located about 50' south of SgrA and is, therefore, not related to the phenomena in the very nucleus of our Galaxy.

8.3.5.3 Positions in the galactic center

Galactic coordinates of the nucleus: $l^{\mathrm{II}} = -3\overset{\prime}{.}35$, $b^{\mathrm{II}} = -2\overset{\prime}{.}77$

Table 2. Equatorial coordinates of the galactic nucleus [92R].

	α (1950)	δ (1950)	Uncertainty
Compact Radio Source SgrA*	$17^h42^m29.316^s$	– 28°59'18.38"	± 0.2"
Centroid of near infrared emission of stellar cluster	$17^h42^m29.32^s$	– 28°59'18"	± 1"

Table 3. Relative positions of compact near-infrared sources with respect to SgrA*.

	Source	$\Delta\alpha$ [arcsec]	$\Delta\delta$ [arcsec]	Uncertainty [arcsec]
	Sgr A*	0	0	
IRS	1W	5.2	0.1	± 0.2"
	3	– 2.4	2.4	0.4
	7	0	5.45	0.2
	9	5.2	– 6.5	0.4
	11	– 8.5	14.0	0.4
	12N	– 3.9	– 7.4	0.4
	13	– 3.3	– 1.7	0.2
	15E	1.4	11.4	0.4
	16NE	2.7	0.8	0.2
	16CC	1.8	0.1	0.2
	16C(GZA)	1.0	0.1	0.2
	16NW(GZB)	– 0.2	1.0	0.2
	16SW-W	0.7	– 1.3	0.2
	17	13.4	5.0	0.4
	Allen/Forrest-He-star	– 6.4	– 10.2	0.5
	IRR1(CCD1)	0.2	0.4	0.4
	IRR2(CCD2)	2.2	2.8	0.4
	Visible star A	8.7	16.5	0.5
	Visible star B	29.8	– 9.3	0.5

Table 4. Coordinates of radio sources in the galactic center region.

Source	α (1950)	δ (1950)	Uncertainty	Ref.
SgrC	$17^h42^m25.5^s$	– 29°26'40"	15" (size 1.5')	89O
SgrA West	$17^h42^m29.3^s$	– 28°59'15"	10" (size 2')	83E
SgrA East centroid	$17^h42^m34^s$	– 28°59'	15" (size 2.5')	83E
SgrA East (cluster of compact HII regions)	$17^h42^m41.2^s$	– 28°58'40"	10" (4 sources)	83E
G0.01+0.02	$17^h42^m19^s$	– 28°55'04"	10"	76P
G0.04+0.02	$17^h42^m27.9^s$	– 28°52'15"	10"	
G0.07+0.04	$17^h42^m27.5^s$	– 28°50'20"	15" (size>1')	78D
G0.10+0.02	$17^h42^m36^s$	– 28°49'30"	15" (size>1')	87Y
G0.09+0.07	$17^h42^m22.5^s$	– 28°47'20"	15" (size>1')	87Y
G0.18-0.04	$17^h43^m03.2^s$	– 28°47'03"	10"	89M5
SgrB2N (MD4,K)	$17^h44^m10.5^s$	– 28°21'12"	5"	78D
SgrB2M (MD5,F+I+J)	$17^h44^m10.5^s$	– 28°22'03"	3"	84B
SgrB2S (H)	$17^h44^m10.6^s$	– 28°22'43"	2"	84B
SgrD	$17^h45^m32.0^s$	– 28°00'43"	5"	89O

Table 5. Coordinates of X-ray sources in the galactic center region.

Source	α (1950)	δ (1950)	Uncertainty	Ref.
1E1740.7–2942 *)	$17^h40^m42^s$	– 29°43'15"	± 0.5'	81W, 87S, 91C
1E1742.5–2859	$17^h42^m30^s$	– 28°59'01"	1.1'	
A1742–294	$17^h42^m54^s$	– 29°29'02"	0.5'	
1E1742.8–2853	$17^h42^m49.4^s$	– 28°53'54"	1.0'	
1E1743.1–2843	$17^h43^m08.9^s$	– 28°43'00"	1.0'	
1E1743.1–2852	$17^h43^m08^s$	– 28°52'36"	1.0'	
SLX1744–299	$17^h44^m15^s$	– 29°59'46"	1.0'	

*) γ-ray source, probably source of 511 keV annihilation radiation

Table 6. Coordinates of near-infrared and millimeter sources in the galactic center region.

Source	α (1950)	δ (1950)	Uncertainty	Ref.
G0.15-0.05 (centroid of quintuplet)	$17^h43^m04.3^s$	– 28°48'30"	10" (≈ 10 sources)	90O, 90G3
M-0.13-0.08(S) (20 km/s cloud)	$17^h42^m26.9^s$	– 29°04'30"	10" (size 1')	90Z
M-0.13-0.08(N) (20 km/s cloud)	$17^h42^m27.1^s$	02'37"	10" (size 1')	90Z
M-0.02-0.07 (50 km/s cloud)	$17^h42^m40^s$	58'38"	10" (size 2')	89M2

Table 7. Coordinates, fluxes, and 40…250 µm luminosities of far-infrared sources in the central 1° of the Galaxy [84O].

Source	α (1950) [a])	δ (1950) [a])	Size [b])	Peak flux density 40…250µm [Jy]	Luminosity [$L_\odot$]
SgrC, G359.44-0.08	$17^h41^m26^s$	–29°27.3'	1.6'	1900	$7{\cdot}10^5$
FIR 5, G359.54-0.07	$17^h41^m38^s$	–29°20.2'	2.7'	1100	$8{\cdot}10^5$
FIR 6, G359.64-0.06	$17^h41^m48^s$	–29°15.1'	2.3'	480	$3{\cdot}10^5$
FIR 7, G359.78-0.00	$17^h41^m45^s$	–29°04.4'	2.6'	870	$6{\cdot}10^5$
FIR 8, G359.98+0.03	$17^h42^m22^s$	–28°54.8'	2.3'	6300	$5{\cdot}10^6$
SgrA, G359.95-0.05	$17^h42^m30^s$	–28°59.1'	1.3'	12800	$5{\cdot}10^6$
FIR 9, G0.07+0.04	$17^h42^m26^s$	–28°51.3'		6200	$8{\cdot}10^5$
FIR10, G0.18+0.01	$42^h41^m44^s$	–28°46.9'	4.5'	1300	$2{\cdot}10^6$
FIR12, G0.18-0.04	$17^h43^m01^s$	–28°47.2'	4.4'	4500	$8{\cdot}10^6$
FIR14, G0.43+0.03	$17^h43^m22^s$	–28°32.0'	3.8'	790	$1{\cdot}10^6$
FIR15, G0.28-0.07	$17^h43^m26^s$	–28°42.7'	2.8'	1950	$2{\cdot}10^6$
FIR16, G0.07-0.21	$17^h43^m22^s$	–28°58.4'	2.8'	1600	$1{\cdot}10^6$
FIR18, G0.52-0.04 (SgrB1)	$17^h43^m53^s$	–28°30.2'	5.3'	2300	$6{\cdot}10^6$

Source	α (1950) [a]	δ (1950) [a]	Size [b]	Peak flux density 40…250µm [Jy]	Luminosity [$L_\odot$]
SgrB2, G0.67-0.05	$17^h44^m09^s$	–28°21.9'	1.3'	25400	$5\cdot10^6$
SgrD, G1.13-0.11	$17^h45^m33^s$	–28°00.5'	1.1'	2150	$5\cdot10^5$

[a]) Typical uncertainty ±50"
[b]) Beam size 1'×1.5'

Table 8. Major recent surveys of the galactic center region.

Tracer		Size of survey	Resolution	Ref.
2.2 µm	continuum	1.8°×1°	10"	87G2
2.2 µm	continuum	30'×40'	2"	89G1
2.4 µm	continuum	10°	0.4°	84H
2.4/3.4 µm	continuum	20°	0.5°	82M
2.4 µm	continuum	120°×30°	0.8°	87M
12…120 µm	continuum	6°×3°	5'	89C
40…250 µm	continuum	8.5°	1.3'	84O
55, 125 µm	continuum	45'×30'	1'	82D
150, 200, 300 µm	continuum	2°×0.5°	10'	82S
5, 10.7 GHz	continuum	1.5°×0.5°	6"→1'	78D
10.5 GHz	continuum	1.5°×1.5°	3.6'	84S
1.7, 5 GHz	continuum	20'	a few arcsec	87Y, 89M5
[CII] $^2P_{3/2} \rightarrow {}^2P_{1/2}$	157.7µm	15'×10'	1'	90G2, 91P
^{12}CO 1→0	115 GHz	2°×0.4°	1'	78L, 83B1
^{13}CO 1→0	110 GHz	1.4°×0.8°	1.7'	87B, 88B
CS 2→1	98 GHz	4.7°×0.8°	1.9'	87B
CS 2→1	98 GHz	60'×30'	17"	89T
CS 1→0	49 GHz	60'×30'	34"	89T
NH_3	22 GHz	30'x6'	40"	81G
H_2CO	4.8 GHz	4.5°×1.4°	2.9'	80B
OH	1.7 GHz	14°×2°	10'	83C
HI	1.4 GHz	3°×3°	9'	81B
		24°×20°	21'	83B2

8.3.5.4 Interstellar gas

The central few hundred parsecs of the Galaxy contain a remarkable concentration of interstellar gas (mean hydrogen density ≈ 100 cm^{-3} as compared to 1 cm^{-3} in the disk), mostly in form of fairly dense and warm giant molecular clouds [89G3].

The galactic center molecular clouds are substantially denser and warmer than their counter-parts in the disk (Table 10). Higher cosmic ray heating, greater UV heating through enhanced massive star formation, or increased ambipolar diffusion heating (because of the presence of strong magnetic fields in the central 100 pc) can all be excluded with some certainty. Perhaps the most likely mechanism is the dissipation of clump-clump turbulence that is created by the strong differential rotation in the central 100 pc [89G3]. The high density can probably be understood as a selection effect. Only fairly dense clouds ($n(H_2) \geq 10^4$ cm^{-3}) can withstand the strong tidal shearing forces and thus survive as identifiable cloud structures.

Table 9. Global characteristics of the central gas layer [89G3].

	Central 500 pc	Galactic disk
Masses and densities		
Stars M_*	$10^{9.8}\ M_\odot$	$10^{11}\ M_\odot$
Gas, atomic	$10^{6.4}\ M_\odot$	$10^{9}\ M_\odot$
Gas, molecular	$10^{8.1}\ M_\odot$	$10^{9}\ M_\odot$
Gas, fraction $\mu = M_{gas}/M_*$	0.01	0.05…0.10
Abundance [HI]/[H_2]	0.05	2
Gas density $<n>$	100 cm^{-3}	1…2 cm^{-3}
Gas surface density σ	$\geq 100\ M_\odot$ pc^{-2}	$5\ M_\odot$ pc^{-2}
Luminosity		
Bolometric luminosity [a])	$1.2\cdot10^{9}\ L_\odot$	$10^{10}\ L_\odot$
Number of Lyman continuum photons	10^{52} s^{-1}	10^{53} s^{-1}
Infrared excess	30	
Star formation		
Rate ϕ	0.3…0.6 $M_\odot$ yr^{-1}	5.5 $M_\odot$ yr^{-1}
Efficiency ϕ/M_{gas}	$5\cdot10^{-9}$ yr^{-1}	$10^{-9}…10^{-8}$ yr^{-1}

[a]) Discrete sources contribute 10…20%

Table 10. Physical properties of galactic center clouds [89G3, 89W].

	Center clouds	Disk clouds
Mass [$M_\odot$]	$10^{5…6}$	$10^{5…6}$
Size [pc]	20…30	20…50
Density [cm^{-3}] $<n>$	10^4	$10^{2.5}$
Temperature [K] $<T>$	40…200	10…15
Velocity dispersion [km s^{-1}]	10…20	≤ 5
Magnetic field [mG]	0.1…1	≤ 0.1
Isotopic abundances		
[^{12}C]/[^{13}C]	25	65
[^{16}O]/[^{18}O]	250	500
[^{14}N]/[^{15}N]	800	300

8.3.5.5 Mass distribution

Table 11. Mass distribution in the galactic center. Uncertainty of masses typically ± 25%.

Radius from dynamic center [pc]	Enclosed mass [$10^6 M_\odot$]
0.15	≥ 2
0.25	≥ 2.7
0.3	≥ 3
1	5
2.5	8
4	13
8	20
30	150
100	1000
250	3300

Measurement of the HI and CO rotation curves (≥100 pc), analysis of the velocities of molecular, atomic, and ionized gas components (0.15…10 pc), of the velocities of OH/IR stars (3…300 pc) and of stellar velocities at 0.5…3 pc can be combined to give the following empirical mass distribution for an assumed distance of 8 kpc [87G1, 88S, 89M1].

The inferred (dynamical) mass distribution can be fit by the combination of a central mass of 2…3·10^6 $M_\odot$ concentrated within the central 0.5 pc, plus an isothermal, King mass distribution with a core radius of 0.5 to 1 pc. The distributed mass can be identified with the dense stellar cluster that is visible on the near-infrared maps. Comparison to the distribution of the 2 μm surface brightness indicates a fairly constant stellar mass to luminosity ratio of about 1.2 $M_\odot/L_\odot$, between 1 and 100 pc.

The nature of the central mass concentration is at present uncertain. It could be a central massive black hole, but a compact cluster of stars not radiating at 2 μm (e.g. neutron stars) cannot be excluded.

8.3.5.6 Circum-nuclear disk

Observations indicate the presence of a dense, warm, and clumpy molecular gas disk (or ring) surrounding SgrA West. Within its sharp inner edge at 1.5 pc there is very little molecular gas. The circum-nuclear gas disk (CND) contains about $10^4 M_\odot$ between 1.5 and 5 pc distance from SgrA*. The CND appears to consist of a number of separate kinematic streamers with a mixture of circular and noncircular motions, probably the result of infall into the central few parsecs of clouds with different angular momentum. The CND cannot be an equilibrium structure; the central 1.5 pc diameter cavity is perhaps the result of winds from the center, or an explosion within the last 10^6 years. It is not likely but cannot be excluded that clumps within the CND are self-gravitating. The ionized streamers of the radio mini-spiral and a dense atomic cloud found to be associated with the "northern" and "eastern" arms of the mini-spiral likely are manifestations of mass infall from the circum-nuclear environment into the central parsec. Reviews of the CND have been given by [87G3, 89G2, 90G2]. The physical parameters of the CND are summarized in Table 12.

Table 12. Properties of the circum-nuclear disk (at $R \approx 2$ pc) [93J].

Parameter	Dense molecular (HCN, CS)	CO	Photo-dissociated gas	HI	Dust
H_2 volume density [cm^{-3}]	$\geq 3 \cdot 10^5$	10^5	$3 \cdot 10^5$		
Temperature [K]	100…200	200 ± 50	170 ± 70		20…80
Average hydrogen column [cm^{-2}]	$10^{23.2 \pm 0.5}$	10^{23}	$10^{21.7}$	$10^{22.1}$	$10^{23.2}$ (≈ 1 mm) $10^{22.5}$ (≤ 400 µm)
Volume filling factor	10^{-2}	0.2	$3 \cdot 10^{-3}$		

8.3.5.7 Characteristics of SgrA West

Table 13. Radio flux densities [Jy] of SgrA [83E, 89M3].

Component	Size	$S_{20\ cm}$	$S_{6\ cm}$	$S_{2\ cm}$	$S_{1.3\ cm}$	$S_{3\ mm}$	$S_{1.3\ mm}$	$S_{0.35\ mm}$
SgrA East	2'	77	31					
SgrA West: diffuse	1.5'	22	15		27	21	21	41
SgrA West: mini-spiral	1.5'	5	15	>9	27	21	21	41
SgrA*	10^{-3}"	0.9	0.8	1.2	1.2	1.2	2.2	

Table 14. Infrared flux densities of central 30" [82B].

Wavelength [µm]	Flux density [Jy]
3.5	20
4.8	50
8	350
11	630
13	1500
24	2000
34	4200
55	3000
100	2000
1000	25

Table 15. Inferred characteristics of SgrA West for an 8 kpc distance [83E, 87G1, 82B].

Parameter		Comment
Peak radio emission measure 1…6 cm [cm^{-6}pc]	$3 \cdot 10^6 \ldots 3 \cdot 10^7$	Higher values for smaller beams (≤1")
R.M.S. electron density $\langle n_e^2 \rangle^{1/2}$ [cm^{-3}]	$2 \cdot 10^3 \ldots 2 \cdot 10^4$	

Parameter		Comment
Electron density from infrared line ratios [cm^{-3}]	$2\cdot10^{3}\ldots10^{5}$	Different line ratios are sensitive to different density regimes and indicate a range of densities
Number of Lyman continuum photons Q_{Lyc} [s^{-1}]	$2.3\cdot10^{50}$	for $T_e \approx 5000\ldots7000$ K
$L_{Ly\alpha}$ ($=Q_{Lyc} h \nu_{Ly\alpha}$) [$L_\odot$]	$1.3\cdot10^{6}$	
$L_{25\rightarrow130\mu m}$ ($\leq$ 1 pc)	$7\cdot10^{5}$	
$L_{3\rightarrow25\mu m}$ ($\leq$ 1 pc)	$7\cdot10^{5}$	
$L_{3\rightarrow300\mu m}$ ($\leq$ 3 pc)	$3.2\cdot10^{6}$	corrected for the fraction of radiation that is not absorbed at $\leq$ 3 pc and converted to FIR radiation. The total luminosity of the central 3 parsecs is inferred to be $7\ldots20\cdot10^{6}\,L_\odot$. Of this the central stellar cluster contributes $3\ldots5\cdot10^{6}\,L_\odot$.
T_{eff} [K]	30000…36000	Effective temperature of UV radiation field

8.3.5.8 Star formation in the galactic center

Large scale

The galactic center region at present is only a moderatively active site of stellar formation [89M6]. Of the $\approx 10^9 L_\odot$ of total infrared luminosity emerging from the central few hundred parsecs about 50% can be accounted for by absorption and re-radiation by dust of short-wavelength radiation emitted by the old stellar population. There are a number of clearly recognizable sites of recent massive star formation associated with prominent infrared sources and compact HII regions, the most prominent of which is the SgrB2 complex at $l \approx 0.67^o$. It has a far-infrared luminosity approaching $10^7 L_\odot$ and is associated with a massive molecular cloud of mass approaching $10^7 M_\odot$. Outside of this and several other isolated sites (e.g. SgrB1, SgrC, and G0.15-0.05 [the Quintuplet], Tables 6 and 7) the usual signposts for recent massive star formation (bright compact HII regions and IR sources, H_2O or OH masers) are rather scarce. Morris [89M4] has, therefore, argued that star formation in the central few hundred parsecs is actually inhibited by strong poloidal magnetic fields. Interactions between magnetic fields and fast moving clouds, and not ionizing radiation of hot stars, could cause the large scale thermal radiation observed in the arched filaments of the Radio Arc, for instance. Against this interpretation and in favor of widespread star formation activity speaks the overall far-infrared line and continuum spectrum that can be very well explained by standard photo-ionization/photo-dissociation processes from hot stars [90G2].

Central few parsecs

Evidence for recent formation of massive stars in the central few parsec is now rather compelling. There is at least one (IRS7) and probably several red supergiants in the central parsec which must have formed less than 10^7 years ago [82R]. A recently discovered small cluster of mass loosing He emission line stars in the same region probably signifies the presence of blue supergiants whose age cannot be much greater than a few 10^6 years [90A, 91K]. Several of the sources of the IRS16 complex close to SgrA* may be members of this cluster. The red and blue supergiants may either have formed in a brief burst of star formativon or, alternatively, O and B stars have been forming continuously in the central parsec and the supergiants are conspicuous because of their much greater luminosity than that of normal O stars.

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8.3.6 Properties of the Galaxy as a whole

The global view of our Galaxy compared to extragalactic systems has not changed very much, see LB VI/2c, subsect. 8.3.6. A general description is given in [e] (Chap. 15). A discussion on the Hubble type, photometric parameters, and the spiral arm pattern can be found in [93K]. A comparison of the surface brightness distribution with respect to other spiral galaxies is reviewed in [90K]. The main new feature is the existence of a pronounced bar (see subsect. 8.3.3.2).

References for 8.3.6

For Proceedings see 8.3.0

90K van der Kruit, P.C.: Proceedings [d], (1990), p. 85.
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8.4 Kinematics and dynamics

The textbooks [a, b, c, d, j] give comprehensive introductions to the concepts of galactic kinematics. Recent reviews on galactic kinematics are included in the monographs [e, f, g, h, i, k, l, m, n].

8.4.1 Kinematics

8.4.1.1 Basic concepts

See LB VI/2c, subsect. 8.4.1.1

8.4.1.2 Velocities

8.4.1.2.1 Space velocities

Modern catalogues of proper motions such as the PPM [91R, 93B] are usually based on the FK5 system. No corrections of the proper motions for unphysical rotations of the reference system are necessary.

The constants required (cf. LB VI/2b, p. 210) to convert proper motions given in the J2000.0 coordinate system to space velocities are

$$\alpha_n = 282°.86,\ l_n = 32°.93,\ \varepsilon = 62°.87$$

The change in the treatment of the elliptical aberration is of no practical consequence [83M].

Further catalogues of space velocities:

OB stars [96F]
Classical Cepheids [96F]
F stars [93E]
Subdwarfs [86N, 87S, 94C]

8.4.1.2.2 Solar motions

The solar motion with respect to samples of stars out of the Bright Star Catalogue [82H] is discussed in [91J, 92J, 93J1]. It is still recommended to use ($U_\odot$, $V_\odot$, $W_\odot$) = (9, 12, 7) km s^{-1}.

8.4.1.2.3 Local standard of rest

The motion of the local standard of rest with respect to samples of distant stars is determined in [93B2] (OB stars), [94 P] (Cepheids), and [94 M] (Carbon stars), however with discrepant results. The reason for the inconsistencies is at present unclear.

8.4.1.2.4 Velocity dispersion

See LB VI/2c, subsect. 8.4.1.2.4

8.4.1.2.5 Representative nearby stars

(See also subsect. 8.2)

A third edition of the Catalogue of Nearby stars has been completed. A preliminary version of the catalogue is given in [91G] and its characteristics are discussed in [93J2]. Results concerning the velocity distribution of nearby stars are summarized in Tables 1 and 2. All values given in Tables 1 and 2 have been obtained by weighting the velocity components of each star with the absolute value of its *W* velocity component. Therefore the velocity distributions are representative for a cylinder perpendicular to the galactic plane.

Table 1. Galactic components of the solar motion $U_\odot$, $V_\odot$, $W_\odot$ and the velocity dispersion σ_U, σ_V, σ_W, σ_υ of stars within $r \le 25$ pc on or near the main sequence weighted by $|W|$.

Group	$B-V$	N	$U_\odot$ [km s^{-1}]	$V_\odot$	$W_\odot$	σ_U [km s^{-1}]	σ_V	σ_W	σ_υ	$<\tau>$ [10^9 a]
6d	$\le 0\overset{m}{.}5$	8	− 2	+ 4	+ 7	14	8	2	16	0.2
6c	0.05…0.19	15	+ 14	+ 2	+ 13	21	7	8	24	0.5
6b	0.20…0.34	21	+ 12	+ 3	+ 2	14	11	8	19	1.0
6a	0.35…0.49	77	+ 9	+ 9	+ 13	25	16	14	32	2.3
5	0.50…0.64	148	+ 18	+ 21	+ 2	40	27	23	54	5.0

Table 2. Solar motion and velocity dispersion of McCormick K and M dwarfs.

Group	N	$U_\odot$ [km s^{-1}]	$V_\odot$	$W_\odot$	σ_U [km s^{-1}]	σ_V	σ_W	σ_υ	$<\tau>$ [10^9 a]
HK emission intensity									
+ 8, + 3	23	11	15	0	20	12	6	24	0.3
+ 2	38	− 2	16	11	23	17	14	32	1.4
+ 1	37	− 11	15	10	33	15	16	40	3.2
0	39	5	24	9	40	21	17	49	5.2
− 1	26	4	16	12	50	29	20	61	7.2
− 2, −5	33	21	31	4	62	28	24	73	9.6
all	336	4	21	7	45	27	22	57	5.0

8.4.1.3 Galactic rotation

For explanations of the symbols see LB VI/2c, subsect. 8.4.1.3 p. 216

8.4.1.3.1 Constants of galactic rotation

The IAU has revised 1985 the galactic constants to

R_o = 8.5 kpc and $\upsilon_c(R_o)$ = 220 km s^{-1}.

The revision included no recommendation concerning A and B, but the revised constants imply $A - B$ = 25.9 km s^{-1} kpc^{-1} [85S]. To a first approximation the rotation curve is flat, so that $A \approx -B \approx$ 13 km s^{-1} kpc^{-1}. As a consequence:

$$\omega_c(R_o) = A - B = 25.9 \text{ km s}^{-1}$$
$$T_{c,\,o} = 2\pi/\omega_c(\mathrm{R_o}) = 2.4 \cdot 10^8 \text{ a}$$
$$\kappa_o = \sqrt{-4B(A-B)} = 36.6 \text{ km s}^{-1}\text{kpc}^{-1}$$
$$T_{\kappa,\,o} = 2\pi/\kappa_o = 1.7 \cdot 10^8 \text{ a}$$

8.4.1.3.2 Galactic rotation curve

New determinations of the shape of the galactic rotation curve are presented in [93B2, 96F, 92M, 94P, 93S]. Fig. 1 reproduces the rotation curve as determined by Brand and Blitz [93B2].

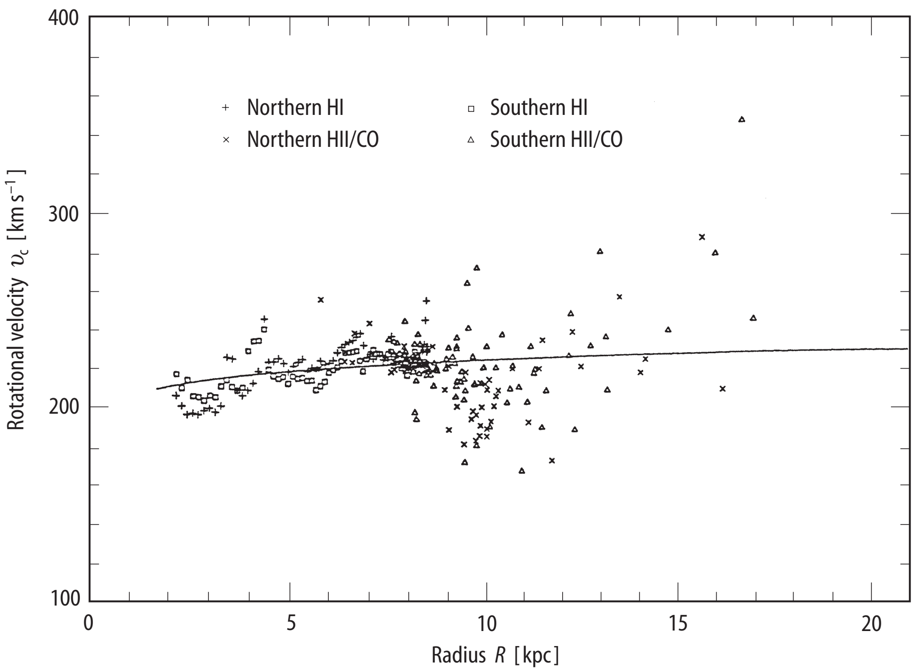

Fig. 1. Rotation curve according to Brand and Blitz [93B2]. Distinction is made between Northern (0° < l < 180°) and Southern (180° < l < 360°) Hemisphere, and HI and HII/CO data: Northern HI (plus signs), Southern HI (squares), Northern HII/CO (crosses), Southern HII/CO (triangles). The line is a power law fit to the data.

8.4.1.3.3 Deviations from circular motion

Systematic deviations of the mean motion of the stars and the interstellar gas from purely circular rotation may be also due to elliptical deformations of the galactic bulge and the disk. The observational evidence for elliptical deformations of the disk is controversial [91B, 94M], whereas there is now compelling evidence for an oval deformation of the galactic bulge (see [96G] for a review).

8.4.1.3.4 Radial variation of the velocity dispersion

The radial velocity dispersion of old disk stars is determined in [89L]. The velocity dispersions of the radial and azimuthal velocity components of the stars decline radially, following an exponential law with a length scale of 8.7 kpc. This is about twice the exponential scale length of the surface distribution (cf. subsect. 8.3.3.2). Assuming that the galactic disk is in hydrodynamic equilibrium and that the ratio of vertical to planar velocity dispersions is constant, this indicates that the vertical scale height of the disk does not vary significantly with galactocentric distance.

8.4.1.4 Bulge, Halo and thick disk

Bulge and Halo of the Galaxy are rotating much slower than the disk. The bulge shows differential rotation rising to an amplitude of υ_c (R = 3 kpc) = 100 km s^{-1} [95I1, 95I2]. The locally observed kinematics of the Halo are [89G, 93M]:

$$\upsilon_c(R_\odot) = 37 \pm 10 \text{ km s}^{-1},$$

and velocity dispersions

$$\sigma_U = 131 \pm 6 \text{ km s}^{-1};\ \sigma_V = 106 \pm 6 \text{ km s}^{-1};\ \sigma_W = 85 \pm 4 \text{ km s}^{-1}.$$

The thick disk rotates nearly as fast as the thin disk and lags about 30…50 km s^{-1} behind the local standard of rest. The vertical velocity dispersion is σ_w = 45 km s^{-1} [89G].

On the kinematics of intermediate population II objects cf. [89G, 93M].

The correlation between the galactic rotational velocities and metallicity of the various subsystems is illustrated in Fig. 2 (taken from [89G]). It is still under debate whether there is a marked discontinuity between disk and halo objects at about [Fe/H] ≈ – 1, with the usual definition

$$[\mathrm{Fe/H}] = \log N_{\mathrm{Fe}}/N_{\mathrm{H}} - \log (N_{\mathrm{Fe}}/N_{\mathrm{H}})_\odot .$$

8.4.2 Dynamics

8.4.2.1 Basic concepts

See LB VI/2c, subsect. 8.4.2.1

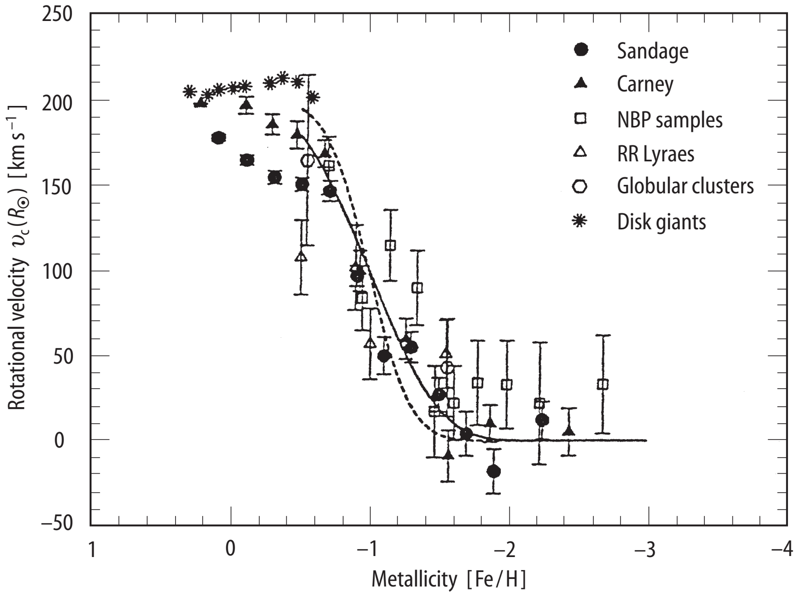

Fig. 2. Correlation between galactic rotational velocities and metallicity of various stellar samples according to Gilmore et al. [89G]. See [89G] for a detailed description of the various samples shown in the diagram. The disk stars lie on the left side, whereas the halo stars lie on the right side of the diagram. The solid line indicates a linear correlation in the range (υ_c = 0 km s^{-1}, [Fe/H] = – 1.5) to (υ_c = 200 km s^{-1}, [Fe/H] = – 0.5). The dashed line indicates the linear correlation assuming a discontinuity between υ_c = 0 and υ_c = 200 km s^{-1}at [Fe/H] = – 1.

8.4.2.2 Mass models and gravitational forces

8.4.2.2.1 Mass models

There are now a number of multi-component mass models of the Galaxy available, [78V, 80B, 81C, 81R, 87B]. Some of them are discussed and compared in detail in [b]. A comprehensive review is also [91F] which gives the most recent estimate of the total mass of the Galaxy of $4 \cdot 10^{11}$ $M_\odot$ (R < 35 kpc).

8.4.2.2.2 Galactic gravitational force K_R

Note that the IAU revised galactic constants ([85S]) give $K_{R,\,o}$ = – 5702 (km s^{-1})^2 kpc^{-1}. Assuming a flat rotation curve would imply $(\partial K_R/\partial R)_o$ = + 1342 (km s^{-1})^2 kpc^{-2}.

8.4.2.2.3 Galactic gravitational force K_z

The galactic gravitational force law K_z has been redetermined in a number of studies: [84B1, 84B2, 87B, 89K, 90G, 91K1, 91K2, 92B, 93F, 94F] (see [96K] for a review). The main result is that the surface density of the old thin disk is about 50 ± 10 $M_\odot$ pc^{-2}. [93F] have shown that this implies a local dynamically determined-mass density of about 0.1 $M_\odot$ pc^{-3} which is consistent with the mass density observed directly in the form of stars and interstellar gas (cf. LB VI/2c, subsect. 8.4.2.2.4, p. 233). The slope of the K_z force law near the galactic midplane is according to these determinations

$$\omega_z^2(R_o) = (73.5 \text{ km s}^{-1} \text{ kpc}^{-1})^2.$$

8.4.2.2.4 Local mass density

See the annotations to subsect. 8.4.2.2.3 on the revised dynamically determined mass density.

8.4.2.3 Stellar orbits

8.4.2.3.1 Unrestricted orbits

See LB VI/2c, subsect. 8.4.2.3.1

8.4.2.3.2 Epicyclic orbits

Note that the numerical constants have slightly changed due to the IAU revision of galactic constants (cf. subsect. 8.4.1.3.1) and the revision of the local dynamically determined mass density (cf. subsect. 8.4.2.2.3).

8.4.2.3.3 Relaxation and diffusion

A number of physical mechanisms have been discussed to explain the diffusion of stellar orbits. Among these are gravitational encounters of the stars with massive molecular clouds or massive black holes out of the dark galactic corona, disk heating by recurrent transient density waves, or the effects infalling, disrupting satellite galaxies (see [91L] and [92W] for recent reviews). There is another interesting manifestation of the diffusion of stellar orbits in the observed increase of the metallicities of stars in the solar neighbourhood with their ages. This is related to the enhanced chance of older stars with larger peculiar velocities to reach the solar neighbourhood from more distant parts of the galactic disk with systematically higher or lower metallicities due to the galactic radial metallicity gradient [96W].

8.4.2.4 Density-wave theory of the spiral structure

An alternative dynamical theory of spiral structure has been formulated in the form of the "swing-amplification mechanism" (see [81T] for a review). According to this concept the spiral arms are not quasi-stationary, rigidly rotating density waves, but take part in the general shearing of the disk and amplify while swinging around from leading to trailing arms. This theory has been applied successfully to explain the spiral structures of external galaxies [87A], but no attempt has been made to model the spiral structure of the Galaxy in this way.

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9 Galaxies and the universe

9.1 General information and integral properties of galaxies

9.1.1 Catalogues, atlases, positions

The manuscript was closed in 1992.
The reference [C-nn] refers to the catalogue no. nn in References for 9.1.1, p. 189.

9.1.1.1 General catalogues of non-stellar objects

ESO	=	The ESO/Uppsala Survey of the ESO (B) Atlas (Lauberts [C-27]).
GC	=	General Catalogue (Herschel 1864 [C-17]).
IC	=	Index Catalogue (Dreyer [C-12]).
M	=	Messier's (1784) catalogue of nebular objects [C-34], modern version [C-16]).
MOL	=	Master List of Non-Stellar Astronomical Objects (Dixon and Sonneborn [C-10]).
NGC	=	New General Catalogue (Dreyer [C-11]).
RNGC	=	Revised New General Catalogue (Sulentic and Tifft [C-44]).

Of 110 entries in Messier's catalogue, the 39 objects listed in Table 1 are now known to be external galaxies (see [C-16] for a modern and accessible compilation). A similarly large proportion of the entries of GC, NGC, and IC are also extragalactic as evidenced by the early examination of the GC [26R], and subsequent modern re-examinations RNGC [C-44]. This latter study is based upon an inspection of the objects as they appear on the POSS-photographs [C-53] and so descriptions are limited to northern objects.

Only as the true nature of the various classes of "nebulae" became known in the early decades of the twentieth century, did external galaxies lay claim to being catalogued in their own right. Nevertheless, in the tradition of the NGC, the "Quick Blue" European Southern Observatory (ESO) Sky Survey was made available with extensive listing and descriptions of all non-stellar southern objects [C-18, C-27] so as to make interesting new galactic and extragalactic objects immediately available to the large reflectors being completed in the southern hemisphere.

Collectively, the compilations cited above contain most of the apparently brightest galaxies in the northern and southern hemispheres in their files. Prior to this the most comprehensive compilation of non-stellar objects drawn from the published literature, and merged purely by a sequential positional ordering, is the *Master List of Non-Stellar Astronomical Objects* by Dixon and Sonneborn [C-10] which contains a listing of over 200,000 entries. Recently the NGC/IC catalogues have been made more accessible in a corrected form, updated to the equinox 2000.0 [C-43].

Table 1. Extragalactic objects in Messier's lists.

Messier	Dreyer	α (2000)	δ (2000)
M31	NGC 0224	$00^h\ 42^m\ 44^s$	+41° 16' 09"
M32	NGC 0221	$00^h\ 42^m\ 42^s$	+40° 51' 52"
M33	NGC 0598	$01^h\ 33^m\ 51^s$	+30° 39' 36"
M49	NGC 4472	$12^h\ 29^m\ 46^s$	+07° 59' 48"
M51	NGC 5194/5	$13^h\ 29^m\ 56^s$	+47° 14' 04"
M58	NGC 4579	$12^h\ 37^m\ 44^s$	+11° 49' 11"
M59	NGC 4621	$12^h\ 42^m\ 02^s$	+11° 38' 49"
M60	NGC 4649	$12^h\ 43^m\ 40^s$	+11° 32' 58"
M61	NGC 4303	$12^h\ 21^m\ 55^s$	+04° 28' 25"
M63	NGC 5055	$13^h\ 15^m\ 51^s$	+42° 01' 45"
M64	NGC 4826	$12^h\ 56^m\ 44^s$	+21° 41' 05"
M65	NGC 3623	$11^h\ 18^m\ 55^s$	+13° 05' 35"
M66	NGC 3627	$11^h\ 20^m\ 15^s$	+12° 59' 30"
M74	NGC 0628	$01^h\ 36^m\ 42^s$	+15° 47' 12"
M77	NGC 1068	$02^h\ 42^m\ 40^s$	–00° 00' 48"
M81	NGC 3031	$09^h\ 55^m\ 33^s$	+69° 03' 55"
M82	NGC 3034	$09^h\ 55^m\ 54^s$	+69° 40' 57"
M83	NGC 5236	$13^h\ 37^m\ 00^s$	–29° 52' 04"
M84	NGC 4374	$12^h\ 25^m\ 04^s$	+12° 53' 14"
M85	NGC 4382	$12^h\ 25^m\ 24^s$	+18° 11' 27"
M86	NGC 4406	$12^h\ 26^m\ 12^s$	+12° 56' 47"
M87	NGC 4486	$12^h\ 30^m\ 49^s$	+12° 23' 28"
M88	NGC 4501	$12^h\ 31^m\ 59^s$	+14° 25' 17"
M89	NGC 4552	$12^h\ 35^m\ 40^s$	+12° 33' 25"
M90	NGC 4569	$12^h\ 36^m\ 50^s$	+13° 09' 48"
M91	NGC 4548	$12^h\ 35^m\ 26^s$	+14° 29' 49"
M94	NGC 4736	$12^h\ 50^m\ 53^s$	+41° 07' 09"
M95	NGC 3351	$10^h\ 43^m\ 58^s$	+11° 42' 15"
M96	NGC 3368	$10^h\ 46^m\ 45^s$	+11° 49' 16"
M98	NGC 4192	$12^h\ 13^m\ 48^s$	+14° 54' 01"
M99	NGC 4254	$12^h\ 18^m\ 49^s$	+14° 25' 07"
M100	NGC 4321	$12^h\ 22^m\ 55^s$	+15° 49' 19"
M101	NGC 5457	$14^h\ 03^m\ 13^s$	+54° 21' 02"
M104	NGC 4594	$12^h\ 39^m\ 59^s$	–11° 37' 28"
M105	NGC 3379	$10^h\ 47^m\ 50^s$	+12° 34' 57"
M106	NGC 4358	$12^h\ 18^m\ 58^s$	+47° 18' 12"
M108	NGC 3556	$11^h\ 11^m\ 32^s$	+55° 40' 15"
M109	NGC 3992	$11^h\ 57^m\ 36^s$	+53° 22' 31"
M110	NGC 0205	$00^h\ 40^m\ 22^s$	+41° 41' 16"

9.1.1.2 Galaxy catalogues

9.1.1.2.1 Primary galaxy catalogues

The following are catalogues listing galaxies as found in specialized searches or surveys of original plate material. Compilations and/or homogenized data sets are listed in the section following on *secondary galaxy catalogues* in subsect. 9.1.1.2.2.

AM	*Catalogue of Southern Peculiar Galaxies and Associations* (Arp, Madore [C-2]): 6,445 peculiar and interacting galaxies found on IIIa-J southern sky survey plates, types, positions and characteristic sizes, cross-identifications and selected photographs; samples are given in [77A2].
CGCG	*Catalogue of Galaxies and Clusters of Galaxies* (Zwicky et al. [C-52]): positions; magnitudes; available redshifts; $m_{\rm lim} \approx$ 15.5 mag; identification charts for some 31,000 northern-hemisphere galaxies.
CGPG	*Catalogue of Selected Compact Galaxies and Post-Eruptive Galaxies* (Zwicky [C-51]): positions and descriptions of over 3,700 compact and related galaxies.
CIG = KIG	*Catalogue of Isolated Galaxies* (Karachentseva [C-23]): cataloged 1,051 isolated northern-hemisphere glaxies with apparent magnitudes $m <$ 15.7 mag; radial velocity study in [79K1].
CPG = KDG	*Catalogue of Isolated Pairs of Galaxies* (Karachentsev [C-21]: cataloged 603 isolated pairs of northern-hemisphere galaxies with apparent magnitudes of the components $m <$ 15.7 mag; 332 of them show signs of interaction; follow-up radial velocity study [80K].
CTG = KTG	*Catalogue of Galaxies Triples* (Karachentsev [C-22]): cataloged 84 isolated triples of northern-hemisphere galaxies with apparent magnitudes of the components $m <$ 15.7 mag; finding charts are provided; radial velocity study in [81K1].
MCG	*Morphological Catalogue of Galaxies* (Vorontsov-Velyaminov et al. [C-49]): positions; rough magnitudes; diameters; inclination classes; coded descriptions; about 29,000 galaxies; $m_{\rm lim} \approx$ 15.0 mag.
SA	*Shapley-Ames Catalogue* [C-42]: one of the earliest and most useful lists containing exclusively galaxies; rough magnitudes; sizes; positions; descriptions; 1249 galaxies; $m_{\rm lim} \approx$ 13.0 mag.
SGC	*Southern Galaxy Catalogue* (Corwin, de Vaucouleurs, A., and de Vaucouleurs, G. [C-6]): provides precise positions, morphological types, luminosity classifications, diameters and axial ratios for 5,471 galaxies, larger than 1.5...2.0 arcmin, south of $\delta = -17°$ found on the UK Schmidt IIIa-J plates.
UGC	*Uppsala General Catalogue of Galaxies* (Nilson [C-35]): 12,939 galaxies $\delta > -2°$ and with diameters > 1 arcmin or m(pg) $\le$ 14.5 mag; diameters; position angles; magnitudes; Hubble types; luminosity classes; cross references to MCG, NGC, IC, CGCG and other lists.
UGCA	*Selected Non-UGC Galaxies* (Nilson [C-36]): 400 late-type spirals, irregulars and dwarf systems; incremental to the UGC.
VCC	*Virgo Cluster Catalog* (Binggeli et al. [C-3]): contains listing of 2,096 galaxies in the Virgo cluster.

9.1.1.2.2 Secondary galaxy catalogues

CGQ *Cataloged Galaxies and Quasars Observed in the IRAS Survey* (Lonsdale et al. [C-29]): 11,444 IRAS point sources positionally associated with cataloged galaxies and quasars giving their flux densities at 12, 25, 60 and 100 μm. See also [86W2, 87L2, 91W] for detailed identifications of IRAS sources in Virgo, Fornax, Hydra, Coma and the South Galactic Pole.

CNG *A Catalog of 2,810 Nearby Galaxies* has been compiled by Kraan-Korteweg [C-25] which up-dates and supersedes an earlier vision [C-26] entitled "A Catalogue of Galaxies within 10 Mpc" which was believed to be complete for galaxies brighter than – 18.5 mag, but includes many galaxies which are intrinsically fainter.

ESO-LV *The Surface Photometry Catalogue of the ESO-Uppsala Galaxies* [C-28]: 37 optical parameters for 16,000 galaxies, including positions, types, redshifts, magnitudes, colours, foreground extinction, dimensions, orientations, profile gradients and surrounding galaxy densities.

NBG *Nearby Galaxies Catalog* (Tully [C-46]): 2,367 galaxies with systemic velocities less than 3,000 km s^{-1}. Types and group affiliations; magnitudes, velocities and line widths with references and cross-identifications. A companion atlas to accompany the Catalog is found in [C-47].

PGC *Catalogue of Principal Galaxies* (Paturel, Fouqué, Bottinelli, Gouguenheim [C-37, 89P]): positions and cross-identifications for 73,197 galaxies; morphological descriptions, apparent major and minor axes, apparent magnitudes, radial velocities and position angles.

RC1 *Reference Catalogue of Bright Galaxies* (de Vaucouleurs [C-7]): published data for 2,599 well-studied galaxies; catalogue does not claim completeness but contains those galaxies with diameter > 30 arcsec having published data, m(pg) < 16 mag, or with redshift < 15,000 km s^{-1}; revised classifications and detailed references to the literature from 1913 to 1963.

RC2 *Second Reference Catalogue of Bright Galaxies* (de Vaucouleurs et al. [C-8]): revised and expanded version of RC1 for 4,364 object; diameters and axial ratios; magnitudes and colours on the UBV system; continuum and 21-cm radio magnitudes; redshifts and classifications; references to published photographs and references from 1964 to 1975.

RC3 *Third Reference Catalogue of Bright Galaxies* (de Vaucouleurs et al. [C-9]): revised and enlarged version of RC1 and RC2 containing 23,024 objects; reasonably complete for galacies having apparent diameters greater than 1 arcmin, B-band magnitudes brighter than 15.5 mag and redshifts less than 15,000 km s^{-1}; diameters and axial ratios, magnitudes and colours, redshifts and classifications, all on a uniform system; references to 1987; objects ordered by equinox 2000.0 positions. Published in three volumes.

RSA *Revised Shapely-Ames Catalog of Bright Galaxies* (Sandage, Tammann [C-40]): positions, Hubble types based on large-scale reflector plates, magnitudes and velocities for 1246 galaxies; illustrative photographs included.

A General Catalog of HI Observations of Galaxies (Huchtmeier, Richter, [C-19]) presents 20,000 entries for over 10,000 galaxies, where the HI data are presented as originally published with detailed references.

Catalog of IRAS Observations of Large Optical Galaxies (Rice et al. [88R]), total flux densities at 12, 25, 50 and 100 μm for 85 galaxies with blue diameters greater than 8 arcmin; infrared brightness profiles and infrared surface brightness contour maps.

Catalogue of HI Data (Paturel et al. [90P1]), a compilation of 21,186 21 cm linewidth measurements, 12,048 HI velocities, 11,161 HI fluxes from 440 references complete to 1988. Weighted mean HI parameters derived from this catalogue are given in [90B2].

A Bibliography on the Structure of Galaxies (Brosche, Einasto, Rummel [74B2]): compilation of kinematic and photometric references on nearby galaxies (V < 1,100 km s^{-1}); complete to May 1973.

List of Elite Galaxies (Tenjes et al. [82T1]): a compilation of kinematic, spectroscopic and photometric data (with references) for over 400 well observed and interesting galaxies.

IRAS Bright Galaxy Sample (Soifer et al. [87S4]): 324 extragalactic objects with IRAS 60 μm flux densities greater than 5.4 Jy, in an area of ≈ 14,500 sq.deg, with galactic latitude > –15° and δ > – 30° for α = 00...12 h; δ > – 15° for α = 12...14 h; δ > – 20° for α = 12...24 h.

An Atlas of 10,632 HII Regions in 125 Galaxies [83H] includes photographs, numbered charts, and tabular off-set positions; see also [69H, 74H].

Atlas of Velocity Dispersion Profiles and Rotation Curves for Elliptical and Lenticular Galaxies [89B]; see also [85D, 85W].

Catalogue of Seyfert Galaxies and Related Objects [86K] and *Catalogue of Seyfert Galaxies* [87L3], each compile data, cross-identifications and references to the literature for approximately 1,000 known Seyfert galaxies.

Catalogue of Low Surface Brightness Galaxies [88K], positions, sizes, magnitudes, cross-identifications, etc. for some 1,500 low surface brightness galaxies.

Palomar-Westerbork Survey of Northern Spiral Galaxies [86W1] represents an atlas of combined radio and optical (U'JF) observations of 16 bright, near-by northern hemisphere spiral galaxies.

Rotation Curve Catalogues: bibliographical information up to 1981 on rotation curves for 271 galaxies [83B1], and for 116 normal S and Ir galaxies [84K2].

9.1.1.2.3 Smaller lists of galaxies

Smaller lists of compact galaxies [68F, 68R, 70F, 71F, 73S3, 75Z, 77F, 78A, 78B4, 78R, 78S1, 79B4, 79F1, 80F1, 81F, 83F, 84F, 85B2, 88F] and compact groups of compact galaxies [57S, 73S2, 74P, 78P, 82H]. See also [74B1, 75B, 76B, 78B1, 79B1, 85A]. Follow-up studies include [74S2, 78S2, 79R, 80R, 81R2, 87T2, 88H1, 88H2, 89H1, 89H2, 91M, 91R, 91Z]. A spectroscopic survey of 145 blue compact Zwicky galaxies [79K3] gave 39 emission-line galaxies and 6 Seyfert galaxies, with the remaining objects being galactic stars or galaxies without emission lines. Spectroscopic and photometric data for 23 faint, compact UV-excess Haro galaxies revealed 18 emission-line objects [81K2]; a list of emission-line compact galaxies [85K3].

A study of double and multiple galaxies including an original list of such systems [37H]; samples of southern binary galaxies [84S1, 87S3]. *A List of Galaxies Possibly Associated with Abell Clusters* is given by Haynes [80H].

Catalogues of low surface-brightness dwarf galaxies [C-2, 59V1, 72K, 73K, 78L, 82L, 85F, 88S, 92S]. See especially [88K]. Listing of 500 Irr II galaxies detected on the POSS prints [78I, 79I, 85I, 88I2, 89I]. Dwarf galaxies in the Virgo cluster [C-3, 56R, 62R, 77R, 81R1, 84S2, 84S3, 85S, 88I1] in the NGC 5128 Group [79W], in the Fornax Cluster [C-4, C-14, 65H, 88D, 90I, 91B]. Irregular and dwarf galaxies in two fields centered on M81 and M101 [50H], in the Leo Group [64H], in the NGC 1023 Group [C-38, 84D], in the NGC 896, NGC 1068, NGC 3190 and NGC 5846 Groups [67E]; in the extended IC 342 and M81/82 Groups [82B1, 82B2, 85B3, 85K1]; in Cl 1046+65 [84B]. See also [87B2].

Positions, morphological types, magnitudes and radial velocities for a complete sample of 180 galaxies in the Virgo cluster (within 6 degrees of M87 and brighter than B_T = 14.0 mag) [82K3]. An atlas of spiral galaxies in the Virgo cluster [85S], and an atlas of dwarf galaxies in the Virgo cluster [84S2]. Blue galaxies in Virgo [83B2]. Catalogues of galaxies in the Coma Cluster [67R]; the Centaurus Cluster [86D]; in the Fornax Cluster [C-5, C-14, C-20, 87C, 87P, 88D], five nearby groups (Leo, Dorado, NGC 1400, NGC 5044 and the Antilla Group) [C-15]. A catalogue of morphological types of galaxies found in 55 rich clusters [80D] gives positions, morphological types, total magnitudes, bulge sizes and ellipticities for some 6,000 galaxies. Redshifts, morphological types, classifications orientations and ellipticities for 129 galaxies in a 6° by 6° region of the Horologium-Reticulum region of the southern sky [83L]. Types, magnitudes and diameters for 220 galaxies in the Hercules supercluster [86B]; data on 581 galaxies in the Hydra I (Abell 1060) cluster [89R].

Approximately 6,500 late-type spirals (including dwarfs) and irregular galaxies south of $\delta = -22°$ including morphological types, luminosity classes, and inner and outer diameters [77C, 78C2, 80C2, 82C]. 580 Magellanic-type dwarf galaxies classified and illustrated [80F2].

Catalogues containing over 7,000 galaxies close to and/or obscured by the galactic plane [75S1, 80W, 90S]; follow-up studies [81P]. A survey of the "Perseus Plane" [87H].

9.1.1.3 Optical identification

9.1.1.3.1 Photographs and photographic atlases

Early photographic studies of northern galaxies: Lick Observatory [08K, 18C], Mt. Wilson 60-inch reflector [17P, 20P]; southern galaxies: Reynolds 30-inch reflector (Australia) [56D], *Cape Photographic Atlas of Southern Galaxies* (Radcliffe 74-inch reflector [C-13], furthermore [21G, 56E, 58D, 61D]. Additional list of galaxies from early photographic surveys [35M, 38S, 41R].

9.1.1.3.2 Positional identification

9.1.1.3.2.1 General survey

(For abbreviations, see subsects. 9.1.1.1; 9.1.1.2; 9.1.1.3) Most of the NGC/IC objects are identified on the *Smithsonian Astrophysical Observatory* (SAO) charts. For northern RC1 Galaxies (x, y) mm positions on the POSS prints are calculated from nominal (α, δ) in [67K]. Sulentic and Tifft [C-44] also give rectangular coordinates measured directly from the POSS. An atlas of transparent overlays for the POSS (marking all objects listed in the MOL) is given in [81D]. In CGCG [C52], galaxies are identified with respect to bright stars and clusters of galaxies on individual charts for each POSS field. For the ESO/SRC survey, the tabulations of [C-18] also give (x, y) millimeter positions for the "Quick Blue" survey, as does the Arp-Madore Catalogue [C-2] for the ESO/SRC J-survey. Finding charts for galaxies with ultraviolet continua can be found in [C-30, C-31, C-32, 76S, 77M1, 77M2, 78B3, 78M, 81M] with a summary listing in [C-33]. Fragmentary lists of peculiar and interacting galaxies are given in [71A, 74S1], containing positions and selected photographs.

9.1.1.3.2.2 High-precision positions

With the advent of high-precision radio source positions, similarly accurate optical positions are needed. To meet this need a number of observers have remeasured positions of galaxies with respect to AGK stars (see subsect. 8.1.1.5 and LB VI/2c, subsect. 8.1.1.5) either directly or by using the intermediate step of producing transparent overlays. Extensive lists of positions are given in [67G, 70G, 71G, 73G, 73P, 75F, 75G, 75S1, 76D, 78K, 78W, 80F3, 81C, 81J, 81K3, 81K4, 81K5, 82B3, 82K1, 82P, 83C, 86V, 87S1, 87S2, 89S, 90A, 90B1]. Depending on the method used and the definition of the galaxy’s nucleus, the accuracies quoted for the best cases are now on the order of 0.1 arcsec, although typical accuracies are 3...10 arcsec.

9.1.1.3.2.3 Electronic services: the NASA/IPAC extragalactic database

Since June 1990 the NASA/IPAC Extragalactic Database (NED) has been freely available for use by the astronomical community world-wide [90H, 91H]. NED is an on-going project that organizes a broad range of published extragalactic data into a computer-based central archive, which is designed for fast and flexible query via electronic networks. See also [88P1, 89P].

NED provides POSITIONS, NAMES, and BASIC DATA for over 800,000 extragalactic objects, as well as some 1,030,000 bibliographic references to 38,000 published papers, theses, notes from catalogs and other publications. NED supports searches for objects and for references, and will forward to the user, upon request, files containing data retrieved during a session. It also allows users to view the contents of several major catalogs, and to browse through abstracts of articles of extragalactic interest that have appeared since 1988 in five major journals (Astron. Astrophys., Astron. J., Astrophys. J., Mon. Not. R. Astron. Soc., Publ. Astron. Soc. Pacific., including their Letters and Supplements).

The NED service may be accessed over INTERNET or NSI-DECNET (previously known as SPAN): (i) On INTERNET, a connection to IPAC may be set up with the command: telnet ipac.caltech.edu. (ii) From a node on NSI-DECNET, use the command: set host IPAC (the absolute address is 5.857). One connected to IPAC and prompted for a "login", simply respond with NED; no password is needed. From this point on, the system is self-documenting, especially through the HELP utilities and the "control-H" key.

9.1.1.3.3 Illustrations to support classification schemes

The Hubble Atlas of Galaxies [C-38], the standard reference for galaxy illustrations, contains pictures of 176 galaxies photographed with the Hale Observatories’ reflectors. This atlas also provides the definitive description of the Hubble-Sandage classification scheme (see subsect. 9.1.3.1). A mini-atlas illustrating a general discussion of galaxy classification is provided by Sandage [75S2]. The first photographs from the Las Campanas 2.5 m and 1.0 m reflectors have been published [78D, 79S], in preparation of publication of RSA [C-40].

The *Atlas de Galaxias Australes* [C-41] gives photographs and isodensity tracings for 59 southern galaxies.

Elmegreen [81E] presents an atlas of 54 galaxies photographically imaged in the blue and near-infrared. This atlas and other published works were then consulted in process of classifying 745 galaxies according to the continuity and symmetry of their spiral arms [82E].

Image tube plates have been used for: an atlas of 41 galaxies designed to illustrate the dust distribution in galaxies [74L], see also [58D, 89K, 90V]; a survey of galactic structure underlying Seyfert galaxies [77A1], a survey of dwarf galaxies in the vicinity of the M81 and Local Group galaxies [79F2].

Color reproductions of galaxies can be found for 606 galaxies in *The Color Atlas of Galaxies* (Wray [C-50]); but see also Malin, Murdin: *Colors of the Stars* [84M] and Lausten, Madsen, West: *Exploring the Southern Sky* [87L1].

Galaxies useful for measuring the cosmological distance scale have been extensively illustrated in an *Atlas of Galaxies* (Sandage, Bedke [C-39]).

Takase, Kodaira, and Okamura published an *Atlas of Selected Galaxies*, giving photographic reproductions and photometric analyses for over 100 galaxies imaged with the Okayama 1.88 m reflector or the Kiso 1.05 m Schmidt [C-45].

Photographic prints and two-dimensional surface brightness distributions are given in a *Photometric Atlas of Northern Bright Galaxies* (Kodaira, Okamura, Ichikawa [C-24]) for 791 RSA galaxies north of $\delta = -25°$ as photographed by the Kiso Observatory 1.05 m Schmidt telescope.

A classification scheme and an illustrated atlas of Virgo Cluster dwarf galaxies [84S3]. See also [56D, 57M, 58M, 59D1].

9.1.1.3.4 Interacting, peculiar and active galaxies

Atlas and Catalogue of Interacting Galaxies [C-48, 77V]: objects found and reproduced from POSS paper prints. Follow-up study in [79B2].

Atlas of Peculiar Galaxies [C-1, 66A]: based on original large-scale reflector plates. *A Catalogue of Interacting Galaxies in the Region $\delta < -37.5°$ and $b < -30°$* by Bergvall [81B] includes 369 systems of interacting galaxies, 47 distorted single galaxies and 329 normal systems.

A Catalogue of Southern Peculiar Galaxies and Associations (Arp, Madore [C-2]): printed in two volumes; the first volume contains positions, descriptions, codings and cross-identifications to 6,445 extragalactic systems, while the second contains selected prints from the original IIIa-J SERC southern sky survey plates illustrating the 24 categories of peculiarity as developed by the authors.

Isodensity tracings and small-scale reproduction of 91 peculiar galaxies [73S1]; photographs of a magnitude-limited sample of 59 interacting galaxies and 38 isolated galaxies in a control sample [90J].

Smaller lists of peculiar and interacting galaxies include [71A, 74S1] which contain positions and selected photographs; photographs, tracings and spectra for VV galaxies and Markarian galaxies in pairs [76C1, 76C2, 78C1, 79B3]; an investigation of morphological features in 12 interacting galaxies [83K2, 84K1]; morphological study of 15 blue dwarf galaxies [76C1]. A candidate list with illustrative photographs of 22 S0 galaxies with polar rings [83S1].

Of course, photographic reproductions of galaxies of all types and descriptions can be found on prints and glass copies of the POSS [C-53] ($\delta > -45°$) and the ESO/SRC (= Science Research Council) Sky Survey ($\delta < -17°$).

Warm IRAS galaxies: a catalogue of AGN candidates based on IRAS colours [87D1]. A morphological CCD survey of 11 emission-line galaxies with compact appearance [87T1].

9.1.1.3.5 Dusty ellipticals

Dusty ellipticals as a class of galaxies characterized by an elliptical-like body and a disk or ring of gas and dust with no substantial population of stars in it were first pointed out by [78B2]. Ebneter and Balick [85E] have published a list of 103 dusty ellipticals as drawn from the literature [78B2, 79K2, 81H, 82T2, 87B1]; see also [79G, 82M, 83S2, 84G, 85B1, 86M, 87V] for detailed studies of these and related objects [78S3, 80S, 83S4, 84S4, 85K2, 89K].

9.1.1.3.6 Ellipticals with shells

Arp [C-1] first drew attention to ellipticals with shells. These were further illustrated in Arp and Madore [C-2] and catalogued by [83M, 88P2]. A review of their status is given in [85A], and also [90P2] which outlines a three-way classification scheme: Type 1 include systems whose shells are aligned; Type 2 have position angles of the shells randomly distributed around the central galaxy; Type 3 includes all other systems where there are only a small number of shells, or where the shells are not manifest as well-defined concentric structures.

9.1.1.3.7 Galaxies with polar rings

Early-type galaxies with polar ring structures are reviewed in [83K1, 85A] with a listing of known such systems appearing in [83S1]; see also [83S2].

9.1.1.3.8 Bulge types

Peanut-shaped (P-type) and Box-shaped (B-type) bulges have been noted by many observers [C-8, C-38, 59B, 66H, 74D, 77B, 80T, 81V, 82K2] and list of 41 such objects (30 of which are from a survey with $\delta < -18°$) is presented by [86J]; an all-sky survey [87D2], complete to B = 13.2 mag, gives 74 box-shaped galaxies including photographs and isophotal tracings.

9.1.1.4 Named galaxies

A number of galaxies are known by name; they are familiar but their positions are not necessarily easy to obtain. Table 2 contains the names, selected cross-identifications and positions for a number of these galaxies.

Table 2. Positions for named extragalactic systems.

Name	α (2000)	δ (2000)
Ambartsumian’s Knot = NGC 3561	$11^h\ 11.2^m$	+28° 42'
Andromeda Galaxy = M31 = NGC 0224	$00^h\ 42.7^m$	+41° 16'
Andromeda I	$00^h\ 45.7^m$	+38° 00'
Andromeda II	$01^h\ 16.3^m$	+33° 25'
Andromeda III	$00^h\ 35.3^m$	+36° 31'
Andromeda IV	$00^h\ 42.5^m$	+40° 34'
Antennae Galaxies = NGC 4038/9	$12^h\ 01.9^m$	–18° 52'
Aquarius Dwarf = DDO 221	$20^h\ 46.9^m$	–12° 51'
Arp’s Galaxy	$11^h\ 19.6^m$	+51° 30'
Atoms-for-Peace = NGC 7252 = Arp 226	$22^h\ 20.8^m$	–24° 41'
Baade’s Galaxies A and B	$00^h\ 49.9^m$	+42° 35'
Barbon’s Galaxy = Mrk 328	$23^h\ 37.7^m$	+30° 08'
Barnard’s Galaxy = NGC 6822	$19^h\ 44.9^m$	–14° 48'
Bear’s Paw = NGC 2537	$08^h\ 13.2^m$	+46° 00'
BL Lac	$22^h\ 02.7^m$	+42° 17'
Black Eye Galaxy = M64 = NGC 4286	$12^h\ 56.7^m$	+21° 41'
Bode’s Galaxies = M81/82 = NGC 3031/34	$09^h\ 55.7^m$	+69° 23'
Burbidge Chain = MCG -04-04-010 to 013	$00^h\ 47.5^m$	+05° 21'
BW Tauri = UGC 03087	$04^h\ 33.2^m$	+05° 21'
Caraffe Galaxy	$04^h\ 28.0^m$	–47° 54'
Carina Dwarf	$06^h\ 41.6^m$	–50° 58'
Cartwheel Galaxy	$00^h\ 37.4^m$	–33° 44'
Centaurus A = NGC 5128 = Arp 135	$13^h\ 25.5^m$	–43° 01'
Circinus Galaxy	$14^h\ 13.2^m$	–65° 20'
Coddington’s Nebula = IC 2574 = DDO 081	$10^h\ 28.4^m$	+68° 25'
Copeland Septet = NGC 3745/54 = Arp 320	$11^h\ 37.8^m$	+21° 59'
Cygnus A	$19^h\ 59.4^m$	+40° 43'

Name	α (2000)	δ (2000)
Draco Dwarf = DDO 208	17^h 20.2^m	+57° 55'
Fath 703 = NGC 5892	15^h 13.7^m	–15° 29'
Fornax A = NGC 1316	03^h 22.7^m	–37° 12'
Fornax Dwarf	02^h 39.9^m	–34° 32'
Fourcade-Figueroa Object	13^h 34.8^m	–45° 33'
The Garland	10^h 04.2^m	+68° 40'
Grus Quartet = NGC 7552/82/90/99	23^h 17.8^m	–42° 26'
GR8 = DDO 155	12^h 58.7^m	+14° 13'
Hardcastle Nebula	13^h 13.0^m	–32° 41'
Helix Galaxy	08^h 55.6^m	+58° 44'
Hercules A	16^h 51.2^m	+04° 59'
Holmberg I = DDO 063	09^h 40.5^m	+71° 11'
Holmberg II = DDO 050 = Arp 268	08^h 19.3^m	+70° 43'
Holmberg III	09^h 14.6^m	+74° 14'
Holmberg IV = DDO 185	13^h 54.7^m	+53° 54'
Holmberg V	13^h 40.6^m	+54° 20'
Holmberg VI = NGC 1325 A	03^h 24.9^m	–21° 20'
Holmberg VII = DDO 137	12^h 34.7^m	+06° 17'
Holmberg VIII = DDO 166	13^h 13.3^m	+36° 12'
Holmberg IX = DDO 066	09^h 57.6^m	+69° 03'
Horologium Dwarf = Schuster’s Spiral	03^h 59.2^m	–45° 52'
Hydra A	09^h 18.1^m	–12° 06'
Integral Sign Galaxy	07^h 11.4^m	+71° 50'
Keenan’s System = NGC 5216/16a/18 = Arp 104	13^h 32.2^m	+62° 43'
Kowal’s Object	19^h 29.9^m	–17° 41'
Large Magellanic Cloud	05^h 23.6^m	–69° 45'
Leo I = Harrington-Wilson No. 1 = Regulus Dwarf = DDO 074	10^h 08.5^m	+12° 18'
Leo II = Harrington-Wilson No. 2 = Leo B = DDO 093	11^h 13.4^m	+22° 10'
Leo A = Leo III = DDO 069	09^h 59.3^m	+30° 45'
Lindsay-Shapley Ring	06^h 42.8^m	–74° 15'
McLeish’s Object	20^h 09.7^m	–66° 13'
Maffei I = UGCA 034	02^h 36.3^m	+59° 39'
Maffei II = UGCA 039	02^h 42.0^m	+59° 37'
Malin 1	12^h 37.0^m	+14° 20'
Mayall’s Object = Arp 148	11^h 03.9^m	+40° 50'
Mice = NGC 4676 = Arp 242	12^h 46.1^m	+30° 44'
Minkowski’s Object = Arp 133	01^h 25.8^m	–01° 21'
Pegasus Dwarf = DDO 216	23^h 28.5^m	+14° 44'
Persus A = NGC 1275	03^h 19.8^m	+41° 31'
Phoenix Dwarf Irregular	01^h 51.1^m	–44° 26'
Pisces Cloud = NGC 0378/80/82–85	01^h 07.5^m	+32° 25'
Pisces Dwarf = LGS 3	00^h 03.8^m	+21° 54'
Reinmuth 80 = NGC 4517A	12^h 32.5^m	+00° 23'
Reticulum Dwarf	04^h 36.2^m	–58° 50'

Name	α (2000)	δ (2000)
Sagittarius Dwarf Irregular (SagDIG)	$19^h\,30.0^m$	–17° 41'
Sculptor Dwarf	$01^h\,00.2^m$	–33° 42'
Sculptor Dwarf Irregular	$00^h\,08.1^m$	–34° 34'
Seashell Galaxy	$13^h\,44.5^m$	–30° 10'
Serpens Dwarf	$15^h\,16.1^m$	–00° 08'
Sextans A = DDO 075	$10^h\,11.0^m$	–04° 41'
Sextans B = DDO 070	$10^h\,00.0^m$	+05° 19'
Sextans C	$10^h\,05.6^m$	+00° 04'
Seyfert’s Sextet = NGC 6027/6027A-E	$15^h\,59.2^m$	+20° 46'
Shapley-Ames 1	$01^h\,05.1^m$	–06° 13'
Shapley-Ames 2 = NGC 4507	$12^h\,35.1^m$	–39° 55'
Shapley-Ames 3	$12^h\,49.4^m$	–10° 07'
Shapley-Ames 4	$12^h\,55.2^m$	+00° 07'
Shapley-Ames 5 = IC 4946	$20^h\,24.0^m$	–44° 00'
Shapley-Ames 6	$21^h\,23.2^m$	+45° 46'
Small Magellanic Cloud	$00^h\,52.7^m$	–72° 50'
Sombrero Galaxy = M104 = NGC 4594	$12^h\,39.9^m$	–11° 37'
Spindle Galaxy = NGC 3115	$10^h\,05.2^m$	–07° 42'
Stephan’s Quintet = NGC 7317-20 = Arp 319	$22^h\,36.0^m$	+33° 58'
Superantennae	$19^h\,31.4^m$	–72° 39'
Triangulum Galaxy = M33 = NGC 0598	$01^h\,33.9^m$	+30° 39'
Ursa Minor Dwarf = DDO 199	$15^h\,08.8^m$	+67° 12'
Virgo A = M87 = NGC 4486 = Arp 152	$12^h\,30.8^m$	+12° 23'
Whirlpool Galaxy = M51 = NGC 5194	$13^h\,29.9^m$	+47° 12'
Wild’s Triplet = Arp 248	$11^h\,46.8^m$	–03° 49'
Wolf-Lundmark-Melotte Object = DDO 221	$00^h\,02.0^m$	–15° 28'
Zwicky No. 2 = DDO 105	$11^h\,58.4^m$	+38° 03'
Zwicky’s Triplet = Arp 103	$16^h\,49.5^m$	+45° 30'

For cross references, see subsect. 9.1.1.1; furthermore:

Arp	=	Arp, Atlas of Peculiar Galaxies [C-1]
DDO	=	David Dunlap Observatory, van den Bergh [59V1]
VV	=	Atlas and Catalogue of interacting galaxies, Vorontsov-Velyaminov [C-48]
		cf. also ‘Local Group’ in subsect. 9.3.3.3

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9.1.2 Apparent integral properties of galaxies

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9.1.2.1 Magnitudes

For abbreviations of catalogues, see subsect. 9.1.1.
For bright galaxies, probably the most widely used system of magnitudes is the B(O) system [61D2]. B(O) is the integrated magnitude derived from photoelectric or modern photographic magnitudes in the Johnson B system (see subsect. 4.2.5.12 in LB VI/2b) or magnitudes transformed to this system. B(O) magnitudes are given for 873 objects in RC1 (= [C-7] in subsect. 9.1.1). To incorporate the rich data base of galaxy magnitudes given by Shapley and Ames [32S], systematic errors in these so-called Harvard magnitudes, m_H, have been investigated in [56D, 57D, 58H]. These magnitudes have been corrected for surface-brightness and luminosity-gradient dependent errors and transformed to the B(O) system as corrected Harvard magnitudes m_c in RC2 (= [C-8] in subsect. 9.1.1). A comprehensive source list of *B* magnitudes is given in RC1 (Table 10) and RC2 (Tables 10 and 11), but some of the more important individual sources of magnitudes of galaxies in the UBV system are [59D1, 59D2, 61D1, 61D2, 64B1, 64B2, 67S, 72D, 72S, 73S, 75S1].

For fainter galaxies, the most extensive photometry in the north is that contained in the CGCG ([C-52] in subsect. 9.1.1) and derived from "Schraffierkassette" photographic photometry down to an estimated completeness limit of $m = 15\overset{m}{.}5$. The MCG ([C-49] in subsect. 9.1.1) also contains magnitude estimates down to $m_{pg} < 15\overset{m}{.}0$. Remarks on the MCG versus CGCG magnitude scales are found in [77K2]. Magnitude errors in the CGCG have been investigated in [69H, 75S3] and more extensively by Huchra [76H], who shows that the CGCG magnitudes differ by $0\overset{m}{.}12$ per mag with respect to B(O) magnitudes and have a scatter of $\approx 0\overset{m}{.}35$; but note the anomaly in Vol. I [84G3], and see also [74B1, 76K, 82A, 82B2]. In the southern hemisphere the ESO-LV ([C-28] in subsect 9.1.1) contains photographic B,R photometry for 16,000 galaxies, based on UBVRI photoelectric data from [84L, 87L, 89P].

Aperture photometry for southern E and S0 galaxies: VRI aperture photometry of 115 galaxies [86P2]; UBVRI aperture photometry for 169 early-type glaxies [88P]; UBVRI photometry for 14 central, dominant galaxies in clusters [90M1]; UBV photometry for 360 objects [84V]; UBV aperture photometry for 169 galaxies [84S1]. 109 galaxies in Virgo designed to serve as photographic B-band photometric standards [84B2]; UBV photometry of 196 non-Seyfert Markarian galaxies [77H]; photographic B-band surface brightness measurements for 1,550 galaxies in Fornax [87P2]; 693 UBVRI aperture photometry measurements for 91 active galaxies [87H1]. UBVRIJHK photometry for a complete sample of interacting galaxies [90J]; UBV photometry of 36 Markarian and S0 galaxies [81P]; UBV photoelectric photometry of 19 nests of galaxies [81A3].

Photographic and CCD surface photometry of 33 early-type galaxies in Virgo is given in [90C1]. Digital surface photometry of 20 Virgo galaxies [82W1]. Other recent compilations of original data include [77K1, 78K2, 82M2, 85D1, 85L, 85M, 87B3, 87J, 88D1, 88M1]; UBV multi-aperture photometry of 46 Virgo E/S0 galaxies. UBVR surface photometry of 16 LSB galaxies [83R]. Surface photometry of NGC 7793, NGC 247 and NGC 300 [85C1]. V surface photometry for 261 brightest cluster members in 63 clusters [86S]. B surface photometry for 69 dwarf ellipticals in Virgo [86I1]. V photographic surface photometry of 13 bright galaxies in the Fornax cluster [78H]; BR CCD photometry of low surface brightness galaxies in Fornax [90D1]; BVI CCD photometry of Fornax LSB galaxies [91B]. UBVR aperture photometry of 107 galaxies and JHK photometry of 80 field, 35 Virgo and 22 Coma galaxies [79P]. JHK aperture photometry [78F, 81A1, 83B3, 86A, 91R]; UBV photoelectric aperture photometry for 61 galaxies [82S3]. UBV photometric catalogue of double galaxies [81D1]; JK surface photometry for 12 bright elliptical galaxies [90P]. B-band surface photometry of 18 S0 and E galaxies [79B2]. Distribution of B luminosity in 26 spiral galaxies [81B]. Detailed surface photometry of 6 galaxies [76S]. Surface photometry for 131 southern elliptical galaxies [88D1]. Types, magnitudes and diameters for 220 galaxies in the Hercules supercluster [86B3].

Extensive compilations of bibliographic references to optical surface photometry of galaxies (complete to January 1985) are given in [82D1, 85P1]. BV CCD observations of galaxies in the Coma and Hercules supercluster [90G]. ubVr photoelectric photometry for 405 E/S0 galaxies [78S2], Gunn r-band CCD photometry of 105 field galaxies [84K] with bulge/disk deconvolution [85K2]; photometric catalog of 463 galaxies in 100 compact groups [89H1]; optical colors of early-type galaxies in compact groups [91Z]; multiwavelength isophotal data for southern ellipticals [91S2]; VRI CCD photometry of 9 early-type galaxies in Virgo [87B2]; UBVRI photometry for 80 compact galaxies [87M1]; optical B(CCD) and infrared (JHK) follow-up studies in 23 IRAS mini-survey galaxies [86M, 87M2].

Radio continuum (20 cm) maps: early-type and late-type galaxies [87G2]; all spirals with $B_T < 12^m$ [87C3]; all spirals with H-band observations [87C4]; the IRAS Bright Galaxy Sample [90C2].

Sources of infrared surface photometry (e.g., [84T, 87A]) can be found in "A Catalogue of Visual and Infrared Photometry of Galaxies from 0.5 μm to 10 μm (1961-1985)" [88D2] or gleaned from "The Catalog of Infrared Observations" [87G1]. IRAS fluxes of galaxies can be obtained in the CGQ and in [87S4, 88C1, 89Y] for the IRAS bright-galaxy sample, and in [84S2] for IRAS mini-survey galaxies; for 196 Virgo galaxies [88H2]. A catalogue of radio, optical and infrared observations of spiral galaxies in clusters [85B2]; optical CCD images and spectroscopy for a sample of 62 extreme IRAS galaxies [91V]; near-infrared imaging survey of interacting galaxies [91S1]; JHK mapping of NGC 2841 [85P4] and NGC 2403 [88C2].

Integrated Hα photometry is available from [83K2, 83K3, 84G1]; Hα/NII survey of a complete sample of 93 spiral galaxies [83K1]; an optical and radio survey of 88 galaxies with $B_T < 12\overset{m}{.}0$ and $\delta > +40°$ [80H]; spectrophotometric survey of 104 Seyfert galaxies [89F2].

While UV surface photometry [90K2] is still very scarce, integrated UV fluxes are available from OAO-2 [82C2, 85C2], the ANS satellites [80C1, 80W, 82D2, 82W2, 86I2, 87S5] and the ASTRON mission [90M2] as well as from sounding rockets [78C, 82S1, 82S2, 83B2, 84H4, 85B1, 87S3] and ballons [80D, 81D2, 83M]. Far UV photographs of M51, M81, M82, M100, M101, M106 [90B]; 2000 Å data for 149 spiral and irregular galaxies [87D2]; IUE spectra for 5 isolated galaxies [84B3].

X-ray fluxes of galaxies can be found in [82F1, 83L1, 84F, 85D2, 85F1, 87C1] while an X-ray catalogue and atlas for 493 galaxies has been published by [92F]; X-ray measurements for 334 active galaxies and nuclei [90D2].

Asymptotic/total magnitudes, B(total)

In order to transform aperture-photometry of galaxies out to "infinite" radius (or zero surface brightness) magnitude-aperture curves for various galaxy types are given in RC2 (= [C-8] in subsect. 9.1.1). These curves were derived from published standard total magnitudes [58D, 59D1, 59D2, 61D1, 61D2, 61D3, 63D1, 64D, 65D, 66B, 67B, 68D1, 69A, 69D, 71A, 73D1, 73D2, 75D, 77F2] and applied to the data in RC2. "A General Catalogue of Photoelectric Magnitudes and Colors in the UBV System of 3,578 Galaxies Brighter than 16th mag" has been compiled by Longo and de Vaucouleurs: [83L2] complete to 1982.

9.1.2.2 Dimensions of galaxies

Isophotal major-axis diameters

Redman [63R] suggested that galaxy diameters should be operationally defined by the μ_B (B) = 25.0 mag/arcsec^2 isophote. This corresponds to a surface brightness about one-tenth of the night-sky brightness and is very nearly the maximum detectable diameter on blue prints of the POSS (= [C-53] in subsect. 9.1.1). Holmberg [58H], however, chose to define his diameters at a few percent of the sky brightness, $\mu_{pg} \approx 26.5$ mag/arcsec^2. The choice is arbitrary, but as fainter isophotal diameters are chosen the constraints on the data become more demanding and, as a result, the diameters in general are probably less well defined.

Major sources for diameters of galaxies are [26R, 32S, 34S, 37H, 41R, 56D, 58H, 60L, 60V, 66L] and others as listed in Table 8 of RC1 (= [C-7] in subsect. 9.1.1) and Table 5 of RC3. In addition, diameters are listed in the

Atlas de Galaxias Australes (= [C-41] in subsect. 9.1.1),
UGC (= [C-35] and also [57D] in subsect. 9.1.1),
UGCA (= [C-36] in subsect. 9.1.1),
MCG (= [C-49] and also [57D] in subsect. 9.1.1),
ESO (= [C-27; but see also [57D, 57M] in subsect. 9.1.1,),
ESO-LV (= [C-28] in subsect. 9.1.1),
SGC (= [C-6] in subsect. 9.1.1),
VCC (= [C-3] in subsect. 9.1.1),
KUG (= [C-45a] in subsect. 9.1.1)

which in turn have been transformed to a standard diameter, $D(25)$, in RC2 and RC3 ([C-9] in subsect. 9.1.1). Standard diameters for 237 galaxies measured at 25 and 26.5 mag/arcsec^2 [85L], revised and up-dated to include 608 standard photometric diameters [87P1] as well as many transformation equations for other studies, based on [84D1, 85M, 85P2, 86B3, 86C] cluster spirals [87C5]; see also Kallogyan’s study [78K1, 80K1, 80K2].

Axial ratios and "face-on" diameters

The measured apparent major-axis diameter is a function of inclination [46H, 55W, 56D, 57D]. Galaxies viewed more edge-on have larger apparent diameters due to finite thickness of the disk resulting in a greater optical path: and thus an increased surface brightness at fixed radius. Corrections to a "face-on" isophotal diameter $D(0)_{25}$ have been investigated [57D], revised [71H] and applied to galaxies in the RC2 ([C-8] in subsect. 9.1.1). However, see also [68T, 72T2]. Axial ratios, necessary for correcting the diameters, are taken principally from the MCG (= [C-49] in subsect. 9.1.1), UGC (= [C-35] in subsect. 9.1.1) or [58H], and are transformed to the standard 25 mag/arcsec^2 isophotal ratio, R_{25}, in RC2 (= [C-8] in subsect. 9.1.1).

Mean surface brightness

The RC2 (= [C-8] in subsect. 9.1.1) tabulates two average surface brightness: M_{25}, the average surface brightness contained within an ellipse of diameter D_{25} and axial ratio R_{25}, and M_e, the average surface brightness within an aperture A_e that contains half of the total light (i.e., containing half of the asymptotic magnitude B_{total}). The first definition is relatively straightforward to compute, the latter is more complicated and somewhat model dependent. See also the mean surface brightness study of isolated and double galaxies [81A2].

9.1.2.3 Colours

In the RC2 (= [C-8] in subsect. 9.1.1) 959 galaxies have total (B-V) colour indices derived from multi-aperture data, 682 have (U-B) colours listed. These colours have been transformed either from original UBV observations from other similar colour systems as enumerated in Table 11 of RC2. Recent UBV photometry for additional galaxies: [76B, 76G, 78G, 79P, 79W, 80C2]. A general catalogue of photoelectric magnitudes and colours in the UBV system for 3,578 galaxies brighter than 16^{m}.

IRAS colours of normal galaxies from the CGQ ([C-29] in subsect. 9.1.1) are discussed in [86H]; for UGC galaxies in [89B]; for normal irregular galaxies in [89H2]; and for the IRAS bright-galaxy sample [87S4] by [88C1].

UV magnitudes and colours for 156 galaxies observed by the IUE satellite have been presented by [91L], while data for other investigations have been summarized in [82C1, 82W2, 87D2]; 1910 Å colours and magnitudes [84D2].

25 very red ((B-V) > $0\overset{m}{.}7$) yet HI rich ($\log(M_{HI}/M_{\odot})/(L_B/L_{\odot}) > -0.6$) spiral galaxies [83B4].

9.1.2.4 Redshifts

Stromberg's original list [25S] of optical radial velocities contained 41 galaxies. some forty years later optical redshifts for 583 galaxies were published [56H]. In the RC1 and RC2 (= [C-7, 8] in subsect. 9.1.1) some 280 references to sources of optical velocity data are listed (Tables 12 and 13, respectively), with an additional 538 references to optical redshifts being found in RC3 (= [C-9] in subsect. 9.1.1). Velocity data is no longer restricted to the optical measurements but includes derivations from 21-cm radio observations (see for instance [78T, 89H3], Table V2 in RC2, and 209 references to radio wavelength redshifts in RC3, complete to 1987); corrections for errors in redshifts [82R3].

A major compilation [83P] contains redshifts and original references for 8,250 galaxies, complete to 1980 and supersedes [79G];
cross-correlation redshifts are discussed for 59 galaxies in [80K4];
redshifts for 115 galaxies [83S2];
a study of a complete sample to field galaxies [78K3];
data for 1093 galaxies with $m_{pg} < 15\overset{m}{.}5$ in a 6 degree strip across the North Galactic Cap [90H];
the southern sky redshift survey [91D];
radial velocities for 301 pairs of galaxies [80K3];
44 galaxies in Perseus [82F2];
359 galaxies in Abell clusters [90Z];
285 galaxies observed for bulge-to-disk ratio estimates [87S1];
IRAS galaxies in the Bootes Void area [87V1];
a deep survey of 280 galaxies [83K4];
deep survey of IRAS galaxies towards to Bootes Void [90D3];
5 suspected superclusters [85C2];
s-type Markarian galaxies [81H];
multi-object spectroscopy of galaxies in Abell 400, 576, 1767 and 2124 [82H];
102 dwarf galaxies [89E];
75 galaxies in Abell 2256 [87L];
387 southern compact and bright-nuclei galaxies [83F1, 88F];
84 brightest Abell cluster galaxies [83S1];
100 galaxies in 10 clusters [87P3];

161 galaxies in 11 clusters [77F1];
71 galaxies in the Indus region [82C3];
galaxies in Abell 496 and 2052 [85Q];
Tololo emission-line galaxies [78B];
298 late-type galaxies in the Virgo Cluster [87H2];
155 galaxies in the winter Galactic Plane [88M2];
135 galaxies in the Virgo region [78E];
472 galaxies in the Pisces-Perseus supercluster [89G];
100 galaxies in the Coma Cluster [72T1];
high-precision 21-cm redshifts for 625 galaxies [88T1];
low surface brightness objects [88S1];
150 galaxies in the Hercules supercluster [79T];
123 galaxies in the Cancer cluster [83B1];
83 galaxies in poor cD clusters [84B1];
21-cm velocities for 440 galaxies between the Local supercluster and the Hydra-Centaurus supercluster [87R];
71 galaxies in the Hydra I (Abell 1060) cluster [82R2];
469 elliptical galaxies [87D1];
342 galaxies toward the Bootes Void [88S2];
88 imagetube spectra of 79 galaxies [71K];
flux-limited sample of 72 IRAS galaxies [87S2];
21-cm velocities for 342 out of 415 galaxies, and 383 galaxies observed in the Pisces-Perseus supercluster [85G, 86G, 88H1];
228 southern galaxies [84D3];
Medium Sensitivity Survey X-ray sources [84G2];
several hundred spiral galaxies in 10 clusters [85B2];
21-cm redshifts for 324 isolated galaxies [84H1];
26 galaxies in the direction of the Coma/Abell 1367 supercluster [88G];
92 galaxies in the direction of the Coma cluster [88T2];
flux-limited sample of IRAS galaxies [87V2];
129 galaxies in groups and clusters [72C];
approximately 40 galaxy redshifts in each of 14 rich clusters [87C2];
1,268 radial velocities in 15 rich clusters [88D3];
157 galaxies in 54 triplets [81K2];
galaxies in the Horologium region [84C];
559 Selected Area 94 objects [87B1];
719 bright galaxies [78S1];
21-cm observations of 1787 nearby galaxies [81F];
21-cm observations for 183 galaxies [78T];
164 field galaxies brighter than $B \approx 15\overset{m}{.}5$ [78K3];
90 IRAS galaxies [88H3];
172 central galaxies and companions [81A4];
530 IRAS galaxies [86L];
70 peculiar objects [82M1];
redshifts in Klemola 27 [84R];
21-cm observations for galaxies in the Pegasus I cluster [82R1];
156 binary systems [83W];
145 blue Zwicky compact galaxies [79K2];
160 galaxies in Abell 194 [88C3];
289 galaxies in Abell 539 [88O];
107 southern galaxies [86P1];
266 galaxies in the Hydra-Centaurus region [89F1];
the Fornax cluster [80J, 85R];

300 galaxies in a strip crossing the Coma cluster [90K1];
galaxies with supernovae [74B2, 79B1, 82B1, 86B2];
compilation of double galaxy redshifts [85P3];
radial velocities of isolated galaxies [85K1];
39 peculiar ESO galaxies [77B];
redshifts for Karachensteva isolated galaxies [79K1], and for Karachentsev isolated triples [81K3];
radial velocities for 21 interacting double galaxies [81K1];
Zwicky compact galaxies [70S].

Accidental and systematic errors in various sets of velocity measurements are discussed in [61H, 61P, 63D2, 72R, 75L, 82R3, 86B1]. A total of 2,713 velocities are reduced to a standard system in RC2; this was increased to 16,693 in RC3.

Corrections for the solar motion
Radial velocities *V*, referred to the galactic centre, must be corrected for the orbital motion of the Sun. Most researchers in the field (e.g., [75S2] or RC2) adopt the standard correction of

$$\Delta V = 300 \sin l \cos b \text{ km s}^{-1}$$

where it is assumed that the Sun is moving at 300 km s^{-1} toward $l = 90°$, $b = 0°$, which is in good agreement with the estimate of $V_{\odot} = (315 \pm 15)$ km s^{-1} toward $l = 95°$, $b = -8°$ for the Local Group velocity centroid [68D2]. For definition of galactic coordinates *l* and *b*, see subsect. 8.3.1.1 in LB VI/2c.

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9.1.3 Qualitative classification of galaxies

The manuscript was closed in 1992.

9.1.3.1 The Hubble-Sandage-de Vaucouleurs classification

Two broad morphological types characterize most galaxies: elliptical and spiral forms. The remaining small percentage of galaxies that cannot be characterized in this way are generally relegated to the irregular class. The earliest classification schemes that have had a continuing influence on modern systems were independently developed by Lundmark [26L] and Hubble [26H]. Discussions of this early history of galaxy classifications: [56D, 71H1, 76B]. Modern reviews of the existing classification schemes: [75V, 77D, 79S, 87V2].

9.1.3.1.1 Ellipticals

Elliptical galaxies show very little or no internal structure and they are simply characterized by their apparent ellipticity. In general, ellipticals with major and minor axes, a and b, respectively, are typed En where $n = 10\ (a–b)/a$. Thus E0 galaxies are apparently circular, E7 galaxies are the most flattened. When n exceeds 7, other structures appear (such as a cusp in the light distribution or rings of apparent obscuration), and the galaxy is designated as lenticular or of the S0 class.

9.1.3.1.2 Spirals

In Hubble's original scheme [36H], spirals were subdivided into three types or stages (Sa, Sb, and Sc) characterized either by an increasing openness of the arms or by the decreasing importance of the light contributed by the bulge compared to the disk. Even before this time Curtis [18C] had paved the way for independently dividing all spirals into two families according to whether they possessed central bar structures (barred spirals) or not. These two form criteria are the basis of the so-called "tuning fork" diagram for galaxies; see LB, VI/1, p. 668.

Extension of the basic Hubble scheme started with Holmberg [58H], who introduced "late" and "early" subtypes for the Sb and Sc galaxies, see Table 1. Shapley [40S] extended Hubble's classification to include explicitly much more ragged spirals, type Sd; while de Vaucouleurs [59D] further extented the system to those galaxies bordering on the irregular classification – having no nucleus and only a hint of spiral structure – type Sm (spirals of Magellanic type).

9.1.3.1.3 Lenticulars and S0 galaxies

Hubble [36H] introduced S0 galaxies as a morphological transition case between ellipticals and early-type spirals. A detailed description of these lenticular galaxies and a possible sub-classification scheme is given in [61S]; see Table 2. Others [63B, 76V] have suggested that S0's actually run parallel to the ordinary spiral stages but form one extreme of gas-depleted disk systems (S0a, S0b, S0c) coupled to the gas-rich spirals by yet another intermediate sequence of "anaemic" spirals (Aa, Ab, Ac). de Vaucouleurs [59D] suggests that lenticulars may be subdivided as well, and his "early-type" and "late-type" classification is also outlined in Table 2.

Table 1. Holmberg's extended Hubble classification for late-type spirals, Holmberg [58H].

Type	Definition	Examples
Sb^-	Extended nuclear region representing a considerable fraction of the total luminosity Mean surface brightness is comparatively high Symmetrical and rather closed system of spiral arms with no pronounced contrast between the arms and the main body In most cases there is no appreciable resolution	NGC 0224 (M31) NGC 3031 (M81)
Sb^+	Comparatively small nuclear region Mean surface brightness lower than Sb^- Arm system is open and symmetrical, with good contrast against the main body	NGC 3952
Sc^-	Small, sometimes semi-stellar nucleus Mean surface brightness about the same as for Sb^+ More or less symmetrical, open and rather pronounced spiral arms Resolution well advanced	NGC 3992 NGC 5194 (M51)
Sc^+	No prominent nuclear region Mean surface brightness less than for Sc^- Confused and loosely defined spiral arm system (short arms) Highly resolved	NGC 0598

Table 2. Sub-divisions of S0/lenticular galaxies.

Type	Definition	Examples
de Vaucouleurs [59D]		
$S0^-$	Traces of structure can be found in the smooth lens and envelope; a small nucleus may be present	NGC 5273 NGC 7166
S0°	A weak trace of a ring appears at the edge of the lens; a distinct nucleus and envelope may be present	NGC 1553 NGC 4459
$S0^+$	A well defined ring is present separating the inner nuclear bulge from outer incipient spiral structure	NGC 2855 NGC 7702
Sandage [61S]		
$S0_1$	The existence of an outer envelope, flattened to a fundamental plane, defines this sub-type; the ellipticals of the central section of such galaxies are flatter than E7	NGC 1201 NGC 3245 NGC 4762
$S0_2$	The first appearance of a circular absorption pattern or a true depletion of material in the envelope defines this intermediate sub-type	NGC 0542 NGC 3065 NGC 4111
$S0_3$	A strong internal circular ring defines this extreme of the S0 class	NGC 5866 NGC 3032 NGC 4459

Note: There are in fact many *non*-ringed S0° and $S0^+$ galaxies also, see Table 3 (p. 35) in [63D].

9.1.3.1.4 Dusty ellipticals

A catalogue of dusty elliptical galaxies is presented in [85E] where the authors also classify the objects based on the relative disposition and morphology of the dust distribution as given in Table 3.

Table 3. Dusty ellipticals, Ebneter [85E].

Type	Definition
O	Oblate – dust lane lies parallel to the optical major axis of the galaxy (this class may be contaminated by normal S0 or Sa galaxies)
P	Prolate – dust lane lies parallel to the optical minor axis of the galaxy
S	Skew – dust lane does not lie parallel to either optical axis of the galaxy
I	Indeterminate – stellar component of galaxy appears spherical;dust is in a well-defined lane
D	Diffuse – dust is distributed in irregular patches in the galaxy
M	Multiple – galaxy has two dust lanes: one on the optical major axis, one on the optical minor axis
W	Warped – dust lane is warped
BE	Bright Edge – dust lane has a bright edge, possibly due to a stellar disk
U	Unknown – dust type could not be determined, but galaxy has been identified as containing dust

9.1.3.1.5 Anemic galaxies

Van den Bergh [76V], following Baade [63B], proposed that the lenticular class of galaxies did not form transition classification between spirals and ellipticals but rather they represent an extreme sequence parallel to normal spirals, where all members of the non-elliptical class are distinguished by means of their disk-to-bulge ratio: "early-type" spirals having large bulges, "late-type" spirals having small bulges. A sequence of "anemic spirals" (typed Aa-Ab-Ac, and found most frequently in clusters) is suggested to populate a sequence intermediate between the gas-rich normal spirals (typed Sa-Sb-Sc) and the gas-poor lenticular systems of type S0 (typed S0a-S0b-S0c).

9.1.3.1.6 Magellanic irregulars and amorphous galaxies

Holmberg [58H] first divided irregular galaxies into two types: Type I irregulars are highly resolved systems similar to the Magellanic Clouds, while Type II irregulars show a smoothed "amorphous" distribution of light, often broken by irregular patches of obscuration. Type I irregulars have subsequently found a natural home as Im galaxies following the late spirals of class Sd and Sm [59D]. Their star-formation history is summarized in [85H]; while global radio, optical and spectral properties are reviewed in [80F2, 82H]. On the other hand, Sandage and Brucato [79S] have suggested that the original Irr II galaxies can be subdivided, and that a single class should be abandoned. The properties of the Irr II class galaxies (also called I0 in [64D]) have been summarized in [74K2]. Those few objects which show no spiral structure, but have unresolved disks, are now termed *amorphous galaxies* [79S]. Examples are NGC 3077, NGC 5253, and M82.

Heidmann et al. [71H2] introduced a numerical code of the morphological types in the revised Hubble system (Table 4). This code was extended and used in the *Second Reference Catalogue of Bright Galaxies*, RC2 (= [C-8] in subsect. 9.1.1).

More detailed tables for coding of Hubble types, revised morphological types (de Vaucouleurs [59D], DDO (van den Bergh) types and Yerkes (Morgan) types etc. are given in the RC2.

Table 4. The numerical code t of the morphological types, Heidmann [71H2].

Morphological type	(Hubble revised)	Code t
Normal elliptical systems	E	–7
Compact (high density) ellipticals	cE	–6
Dwarf (low density) ellipticals	dE	–5
Giant ellipticals with extended optical coronae (in particular the Morgan type cD)	E+	–4
Lenticular system	L–	–3
	L	–2
	L+	–1
Irregular systems of type II	I0	
Lenticular-spiral systems	S0/a	0
Spiral systems	Sa	1
	Sab	2
	Sb	3
	Sbc	4
	Sc	5
	Scd	6
	Sd	7
	Sdm	8
Spirals of Magellanic type	Sm	9
Irregular of Magellanic type (= Irr of type I)	Im	10
Compact blue irregulars (isolated extragalactic HII regions)	cI	11

9.1.3.2 Alternate systems and modifications

9.1.3.2.1 The Yerkes classification

Morgan [50M, 57M, 58M, 71M2] has produced a system for classifying the central concentration of light in a galaxy to give population groups which apparently correlate with the stellar content of the inner parts of the galaxy [57M] as judged by integrated spectral types. These population groups a, af, f, fg, g, gk, and k imply early and late spectral-type stars, respectively, as contributing most of the light from the nucleus; however, the designation is found by inspecting the central concentration of monochromatic light: a galaxies have little or no central concentration while k galaxies are highly concentrated. In addition, Morgan identifies form families, which are explained in Table 5; these correspond to the most basic classification, see above. A recent application of this classification system to southern galaxies is given in [74G].

According to [64M] dumb-bell galaxies are a group of objects allied to the D galaxies, in which two, separated approximately equal nuclei are observed in a common envelope. They may well be related to galaxies that have one or more fainter components in their envelopes. Dumb-bell galaxies are then the extreme cases of very close multiple galaxies in which there are only two, but equal, components. A catalogue of dumb-bell galaxies can be found in [88V].

Table 5. Form families of the Yerkes system, Morgan [50M, 58M].

Form family	Description
B	Barred spirals
D	Galaxies with rotational symmetry but showing neither spiral structure nor ellipticity
cD	Supergiant D galaxies, predominantly found in clusters [64M] and embedded in an extensive halo
db	Dumb-bell systems
E	Ellipticals
Ep	Peculiar ellipticals containing conspicuous absorption patches
I	Irregulars
L	Low-surface-brightness systems
N	High-luminosity nucleus superimposed on a considerably fainter outer envelope, see also [71M2]
Q	Quasi-stellar objects
S	Ordinary spirals

9.1.3.2.2 Spiral varieties

With reference to the inner structure of galaxies, the manner in which the spiral structure terminates is a valid classification parameter [59D]. If the spiral arms continuously circle into the nucleus "(s)" is suffixed to the stage and family classification. If the spiral structure ends in a ring structure "(r)" is added. Transition cases "(rs)" are also found. For more details see also LB VI/1, p. 668.

9.1.3.2.3 Dwarf galaxies

As a precursor to the luminosity classification of all galaxies, van den Bergh’s [59V] division of the intrinsically lowest luminosity galaxies into four groups is outlined in Table 6. The so-called "nucleated dwarfs" described in [56R] must be added to this classification; the prototype of this sub-class is IC 3475 (see Table 6). These specific low-surface-brightness objects have luminous knots but no global structure other than nuclei in a number of instances. In fact about thirty percent of the dwarfs in the Virgo cluster have discernible nuclei, unlike the Local Group in which none of the dwarfs possess nuclei [77R]. The nucleated dwarfs in Virgo are however 3…5 mag brighter then the dwarf spheroidals in the Local Group.

Photographic images of 138 dwarf galaxies in the Virgo Cluster have been examined, following [81R], and have been systematized into the various types of morphology encountered there, noting in the first instance that there are no real dwarf spirals in the sample. The following types of low-luminosity galaxies were found: (a) Dwarf ellipticals dE are the most common type of dwarf in the Virgo Cluster. They are characterized by a smooth intensity distribution over the face of the galaxy, and by their low surface brightness which is "an unfailing indicator of low intrinsic luminosity". Some members of this class have a central star-like nucleus. (b) Dwarf S0 galaxies dS0 are still only tentatively identified as an entirely new class of objects. They are characterized by the presence of two components, a disk and a bulge, both of which are smooth and symmetric. The surface brightness of dS0 galaxies is also low, as with the dwarf ellipticals. (c) Sm galaxies still show some fragmentary evidence of spiral structure, while Im galaxies are totally chaotic. (d) Huge Im and dE types are very low surface brightness galaxies with large (up to 10 kpc) diameters. (e) Blue compact dwarfs, BCD galaxies consists of several knots and show some low surface brightness fuzz of an underlying structure. Finally, (f) galaxies with BCD components. These objects are thought to be basically Im galaxies with a small number of intense star-formation events dominating their presently observed morphology.

Table 6. Classification of dwarf galaxies, van den Bergh [59V].

Type	Description	Examples
D Ir	Dwarf irregular	NGC 6822
		IC 1613
D Sp	Dwarf spiral	NGC 3057
D El	Dwarf elliptical	NGC 185
		NGC 205
D Sph	Dwarf spheroidal	Draco, Leo B
	Nucleated dwarf spheroidal	IC 3475

9.1.3.2.4 Luminosity classification

In a series of papers van den Bergh [60V1, 60V2, 66V] suggested that the coherence of the spiral structure could be used to infer the intrinsic luminosity of spiral galaxies. Systems with well-developed global spiral structure are of Type I (supergiants) while those with ragged ill-defined spiral arms are of Type V (dwarfs), as in the stellar luminosity-class nomenclature. The basic criteria of this DDO-classification (DDO = David Dunlap Observatory) are outlined in Table 7.

Calibrations of the absolute magnitudes of Sc galaxies as a function of luminosity class are controversial; see discussions in [60V3] and [74S]. de Vaucouleurs [77D] has also discussed this problem, but in terms of his luminosity index which is a simple average of his stage and the DDO luminosity class. The absolute magnitudes of Sb galaxies as a function of luminosity class have been recently discussed in [80S2]. Irregular galaxies may be roughly typed according to intrinsic luminosity [59V, 66V] through Holmberg's [58H] relation between absolute magnitude and apparent surface brightness. Similarly, giant ellipticals have a higher mean surface brightness than dwarf ellipticals [78S2]. In addition, though, ellipticals show a correlation of their luminosity with colour [59B, 61D] in the sense that giant ellipticals are redder than their dwarf counterparts.

Table 7. DDO luminosity classification for Sc galaxies, van den Bergh [60V1, 60V2, 66V].

Luminosity	Description	Examples
Sc I	These supergiants galaxies are characterized by long well-developed arms of relatively high-surface-brightness	M 101 M 51
Sc II	The spiral structure of these bright giant galaxies is less well developed as compared to Sc I galaxies	NGC 3184 NGC 3319
Sc III	Short patchy arms extend from a fairly high-surface-brightness main body	NGC 2403 NGC 672
S IV	Outer regions give only a hint of spiral structure emanating from a relatively low-surface-brightness disk	NGC 247 NGC 2500
S V	Dwarf spirals; only a hint of spiral structure is seen in these low-surface-brightness objects	DDO 122

9.1.3.2.5 Byurakan nuclear types, bright nuclei galaxies, and Seyfert galaxies

Kalloglyan and Tovmassian [64K] have introduced a classification of galaxies judged solely on the degree of central concentration of galaxy images (Table 17); examples of this systems are also to be found in [65T, 66T, 67T, 68I, 68O, 68S, 69S, 73M2, 73S].

Keel and Weedman [78K] provided a survey of 448 so-called "bright-nuclei" (BN) galaxies of type 4 and 5 (Table 16), drawn from the Byurakan master list [75A2] of nuclear types for 711 galaxies. They draw attention to 10 galaxies which have nuclei morphologically resembling Seyfert galaxies, were originally defined by their optical appearance [43S] but now have a strict spectroscopic classification first suggested in a simpler form [74K1], and then refined and expanded upon by [77O, 81O, 83O] and outlined in Table 15. More sophisticated diagnostic diagrams involving various optical emission-line ratios can be found in [87V1] and [81B], which quantitatively discriminate between HII regions, starburst galaxies (see [87B1] for far infrared and optical models), HII galaxies, narrow-line galaxies, LINER (low ionization nuclear emission region) galaxies and Seyfert 2 galaxies. In this respect it is worth noting that the N galaxies [64M] now satisfy Seyfert’s original morphological criteria as a separate class. Compilations of Seyfert galaxies and related objects can be found in [77W1, 78W, 86K1, 87L2]. Early-type galaxies with emission lines are brought together in [87B2]. Hα emission-line strength surveys of 200 normal galaxies [83K2] and 26 Virgo galaxies [83K3].

Several surveys of Seyfert nuclei have discussed the morphology of the host galaxy [77A1, 77W2, 80S1, 85D, 89A]; other studies [85K2, 86N, 87K4, 89F, 89K] have investigated the relation of Seyfert activity to their environment: Dahari [85D] defines interaction classes for galaxies, in the context of nuclear activity, based on environmental criteria, given in Tables 10, 11, 12, 13; MacKenty [90M] offers a simple two-way classification scheme (Table 9) involving both the host morphology and the environment (in the form of a statement concerning interaction); [89K] list 113 galaxies in 15 Seyfert groups and 9 non-Seyfert groups and assign activity classes (see Table 14) to these galaxies.

Further environmental groupings have been assigned [91C3] for violently star-forming galaxies, as given in Table 8.

Table 8. Environmental groupings for violently star-forming galaxies, Campos-Aquilar [91C3].

Group	Description	Examples
1	Morphologically normal galaxies with nuclear starbursts In all cases a companion is detected well within 1 Mpc projected separation, and $\Delta V < 500$ km s^{-1}	To 1004-296 UM 0499 Mrk 0710
2	A burst of star formation appears to be located in a small companion, or corresponds to an HII region in the galaxy	To 1116-325 UM 0501 Mrk 1315
3	Magellanic irregular, or dwarf irregular Appears to be near other galaxies, and could be interacting	To 1400-41 UM 0523 NGC 1487
4	Small and compact At least one massive galaxy is seen in the neighbourhood	To 1147-283 UM 0462 Mrk 1318
5	Small and compact Nearby galaxies are not normal, being Magellanic irregulars or unclassified	To 1924-416 UM 0160 II Zw 040
6	Compact morphology and small size Isolated (no companions within 500 km s^{-1} or 1 Mpc. projected separation)	To 1148-2020 UM 0439 NGC 5253

Table 9. Classification sequence for Seyfert galaxies, MacKenty [90M].

Class	Host morphology class	Interaction class
0	Amorphous/unresolved	Isolated
1	Spiral	Companion
2	Bar and/or ring	Companion is disturbed or at same redshift
3	Peculiar or distorted	Bridge, tail or jet

Table 10. Interaction classes (IAC) for single galaxies, Dahari [85D].

IAC	Description	Example
1	Symmetric	Arp 027
2	Slightly asymmetric; diffuse extensions	Arp 026
3	Asymmetric, extended arm	Arp 222
4	Distorted; out of shape	Arp 224
5	Strongly distorted	Arp 220
6	Aftermath; severely distorted	Arp 157

Table 11. Interaction classes (IAC) for double galaxies, Dahari [85D].

IAC	Description	Example
3	Large separation, and no apparent contact	Arp 305
4	Large separation, but components are connected or	Arp 314
	small separation, but no contact	Arp 271
5	Small separation, and evidence of contact	Arp 283
6	Galaxies overlap	Arp 166

Table 12. Interaction classes (IAC) for galaxies with companions, Dahari [85D].

IAC	Description	Example
2	Large separation, no contact	Arp 023
3	Large separation, but signs of connection	Arp 304
4	Small separation, but no contact or	Arp 112
	small separation, and sign of contact	Arp 085
5	Companion overlaps parent galaxy	Arp 309

Table 13. Interaction classes (IAC) for galaxies with much small companions, Dahari [85D].

IAC	Description	Example
1	Large separation, no contact	
2	Large separation, but connected	Arp 024
3	Small separation, but no contact	Arp 290
4	Small separation, connected or	Arp 082
	companion overlaps primary galaxy	Arp 239
5	Companion overlaps parent galaxy	Arp 309

Table 14. Spectroscopic criteria for nuclear activity classes, Kollatschny [89K].

Class	Spectrum
1	Seyfert 1 or Seyfert 2
2	Starburst nucleus with [OIII]λ5007 > Hβ
3	Hα present; [OIII]λ5007 < Hβ
4	Hα+[NII] present, but weak
5	Hα or [NII] weak
6	Absorption lines only

Table 15. Nuclear emission-line type (NET) [74K1, 77O, 81O, 83O, 87L2].

NET	Class	Description	Example
1	Seyfert 1	Widths of the Balmer emission lines are much broader (several 1,000 km s^{-1}) than the "narrow" forbidden line widths	NGC 4151
1.5	Seyfert 1.5	Easily apparent, narrow Hβ profile superposed on broad wings	NGC 4151 Mrk 0006
	Seyfert 1.8	Narrow component of Hβ stronger than Sy 1.5 weak, but defi-nite, broad Hβ	NGC 2622
	Seyfert 1.9	Broad Hβ cannot be detected by mere visual inspection	
2	Seyfert 2	Balmer lines and forbidden lines have similar widths, typically 500…1000 km s^{-1} λ5007/Hβ > 3.0 λ6583/Hα > 0.5 λ6300/Hα > 0.1	NGC 1068
2.5	Marginal Seyfert	λ5007/Hβ ≈ 3.0 λ6583/Hα ≈ 0.5 λ6300/Hα > 0.1	NGC 4388 NGC 7436
3	LINER (Seyfert 3)	λ5007/Hβ < 3.0 λ6583/Hα > 0.5 λ6300/Hα > 0.1	NGC 3312 NGC 7393
4	HII Region	λ5007/Hβ > 3.0 λ6583/Hα < 0.5 λ6300/Hα < 0.1	NGC 4765 NGC 7253
5	Weak Hα		NGC 3920 NGC 5410
6	No emission	*EW* Hα < 10 Å	NGC 1143
7	No emission	Noisy or not observed when no nucleus is seen	NGC 0942 NGC 1347

Table 16. Byurakan nuclear types [64K, 76A2]. (N galaxies).

Type	Description	Example
1	No central condensation	NGC 4088
2	Weak central condensation	NGC 5850
3	Strong central condensation but not stellar	NGC 4442
4	Stellar nucleus blending into nebulous background	NGC 1300
5	Strongly stellar nucleus	NGC 3992

9.1.3.2.6 Compact galaxies: Zwicky and Arakelian

According to Zwicky [71Z] compact is a term that applies to "any galaxy, or any part of a galaxy, whose surface brightness photographically, visually or bolometrically is greater than that which corresponds to m < 20 mag/arcsec^2)". Alternatively, Zwicky [64Z] also defined a *compact* galaxy as "those which can just be distinguished from stars taken with the Palomar 48-inch telescope and which have diameters of 2 to 3 arcsec", whereas *moderately* compact is invoked "if its image, on photographs taken with the 18-inch Palomar Schmidt telescope can barely be distinguished from stars of the same apparent brightness. These systems have diameters of about 5 to 10 arcsec". Spectroscopic follow-up in [70S].

Arakelian [75A1] lists 621 galaxies of high surface brightness, defined as having average surface brightnesses greater than 22 mag/arcsec^2.

9.1.3.2.7 Purely morphological schemes

Systems of classification that in fact are more descriptive than interpretive can be traced back to the early work of Wolf [08W] which captured the development of complexity of forms, and that of Shapley [29S, 30S]. The most extensive application of this approach to galaxy taxonomy is the work of Vorontsov-Velyaminov and his colleagues as published in the five volumes of the *Morphological Catalogue of Galaxies* [62V].

In the MCG no attempt is made to systematize and/or distill the forms found; rather the essential components are all laid out in as much complexity (or simplicity) as the system demonstrates, ordered simply as a function of radial zones within the galaxy; different zones are divided by a semicolon, those referring to the same zone are separated by a colon. A double colon means that the outer details are completely detached from the inner ones. Symbols are placed inside of parentheses if they are doubtful. An exclamation mark, or the repetition of the lowercase descriptors are used to accentuate a detail or quantity. Table 17 lists the essential features of this powerful, albeit infrequently used system.

See also Table 4 in subsect. 9.1.3.6.

Table 17. Morphological catalogue symbols [62V].

Symbol used in MCG	Description
E	Elliptical
F	Flat galaxies usually highly inclined, with no distinguishable form
G	Small galaxies, difficult to describe but not stellar
N	Large nucleus
n	Small nucleus
Ne and ne	Elongated nuclei
(N)	Overexposed image with traces of structure which imitate a nucleus N
N_n and n_n	Nebulous nuclei
H	Haze or halo
Hp	Very asymmetrical or disturbed haze
D	Disk
D^-	Incomplete disk
L	Lens
R	Ring
RR	Several rings
R^-	Incomplete ring
$D \rightarrow R$	Disk is brighter at its rim (ring effect)
B	Short bar with no nucleus

Symbol used in MCG	Description
B^-	Very short bar
BB	Long bar
BBB	Very long bar
2B	Bar seen on both sides of N or L
N;2B	Bar is faint relative to nucleus
N,2B	Nucleus and bar are of comparable strength
S and Z	Long spiral arms 2S = two arms, 3S = three spiral arms, etc.
s and z	Short spiral arms
SS and zz	Indefinite numbers of arms
SS' and ss'	Arms with indefinite direction of winding
ZS	Arms wind in opposite directions
Sss	Branching spiral arm
r	Ray
γ	Emergent spiral arms form a γ-shape
$\gamma \rightarrow$ R	γ-arm tends to form a ring
2S $\rightarrow$ 8	Spiral returns to nucleus forming a figure-eight
S $\rightarrow$ R	Arm merges into a ring
(N);ss or F;ss	Ends of a flat system are visible
D, (2S) or L, (2s)	Arms are suspected in a D or L system
2l	Two wings (flattened component seen edge-on)
P	Indefinite patch
A	Absorption feature
T	Tail
C	Connecting filament (in interacting system)
+*	Star superimposed
m	Massive
f	Filamentary
w	Wide open arms
t	Tightly wound arms
o	Open arms
z	Arms start a right-angles to the bar
$\rightarrow$	Appears to transform to
$\rightarrow$8	Transforms to a figure-eight or loop
A	Very smooth
b	Smooth
c	Patchy
d	Very patchy
i	Irregular patchiness
p	Deformed detail (not the peculiarity in general) used to accentuate any particular detail
( )	Symbols are put in paretheses when a *detail is only suspected*

9.1.3.2.8 Spiral arm types

Smooth-armed spirals as a class were first introduced by Strom [76S2]; see also [78S1] and [80W] for a preliminary list. Later, [82E, 87E] the systematic variations in the orderliness of spiral arms were categorized (see Table 18); broadly considered, arm classes 1 through 4 were termed *flocculent*, while arm classes 5 through 12 were said to be *grand design*. Discussions of arm classes and their correlation with other parameters can be found in [83E, 85P, 85R, 86E, 86M3, 89G, 90E1, 90E2]. Arm widths are discussed by [82B].

Table 18. Arm classification for spiral galaxies, Elmegren [82E, 87E].

Arm class	Description	Prototype
1	Chaotic appearance; no symmetry; fragmented arms with differing pitch angles	NGC 2500
2	Short, fragmented spiral arm pieces defined mostly by HII regions, no regular pattern; loose, open arms	NGC 7793
3	Fragmented arms, uniformly distributed around the galaxy center	NGC 2841 NGC 5055
4	Only one prominent arm; otherwise fragmented spiral arms with no regular pattern in the rest of the galaxy	NGC 2403
5	Two, symmetric short arms in the inner regions; irregular arms in the outer region	NGC 1313 NGC 0598
6	Two symmetric arms; feathery appearance in the outer arms, which tend to wrap tightly and tightly and form a ring-like structure	NGC 2935 NGC 1637
7	Two symmetric, long arms in the outer regions, and irregular or feather arms in the inner regions	NGC 2903
8	Tightly wrapped arms forming a ring-like structure with over-all symmetry	NGC 3992
9	Multiple, long and continuous arms in the outer parts two symmetric and continuous arms in the inner parts	NGC 5457 NGC 1232
10	Two long arms extending from either end of a prominent bar (abandoned in later applications [87E])	NGC 1300 NGC 5383
11	Two long symmetric arms in the inner regions with a long drawn-out arm or arms in the outer regions; near-by galaxy apparently interacting (abandoned in later applications [87E])	NGC 7753 NGC 5194
12	Two long, sharply defined symmetric arms dominating the total appearance	NGC 4321

9.1.3.3 Spectroscopic criteria

The properties of UV excess galaxies are reviewed in [87K3]. A list of active galaxies is contained in [87C]. Seyfert galaxies: see subsect. 9.1.3.2.5, Table 15, and sect. 9.5. For recent compilations see [74K1, 74V, 86K1, 87L2]. A survey of 75 bright galaxies for signs of dwarf Seyfert activity [85F]; see also [83K4]. A spectrophotometric catalogue of 425 HII galaxies [91T2]; Hα galaxies [83K2, 85W, 89R]; Hα galaxies in Abell 347/1367 [88M2].

Wolf-Rayet galaxies are defined to be that subset of emission-line galaxies in which broad emission from HeII λ4686 is present in the integrated spectrum, and is attributed to Wolf-Rayet stars, in the nucleus or in giant HII regions. A list of known Wolf-Rayet galaxies is given in [91C2]; see also [85K3, 86K2].

9.1.3.3.1 The Byurakan surveys

Using objective-prism techniques Markarian and his associates [67M, 69M1, 69M2, 71M1, 72M, 73M1, 74M, 76M1, 76M2, 77M4, 77M5, 79M1, 79M2, 79M3, 81M2] have been identifying galaxies with strong ultraviolet continua. They found two main types: (i) the source of the ultraviolet radiation is the nucleus of the galaxy or (ii) sources of emission and ultraviolet continuum radiation are spread throughout the galaxy. The first type further subdivides into (a) Seyfert galaxies and (b) simple, bright-nucleus (BN) galaxies [73W]. The second type includes (a) simple irregular galaxies with active star formation and (b) intrinsically faint systems showing strong high-excitation emission lines. These are the "extragalactic HII regions" in [72S] and are also found in the lists of compact galaxies [71Z] because of their high surface brightness and small physical dimensions.

A massive compilation of data and literature on Markarian galaxies complete up to 1985 is presented in [86M2]. A review of the status of the first Byurakan survey can be found in [87L1], and that of the second Byurakan spectral sky survey [83M, 84M1, 84M2, 85M, 86M1, 88M1] is in [87M2]. A morphological study of 40 Markarian galaxies [75B].

Galaxies with UV continua, but also having double or multiple nuclei are listed in [75S1, 78P], with follow-up studies in [79P1, 79P2, 81K4].

9.1.3.3.2 The Calan/Tololo/Michigan surveys

The Tololo surveys [75S3] also use objective-prism techniques and line-emission classification criteria. The nature of the objects in the lists of [76S1, 77M1, 77M2, 77M3, 78M, 81M1] is discussed in [78B] with the conclusion that, while only about one-third of Markarian-type galaxies have sufficiently strong emission lines to be included in the Tololo listings, the latter contain about 2% class 1 Seyferts, 10% class 2 Seyferts, with the remainder being galaxies with emission lines produced by hot stars. 30 Seyferts class 1 galaxies are the first-reported objects in the Calan/Tololo thin UV prism survey for emission-line galaxies and quasars [89M2]; follow-up spectra are reported in [89M1].

Fairall [80F1] has divided the narrow-line emission objects into four groups based on morphological and spectroscopic studies of 47 galaxies from the Tololo survey. These groups comprise systems where:

(a) The entire galaxy is an emission-line source. These are generally blue ellipticals with Hβ/λ4959 just less than unity;
(b) the outer regions are emission-line sources. These are generally outlying HII regions in late-type spirals;
(c) only the nucleus is an emission-line source. Hβ/λ4959 is low and these systems appear to be related to class 2 Seyferts;
(d) multiple systems with high Hβ/λ4959.

9.1.3.3.3 The Case survey

The Case survey is low-dispersion objective-prism photographic survey with spectral coverage from 3300 to 5350 Å, reaching $B \approx 18^{\mathrm{m}}$; containing northern hemisphere blue and emission-line galaxies, as well as QSO candidates (and galactic blue stars) [83P1, 86P, 88P, 89P] and [84S2, 87S1, 89S, 90S].

9.1.3.3.4 Wasilewski survey

96 moderately strong emission-line galaxies found in 825 square degrees crossing the North Galactic Cap [83W]. CCD, spectroscopic and IRAS follow-up study by [89B].

9.1.3.3.5 The Kiso survey

The Kiso survey [84T, 85T, 86T, 87T3, 88T, 89T, 90T, 91T] uses broadband double imaging techniques to isolate UV-excess objects following earlier applications of this technique by Haro [56H] and others [81K3, 82M, 83S]. Review of survey status in [87T1]; spectral analysis [87M1].

9.1.3.3.6 Haro galaxies

Haro [86H], using both objective-prism Schmidt plates and three-colour direct plates, discovered 44 decidedly blue or ultraviolet galaxies, one quarter of which had obvious emission lines.

9.1.3.3.7 Kazarian galaxies

Five lists published by Kazarian and Kazarian [79K1, 79K2, 80K, 82K1, 83K1] contain UV-excess galaxies as identified on objective prism photographic survey plates. Spectral and morphological follow-up studies of such galaxies [77K, 78E, 81K1, 81K2, 82K2, 82K3, 84K, 85K1, 87K1, 87K2, 87T2]; while super-associations in galaxies with UV excess have been investigated by [83P2, 84P1, 84P2].

9.1.3.4 Peculiar and interacting galaxies

A preliminary scheme for grouping peculiar galaxies was given in [66A1, 66A2]. Independently, Arp and Madore [77A2] give 24 natural groups listed in Table 19. Karachentsev [72K], an the other hand, suggests a much more modest morphological classification for non-equilibrium systems as outlined in Table 20. Because of the very nature of peculiar galaxies none of these systems has found wide applications.

Ring galaxies, as a subset of peculiar and interacting galaxies, are widely recognized [59D], subdivided and internally classified as in [76T] as explained in Table 21; or as outlined in [86F] and Table 22; while [92F] present a report on classifying ring galaxies according to the morphology of their nuclear component alone. "Ringed" galaxies, on the other hand, are discussed in detail in [84B]; shells and rings around galaxies are reviewed in [85A]; warped disks and inclined rings are the topics in [91C1].

Table 19. Arp-Madore codings and descriptions of peculiar galaxies and associations, Arp [77A2].

Code	General description	Percentage
1	Galaxies with interacting (smaller) companion(s)	5.5
2	Interacting doubles (galaxies of comparable size)	12.6
3	Interacting triples	2.0
4	Interacting quartets	0.5
5	Interacting quintets	0.1

Code	General description	Percentage
6	Ring galaxies (or morphologically similar objects)	3.1
7	Galaxies with jets	2.4
8	Galaxies with an apparent (smaller) companion(s)	11.5
9	M51 types (companion at end of spiral arm)	2.0
10	Galaxies with peculiar spiral arm(s)	4.1
11	Three-armed and multiple-armed spiral galaxies	0.5
12	Peculiar disks (major asymmetry or deformation)	2.8
13	Compact (very high-surface-brightness) galaxies	6.4
14	Galaxies with prominent or unusual dust absorption	1.6
15	Galaxies with tails, loops of material or debris	3.5
16	Irregular or disturbed (apparently isolated) galaxies	4.2
17	Chain of galaxies (four or more galaxies aligned)	4.0
18	Group of galaxies (four or more galaxies not aligned)	4.9
19	Cluster of galaxies (only very conspicuous, rich clusters)	1.6
20	Dwarf galaxies (low surface brightness)	6.8
21	Stellar object with associated nebulosity	0.7
22	Miscellaneous (very rare or distinctive objects)	1.4
23	Close pairs (not visibly interacting)	11.4
24	Close triples (not visibly interacting)	5.6

Table 20. Karachentsev's classification of non-equilibrium galaxies [72K].

Type	Explanation
LIN	Galaxies exhibiting strong interaction in the form of – bridges = LIN(br) – tails = LIN(ta) – bridges and tails = LIN(br+ta)
ATM	Systems with two or more components in a common halo
DIS (n)	Systems with signs of distortion (n) individual components

Table 21. Theys' and Spiegel's classification of ring galaxies [86T].

Ring type	Description	Examples
RE	Crisp, elliptical ring with photographically empty interior	Arp 146, Arp 147, VII ZW 466
RN	Elliptical ring with an of-center nucleus	II Hz 4, Lindsay-Shapley Ring
RK	Ring with a single, very prominent knot in the ring; large-scale brightness distribution is markedly asymmetrical	I ZW 45, II ZW 028

Table 22. Few and Madore’s classification of ring galaxies [86F].

Ring type	Description
O-type	Smooth structure and centrally located nucleus
P-type	Crisp, knotty structure and often dispaced nucleus

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9.1.4 Properties of galaxies

9.1.4.1 Linear dimensions and true axial ratios

Linear diameters require knowledge of both the apparent diameters and the true distance. Apparent diameters are not uniquely well defined, and distances are still generally quite uncertain. The standard compilation of diameters defined at a variety of isophotes is RC3 (see general references). Redshifts combined with an adopted Hubble constant can be used to derive distances for galaxies well beyond (> 2000…3000 km s^{-1}, say) the obvious perturbations of nearby clusters (e.g., Virgo).

It has been demonstrated [70S] that the observed distribution of axial ratios for elliptical galaxies could result from an intrinsic distribution $R(a)$ where the $R(a) = 0.0$ for $0 < a < 0.3$ and $R(a) = 1.0$ elsewhere, or from an intrinsic Gaussian distribution with a mean ellipticity $< a > = 0.65$ and $\sigma \approx 0.2$.

9.1.4.2 Luminosity and absolute magnitude

The *general luminosity function* $\phi(M)$ is the differential probability distribution of galaxies of all types over absolute magnitude M. A distinction is often made between the *field* luminosity function and that derived for *cluster* galaxies ostensibly because of the well documented differences in the mixture of morphological types between these two extremes in the prevailing environment (density). With additional information it has also been possible in some situations to further subdivide luminosity functions according to morphological type T, viz $\phi_T(M)$.

A comprehensive and critical review of optical luminosity functions is given by [77F] which draw upon the published data from [61K, 61V, 70A, 73H, 74H, 75C, 76S, 76T], while [88B] includes data from [79K, 79S, 80D1, 84Y, 85C3, 86C, 87C, 87P, 87Y] and reviews both field and cluster luminosity functions. The dependence of luminosity functions on Hubble type and environment is also reviewed in [87B1].

More recent studies of nearby clusters including Leo, Dorado, NGC 1400, NGC 5044, Antlia, Virgo and Fornax are presented in [88F, 89F, 90F, 91F].

A commonly adopted (2-parameter) fitting function is the so-called "Schechter function" [76S] described by a power-law at faint magnitudes and an exponential cut-off at bright magnitudes, with the break between these two regimes occuring at a characteristic luminosity L_*

$$\Phi(L / L_*)\,\mathrm{d}(L / L_*) = \Phi_*(L / L_*)^{-\alpha} \exp(-L / L_*)\,\mathrm{d}(L / L_*)\,.$$

An infrared luminosity function based on IRAS data for a northern hemisphere sample of galaxies has been published in [86S], revised in [87S2] and updated in [96S].

The neutral hydrogen luminosity function has also been derived [93B, 96S1].

The absolute magnitudes for a select number of galaxies have been obtained from distances derived from the discovery of Cepheids from the ground and using the Hubble Space Telescope [97F] and applying the Cepheid Period-Luminosity relation [91M]. More distance galaxies can be calibrated absolutely once a value of the Hubble constant is adopted (modulo caveats concerning large-scale flow velocities and questions of group membership in clusters and/or small groups).

9.1.4.3 Surface brightness

Various operational definitions of surface brightness for galaxies are to be found in the literature. For instance RC2 (= [C-8] in subsect. 9.1.1) tabulates m_e', which is the mean surface brightness of a galaxy as seen through a circular aperture of a diameter chosen to contain exactly half of the total light. Alternatively, for spiral galaxies, S_e is defined [85D] as the central surface brightness of an equivalent pure exponential disk that would reproduce the total magnitude (B_T) and diameter (D_{25}) of a galaxy if seen face-on, and corrected for internal absorption and redshift effects.

Considerable interest is currently being focused on the lowest surface brightness objects [87B2] in order to establish their relative frequency and contribution to the total mass and luminosity content of the Universe.

For elliptical galaxies the central surface brightness can be defined by the best-fitting King model [66K]. Plots of this central surface brightness μ_0^{king} versus absolute magnitude, M_{B_T} suggest two separate sequences where, for gaint ellipticals the surface brightness *decreases* with *increasing* absolute magnitude; while for dwarf ellipticals the opposite is true. The outstanding apparent exception (to both relations) being the low-luminosity, high-surface brightness elliptical M32 (companion to the Andromeda galaxy, M31).

9.1.4.4 Masses

The methods for determining masses of galaxies and the resulting mass-to-light ratios are reviewed in [87T]. In many instances the only physics needed is the simple dimensional argument based on $M \approx V^2R/G$, where velocity support at a given radius is equated to the mass internal to that point. A variety of means of obtaining indicative velocities are listed below.

Rotation curves

Many rotation curves are flat or even rising out to large radii. Extending beyond the optical limits for measuring rotation, HI rotation curves suggest $M/L \approx 20\ldots30$ with some 75 % of the matter apparently contained in a dark halo [85B2, 85C2, 85V, 86K]. Reviews of the gas velocity fields are found in [78V, 79F, 79R1, 79R2, 81B2, 82B, 82R].

Linewidth of the 21-cm HI line

A large number of HI rotation curves can be found in [85V].

Velocity dispersion of the stars
Reviews of absorption-line kinematics in galaxies can be found in [79C, 81B1, 81I].

Planetary nebulae and globular clusters
Both planetary nebulae and globular clusters each act as point-source probes of the halo potential in Population II rich systems. Globular clusters appear to have larger velocity dispersions at the same radius as compared to the unresolved field population [86H, 86M]; projection effects may be involved as well as true dynamical differences.

Kinematics of companion galaxies
Companion galaxies can probe the outer halos of parent galaxies; however satellite-rich systems are relatively uncommon. A rare example is NGC 720 [86D] which has six physical companions.

The Local Group
Using the virial theorem, the mass of our Local Group has been variously estimated to be in the range $2\ldots7\cdot10^{12}$ solar masses, [55H, 85M] with the Milky Way contributing about 10 % of this mass out to a radius of 20 Mpc.

Binary galaxies
Velocity differences and projected separations have been statistically studied for pairs of galaxies [52P, 62P, 79P, 83W, 84B2, 84L, 85K, 87S1]. Under a variety of assumptions regarding the intrinsic eccentricity of the orbits the enclosed total mass can vary more than a factor of two. Removal of physically associated but unbound pairs, interlopers, and accidental projections are problematic.

Velocity dispersion in groups and clusters
Small groups and clusters have derived virial masses near to 10^{13} solar masses [61B, 83G, 84B1, 85B3, 85C1, 86B]; however, careful attention needs to paid to selecting only those systems that are bound [74M, 82K, 86V].

Superclusters
If bound, superclusters are typically required to have $10^{16\ldots17}$ solar masses contained within fiducial radii of 30…50 Mpc [61A]. This results in calculated values of M/L in the range 100…300 [80D2, 81F, 81H, 86P].

9.1.4.5 Mass-to-light ratios

Various methods for determining mass-to-light are reviewed in [87T]. For the visible portions of normal elliptical galaxies M/L probably lies in the range 7 to 20 [85B1, 85J]. The situation for spiral galaxies is more problematic because of their flat rotation curves extending (unconstrained) to radii where no further light is detected, at which point values of $M/L \approx 25$ are derived. Spiral galaxies with substantially lower M/L ratios may have experience recent bursts of star formation; high values can occur in disk galaxies in quiescent phases of star formation.

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9.2 Internal structure and dynamics of galaxies

In this section all masses *M* and luminosities *L* are given in solar units.

9.2.1 Stellar and gaseous content of normal galaxies

Reviews:
Populations in Local Group galaxies [k, m, n, p, u, v, af, 89H3]. Physical parameters along the Hubble sequence [94R4]. Elliptical galaxies [91D2]. On the understanding of the Hubble sequence [92L2], on dust and gas properties of galaxies [92S1].

9.2.2 The ellipticity of galaxies

The observed apparent ellipticities (axial ratios) of galaxies are used together with certain plausible assumptions on their intrinsic flattening (for spiral and irregular galaxies) or they are compared with frequency functions of ellipticities of spherical systems in order to derive their true ellipticities (e.g. Vol.VI/2c, p. 256). However, for elliptical galaxies the situation is more complex. Triaxial configurations have been assumed in order to explain the observations [e.g. Kormendy [a] p. 115]. On the shape of elliptical galaxies [92R1, 94N1], on the true shape of galaxies [92L1, 95W1].

9.2.3 Luminosity distribution

Reviews: [m, u].
Surface photometry of elliptical galaxies [89K5]. Galaxy luminosity classification [92O1]. Spiral galaxies [94A1, 92B1], inclination effects and internal absorption in spiral galaxies [92K1, 93P1, 94G1], opacity of spiral disks [ak]. Surface photometry of elliptical galaxies [92N1, 94G1]. Magellanic clouds [90W5].

9.2.4 Spiral structure

Reviews: [l].
Distribution of pitch angles [92R4, 93R1]. Galaxy bars and resonances to drive the spiral structure [93B1, 93B2, 93Y1], tidal interaction as the origin of spiral structure [93S1, 93V1].

9.2.5 Radio radiation of normal galaxies

9.2.5.1 Radio continuum structure

Reviews: [l, n, 86S1, 87G1].
Radio emission from normal galaxies [92C8]. Surveys of normal galaxies [92C1, 92C4, 92C8, 92H4, 93D3, 93D6, 93W1, 95D1, 95N1]. Magnetic fields derived from radio continuum emission [86S1, 93S1, 93W1, 95H1, 95S1]. The correlation between far-IR and radio emission in galaxies [92F1, 94H7, 94M2].

9.2.5.2 Neutral hydrogen (HI) in galaxies

Reviews are given by Haynes, Giovanelli and Chincarini [84H1], Haynes and Giovanelli [l], by Huchtmeier, p. 221 in [b], and by Roberts and Haynes [94R4]. A catalog with all extragalactic HI observations until 1989 was prepared by Huchtmeier and Richter [89H7].

Surveys [86H1, 86H2, 87R1, 88B1, 88H5, 88S6, 89D1, 89W1, 90F1, 90S5, 92G1, 92H2, 92W3, 93G1, 93H4, 93M1, 94B12, 94H6, 94R1, 94R5, 94S1, 94S10, 95A2, 95G1, 95H3, 95M1, 95T1, 95V4].

Observations:

- individual disk galaxies [88B3, 88B4, 88C2, 88H3, 88S1, 88S3, 88V1, 88V3, 88V4, 89B3, 89B6, 89C1, 89C7, 89D2, 89E1, 89I1, 89L1, 89O1, 89O2, 89S9, 89S12, 89T4, 89V1, 89V2, 89V3, 90B1, 90B4, 90C2, 90C3, 90D2, 90D4, 90F1, 90I2, 90P1, 90R2, 90S11, 91B1, 91C1, 91D3, 91E1, 91E2, 91H4, 91R3, 91S1, 91T2, 91V1, 91V2, 91W4, 92G1, 92P1, 93C1, 93I1, 93K1, 93K2, 93W3, 94B10, 94H4, 94H6, 94J1, 94M1, 94R3, 94S2, 94S5, 94T3, 94V1, 95B4, 95C1, 95D4, 95G2, 95J2, 95K1, 95L1, 95M3, 95M6, 95M7, 95R2, 95R4, 95S4],
- irregular galaxies [85H1, 87H3, 87S2, 87S3, 88B7, 89B6, 89C1, 89H6, 89S9, 90S5, 91P5, 91P6, 91W1, 92H5, 92L4, 92S2, 92S10, 93L2, 93M1, 93T1, 94T3],
- IRAS galaxies [87G1, 88M4, 88M5, 89H9, 89M5, 90M1, 90W2, 94R5, 95A2],
- elliptical galaxies [88B6, 88L1, 88K1, 89S7, 90B6, 90B10, 90M8, 90W2, 91R2, 92B9, 94H4, 94L3, 95H8],
- early-type galaxies [87B2, 88V5, 89V1, 89V2, 91E1, 91R2, 92B11, 93V4, 95B6],

- high-velocity clouds in nearby galaxies [88V1, 89W1, 94S2],
- HI haloes [82H1, 82H2, 88C7, 89I1, 90B7, 95V4],
- galactic warps [90B8],
- interacting galaxies [88V6, 92M3, 94H3, 94M3],
- intergalactic HI-clouds [87A1, 87S5, 89S6, 90D7, 90M3, 92H6, 94M3],
- galaxies in the zone of avoidance [87K1, 90C6, 90L1, 90M1, 92K5, 94C1, 94P1, 94S3, 95H7],
- Voids [89B7, 89H2],
- polar-ring galaxies [94R1, 95V2],
- new nearby galaxies [94K1, 95H7, 95K2],
- compact groups [88W6, 90R3, 91W3, 95P3].

Observations of cluster galaxies:

- Virgo cluster [85H1, 86H2, 87H3, 87S3, 88G2, 88P1, 88V4, 88W1, 88W2, 88W3, 88W4, 89H4, 89H5, 89H6, 89H8, 90C5, 90S5, 94C3, 94B8],
- Hydra-Centaurus cluster [87R1, 89A1, 92M1],
- Coma cluster [87G2, 89G1, 91C2, 91D1],
- Perseus-Pisces cluster [84F1, 87H1, 89C4, 89G2, 90C6, 94S3],
- Hercules cluster [88F1, 88F2, 95F2],
- Fornax cluster [95D2, 95H6],
- galaxy clusters [88M1, 91H1, 91H4, 91R1, 91W2, 92S3, 93H1, 93S3, 93V2, 94D2, 94O1, 95G2, 95M2],
- cooling flows [90M4, 94D2],
- HI-absorption in galaxies [88B9, 88D1, 88K3, 89V3, 92B1, 92C2, 92D4, 92S12, 93D4, 93S2, 94G1, 94O1, 94S1, 94T2, 95C3, 95D4, 95T2],
- HI in radio galaxies [89V3, 90E4, 90J1, 90M6, 90V2, 91I1, 92C3, 92W3, 93S2, 95D4],
- general [92B11, 93E1, 93M1, 93R2, 93V2, 94G5, 94T2, 95B5, 95C2, 95B8, 95H2, 95S9].

The so-called Tully-Fisher-relation is an empirical dependence between the luminosity and the dynamical mass (i.e. the maximum rotational velocity) of galaxies. The observed magnitude has to be corrected for extinction in our galaxy (depending on galactic latitude to the first order) and for intrinsic absorption within the observed galaxy (depending on the inclination and the morphological type of the galaxy). The indices 0 and i indicate that these corrections have been applied. The correlation between corrected absolute magnitude $M^{0,i}_{B,T}$ and the corrected full line width of the integrated neutral hydrogen profile $\mathrm{d}v_{0,i}$ - the Tully-Fisher relation:

$$M^{0,i}_{B,T} \propto \log \mathrm{d}v_{0,i} \;,$$

has been used as a tool for determining extragalactic distances [87B1, 87T1, 88K2, 89B1, 89M7, 90B3, 90F1, 90F2, 90F3, 90P1, 90T3, 91F1, 91F2, 91H1, 91K1, 91P1, 91P2, 92B1, 92B6, 92T1, 93F2, 93G4, 93P1, 93R3, 93T2, 94B6, 94F2, 94F3, 94R3, 95D1, 95S2, 95S10, 95V3]. Calibration and corrections for Malmquist bias [91W1, 93T1, 94P1] and galaxy shape [90F3, 92F1, 94F1, 95S2], using CO linewidths [92D5, 92S5, 94S11], for dwarf galaxies [94P1]. The lower absorption in the IR reduces the scatter of the (blue) TF relation [90F1, 91P2, 93G1, 93P1, 94B6, 94S2]. The most optimistic estimate for the accuracy of distances derived from the IR TF relation is 5 % [94B1] for the calibrator galaxies.

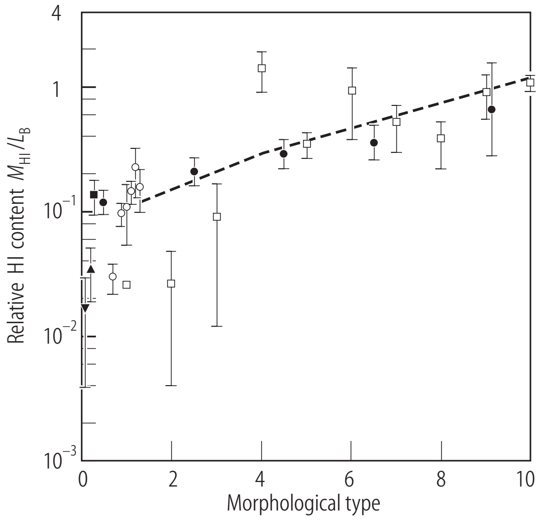

Fig. 1. The relative neutral hydrogen content as a function of morphological type. The distance-independent quantity M_{HI}/L_B is often used as the relative HI content to be compared with other global galaxian parameters. Here we compare the dependence of M_{HI}/L_B with morphological type for two galaxy samples. The averages per morphological type are given for the:

1) sample of nearby galaxies ($v_0 \leq 500$ km s^{-1}), data from [88H5] are shown as open squares,

2) sample of galaxies from [94R4] are given as filled circles.

3) sample of Sa galaxies [95H10] from the RSA [ba] are shown as open circles for the morphological subtypes as defined by Sandage [93H1]. The general trend of M_{HI}/L_B to increase with morphological type seems to be valid even for the Sa subtypes. However, the M_{HI}/L_B for the earliest subtype is very low as most Sa galaxies of this subtype are HI-deficient objects in the Virgo cluster and in nearby groups. The filled square represents the mean M_{HI}/L_B value for Sa galaxies outside the Virgo cluster, the filled upper triangle the mean for Sa galaxies within the Virgo cluster, and the filled lower triangle the mean for the Sa galaxies in the Coma I cloud [94G2]. The broken line represents the whole data set of "normal" galaxies and will be used in the following figures for comparison with different galaxy samples.

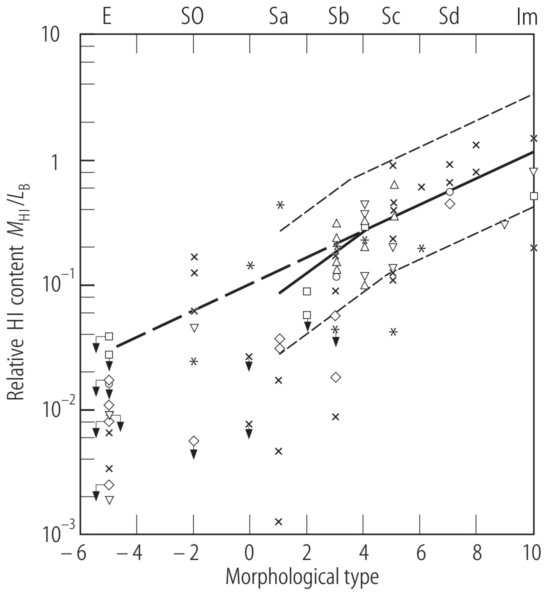

Fig. 2. HI-deficiency in selected groups of galaxies. M_{HI}/L_B versus morphological type is given for a selected sample of seven galaxy groups (from [bb]) [95H11] with early-type galaxies in their central areas.

Galaxy group: 21-1 (triangle down), 41-1 (square on top), 42-1 (triangle up), 42-13 (square), 51-4+4 (star), 52-7+7 (circle), Coma I group (x), upper limits are indicated by arrows. The full line represents the sample of nearby galaxies (see Fig. 1), the two broken lines mark the 95 % confidence intervall. Most disk galaxies from these selected groups fit nicely to the relation defined by the sample of nearby galaxies. However, a small number of early-type disk galaxies is definitely HI-deficient (up to two orders of magnitude for the Sa galaxy NGC4314 in the Coma I group). The HI detected elliptical galaxies show very low values of M_{HI}/L_B (compared to the thick broken line, an extrapolation of the HI-rich part of the relation for nearby galaxies).

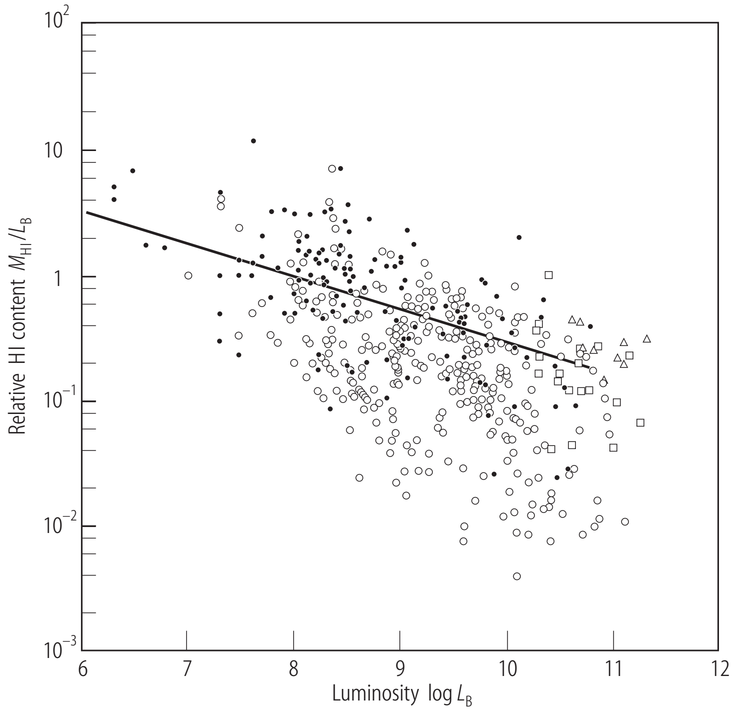

Fig. 3. HI-deficiency in the Virgo cluster. The relative HI content M_{HI}/L_B is plotted versus blue luminosity. The nearby galaxy sample (filled circles, [88H5]) is fitted by the full line. Virgo galaxies (open circles, [89H8]) partly fall in the range of the diagram occupied by the nearby galaxy sample. A considerable number of Virgo galaxies has M_{HI}/L_B values much lower than expected for their luminosity. This is the manifestation of the HI deficiency observed in several clusters and in a few nearby groups (see Fig. 2). Other manifestations of the HI deficiency are found in plots of M_{HI}/L_B against a number of different global parameters like morphological type, total mass, linear extent. Open squares indicate bright galaxies from the Hydra cluster [93H6].

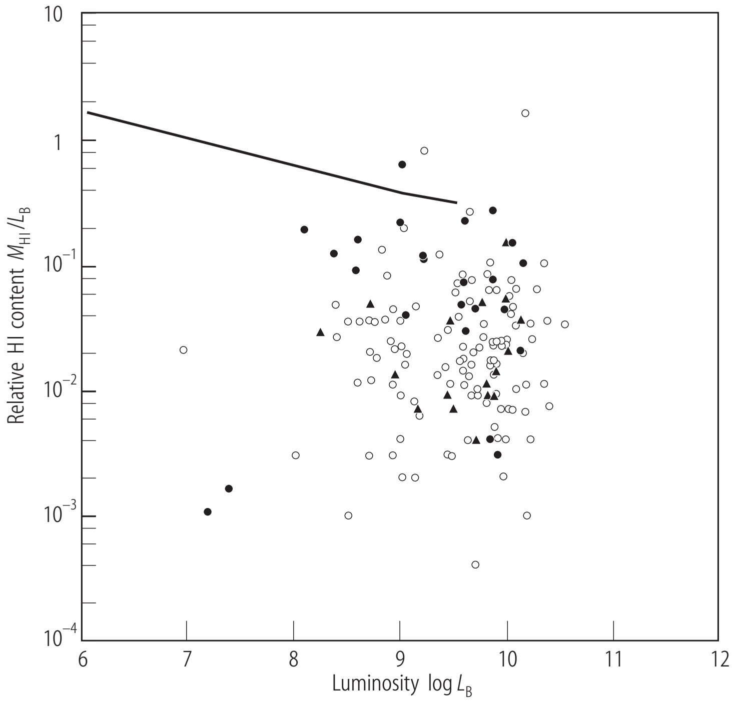

Fig. 4. The relative HI-content of elliptical galaxies. M_{HI}/L_B versus L_B is given for two complete samples of elliptical galaxies [95H8]:

a) elliptical galaxies from the RSA [ba], filled triangles,

b) elliptical galaxies with IRAS 100 µm fluxes ≥ 0.5 Jy [89K6], filled circles.

Upper limits for both samples are given by open circles. The full line represents the nearby galaxy sample [88H5], see Fig. 3. The great number of upper limits is partially due to lack of sensitivity. In general elliptical galaxies are poor in HI, low upper limits and detection are as low as three orders of magnitude below the expected values (full line) for disk galaxies. However, a few elliptical galaxies have M_{HI}/L_B values as high as spiral galaxies. These objects are in some way peculiar and tend to have blue colors (indicated by greater filled circles).

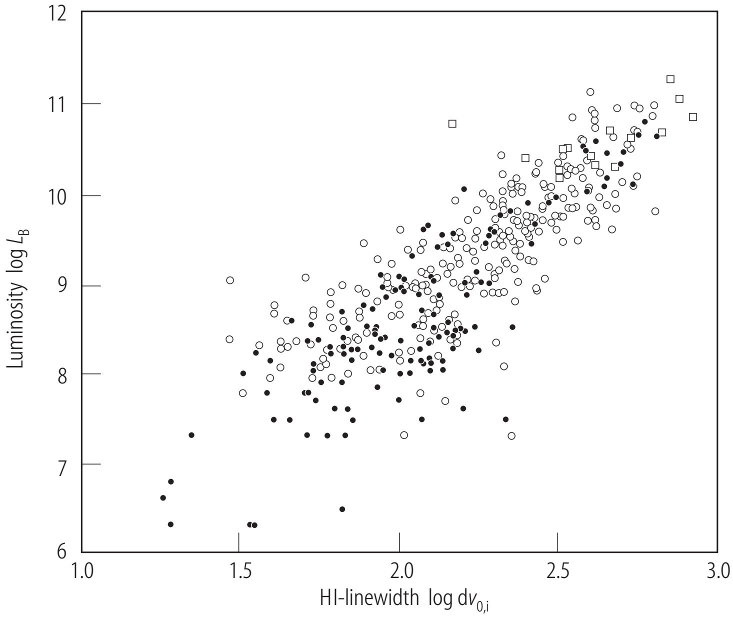

Fig. 5. The "blue" Tully-Fisher relation - logarithm of the corrected total blue absolute magnitude $M_{B,T}^{0,i}$ versus logarithm of the corrected HI-linewidth $dv_{0,i}$ - for the sample of nearby galaxies (filled circles [88H5]), the Virgo cluster sample (open circles [89H8]), and the Hydra cluster (open squares). Dwarf galaxies show a greater scatter due to uncertainties of their inclination values. Cluster galaxies show a higher scatter due to the greater observational errors (greater distances).

9.2.5.3 Molecules in galaxies

Reviews: [82M1, 89M3, 90S1, 91H3, 91Y1].

A catalog of galaxies observed in CO was prepared by Verter [85V1,90V3]. Conference proceedings are edited by Fabbiano et al. [p] and by Combes and Casoli [r].

Catalog of published CO surveys [91Y1],

Surveys [92D6, 93B4, 93B5, 93S1, 94D1, 95B1, 95C5, 95H2, 95Y2],

Catalog of CO studies in individual galaxies [85V1, 91Y1],

CO observations of individual galaxies [87H2, 87P1, 87V2, 88B8, 88C3, 88C4, 88C6, 88G1, 88I1, 88L1, 88O1, 88P1, 88S2, 88S4, 88T2, 88W5, 88Y1, 88Y2, 89A2, 89D2, 89K3, 89P1, 89P2, 89S1, 89S4, 89S10, 89S11, 89T1, 89V4, 89W3, 90E3, 90E5, 90H4, 90L2, 90L3, 92C6, 92D3, 92H1, 92I1, 92I2, 92K1, 92S6, 92S6, 92S7, 92T3, 92W2, 92W7, 92Y1, 93B1, 93B6, 93C2, 93D1, 93D2, 93D5, 93K1, 93R1, 93S5, 93S7, 93S10, 93T3, 93W3, 94A1, 94B1, 94G7, 94H2, 94J1, 94N1, 94S7, 94S8, 94S10, 94W7, 94W8, 95A3, 95B5, 95H1, 95H3, 95L2, 95M3, 95S3, 95S7].

CO in spiral galaxies [87S4, 87V1, 90S1],
- irregular galaxies [87T1, 92O1, 92W6, 93H4, 94L1, 95B3, 95T1, 95V6],
- early-type galaxies [89S2, 89T2, 90W7, 92W8, 94W3, 94T1, 95W1],
- elliptical galaxies [88H3, 90G1, 92W1, 92W4, 93S8, 94H5, 94L3],
- interacting galaxies [88C5, 89S5, 90D8, 90S13, 93S9],
- polar-ring galaxies [92C7, 92R1, 94W1],
- Markarian galaxies [90K3],
- Seyfert galaxies [87F1, 90M1],
- IRAS galaxies [87S1, 88M3, 89M6, 89S8, 90S11, 92B13, 92K3,92S1, 92S9,92T2, 93H5, 93L1, 93M2, 94T4, 95A2, 95V1].

CO emission from galaxies in clusters: [94B9, 94B10],
- Virgo cluster [87K2, 89K4, 92R3, 92W8, 94B8],
- Fornax cluster [95H4],
- Cooling flows [88B5, 94A3, 94B10],
- Molecules in galaxies [88H1, 89M3, 92N1, 94X1, 95H1, 95I2, 95J1, 95P1].

CO to H_2 conversion factor [90S1, 93O1].

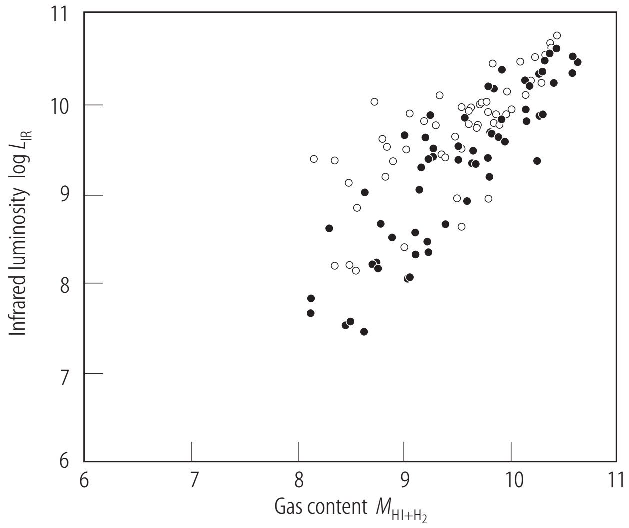

Fig. 6. Infrared luminosity and gas content (sum of neutral and molecular hydrogen the latter being derived from the CO-flux using the conventional conversion factor CO-flux to M_{H2} [91Y1]) for normal spiral galaxies in the field and in groups (sample of selected nearby galaxies and the Virgo cluster sample [87K2, 89K4] follow the same relation. Selected nearby spiral galaxies are given by black dots, Virgo cluster galaxies by open circles. The infrared luminosity and the dust mass have been calculated following [89Y1].

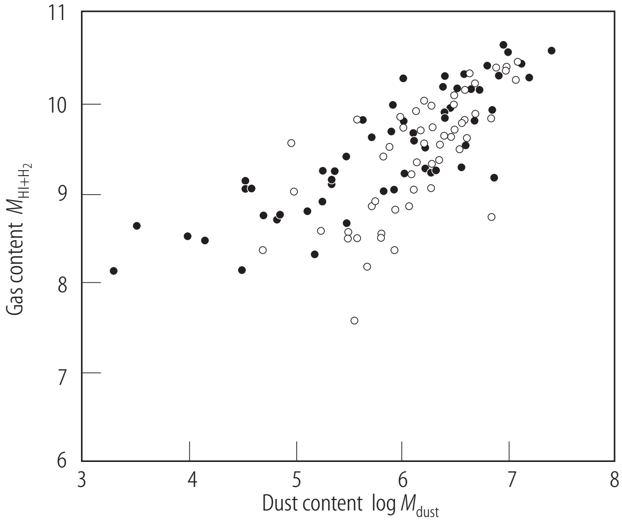

Fig. 7. The (total) gas to dust ratio in the field (dots, nearby sample as in Fig. 6) and in the cluster (open circles for the Virgo sample, see Fig. 6) seems to be very similar. The dust mass has been derived from the 60 μm and 100 μm IRAS fluxes. The solid line represents a gas-to-dust ratio of 1000.

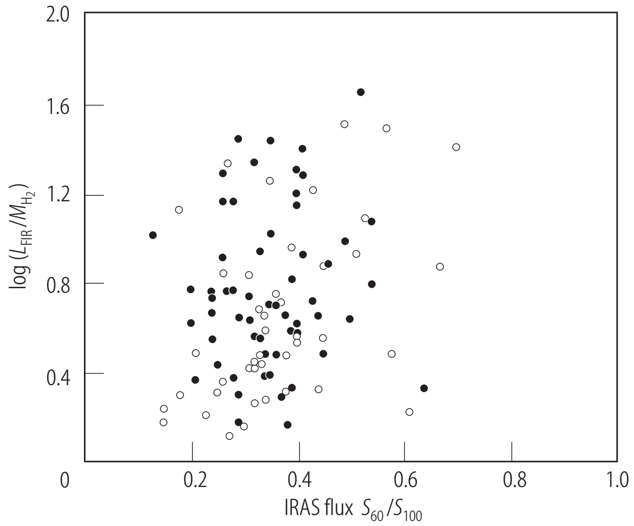

Fig. 8. The quantity $\log(L_{FIR}/M_{H2})$ has been considered as a coefficient of star formation in galaxies. This quantity is plotted against the ratio S_{60}/S_{100} of IRAS fluxes at 60 μm and 100 μm which corresponds to a temper-ature scale (ca. 25 K to 40 K for most of the normal galaxies), dots for the nearby galaxies, open circles for the Virgo sample. Interacting and merging galaxies (open triangles from Young et al. [91Y1]) tend to show definitely more FIR emission and higher temperatures.

General discussion [87V1, 88S5, 88V7, 90D3, 90S6, 90W3,90W4, 92C5, 93G3, 93S13, 94C4, 95A1, 95H4, 95S10].
Extragalactic megamaser [87H2, 87M1, 88M2].
Quasars [93B7, 93S4, 94O1, 94W6, 95I1].

9.2.6 Rotation, kinematics, dynamics

Textbooks were written by Saslaw [d] and by Binney and Tremaine [h]. Reviews [o, i, t, ab]. Conference Proceedings on this topic are to be found in [i, q, r, t]. Reviews are given by Contopoulos and Grosbol [89C6]. Warps [92B6], gravitational interaction [92B3]. Dynamics of elliptical galaxies [93B1, 93M1], and of spiral galaxies [92B1, 92B2, 94H1]. Evidence for counterrotation [93D1, 94M1]. Early-type galaxies [94C1].

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e Galaxy distances and deviations from universal expansion (B.F. Madore, R.B. Tully, eds.), NATO ASI Ser. C **180**, Dordrecht: Reidel (1986).
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9.3 Galaxies with special peculiarities; pairs, groups and clusters of galaxies

Abbreviations of satellites:

COBE	COsmic Background Explorer
EXOSAT	EXOsphere SATellite
GINGA	3rd Japanese X-ray satellite
GRO	Gamma Ray Observatory
HST	Hubble Space Telescope
IRAS	InfraRed Astronomical Satellite
ROSAT	ROentgen SATellite
TENMA	2nd Japanese X-ray satellite

9.3.1 Galaxies with special peculiarities

Most of the progress in this field has come from satellite observations (EINSTEIN, IRAS, EXOSAT, TENMA, GINGA, ROSAT, HST, GRO) as well as extremely sensitive ground-based observations, which have provided already or are presently providing data to yield complete samples of galaxies, both normal and those which seem peculiar in various ways. Especially the whole sky surveys conducted by IRAS, ROSAT and GRO as well as the dedicated observations by HST are still providing us with good data, which will take years to digest. On the other hand, the deep CCD and optical line surveys of special fields at various wavelengths together with sensitive radio surveys are also giving us increasingly better data, much of which is still unpublished. The new observations of the microwave background fluctuations of the COBE satellite also motivate us to reassess our ideas for galaxy formation as well as the formation of the large-scale background of the distribution of dark matter as well as galaxies.

In the following we provide lists of relevant data papers on galaxy surveys on the basis of first satellite data, then ground-based observations, ordered by wavelength:

IRAS: [85A1, 91A3, 91B20, 88C1, 90C2, 86C2, 90D5, 91D7, 91D8, 86F3, 91F8, 88F2, 92G6, 87G2, 84J2, 86K5, 86L4, 89L3, 88M4, 91R5, 88S2, 87S7, 89S8, 91S14].
ROSAT: [92B11].
EINSTEIN: [92E2, 87F1, 88F1, 92F1, 90G2, 91G5, 92G6, 92K5, 88M1, 91P12, 91S16].
GRO: [93S1].

Ground based observations:

Radio continuum and lines: [85A3, 88C6, 91C11, 91D7, 88K5, 89R3, 84S1, 84S2, 84S3, 85S1, 83S3, 84S7, 91W10, 89Y1].
Molecular lines: [91D8].
Low surface brightness galaxies: [90B4, 85B6, 86B4, 83D1, 92K6, 82L1, 92S9, 88S5, 92S10, 90S7.
Dusty ellipticals: 82A1, 88B5, 92B9, 87B3, 85E1, 82L2, 92M8, 85S9].
Boxy, disky ellipticals: [88B4, 89F4, 85L1].
Blue compact dwarf galaxies: [84G1, 86G3, 90I1, 91K6, 92M6].
Optical and infrared broad band and spectral line work: [86B1, 84B4, 87B4, 84D1, 83E1, 91I4, 87K2, 88K2, 89L5, 90L3, 87M1, 83M3, 84M1, 84M2, 84M3, 85M1, 85M2, 85M3, 86M1, 87M3, 88M3, 92M5, 84P1, 84S1, 84S2, 84S3, 85S1, 89S10, 90S12, 86T2, 91T5].
Accurate positions: [82K1, 84K2, 85K2, 84M5, 88N1, 90S6].

Many of these data are now available through databases maintained by NASA or at Strassburg, or through CD-Roms.

9.3.2 Pairs of galaxies

New lists: [92S8, 83W2].

9.3.2.1 Observations

Interaction of galaxies has been studied in numerous examples, and has led to an understanding that many interesting and peculiar phenomena can be linked to interaction and merging. There is also an increasing recognition that the gas and the stars have to be studied separately, but are closely linked through the newly formed stars that often then produce a deeper potential well than given by the older stellar population. In many of such observations the young stellar population is studied; in the resulting intense short phase of star formation, often rather massive stars dominate the visible phenomena, in the radio by the young radio supernovae and young supernova remnants, in the infrared through excited fine structure lines, in the optical through the HII regions and their stars, and, in the X-rays, through hot gas emitting free-free radiation as well as inverse Compton radiation. General discussions were done in [92B6, 91B17, 91C5, 92D3, 90G3, 91G5, 86H4, 91J4, 84J3, 85J2, 91K4, 91K8, 84K3, 89L3, 91L7, 90M10, 91M8, 91M9, 91N3, 91P5, 90S4, 91S8, 91T7, 91T8, 91V1, 91V5, 88W9, 91X1, 91Z3].

Observations have been made of many objects and features:

Warps: [91F6, 92K1, 92Q1].
Tidal bridges and tails: [88C4].
Shells: [88C2, 83M1, 88S6, 90T1, 87W1].
Polar ring galaxies: [89M2, 90S1, 84S5, 83S1, 90W2].
Ring galaxies: [92A2, 82F3, 86F4, 90Z2].
Interaction driven spirals: [91C1].
Merging: [91A1, 91A2, 89B4, 88C3, 90D6, 91F1, 91F8, 91G6, 88J1, 91M1, 89M7, 88P4, 89S9].
Counterrotating cores: [88B3, 90B3, 91B10, 91C12, 88F4, 91R3].
Dust Lane ellipticals: [88B5, 92B9, 91B21, 85L1, 86M5, 87M6, 83N2, 83S2, 89V2, 88V1, 83W1].
Multiple nucleus galaxies: [90A1, 82A1, 86L3, 85S7, 85T4].
Spheroidal versus disk system: [89B3, 91F4, 91F5, 88R1, 92R2, 90S5, 87S4].
Absorption line studies: [92B1].

9.3.2.2 Theoretical concepts

General discussion of the underlying physics were done in [R92B1, R90B1, R87S1, R91Z1, 90B1, 92B4, 92B6, 91C2, 92G2, 83G2, 92J2, 84K1, 92K8, 91N1, 90N1, 83N1, 86N4, 91N5, 82P1, 92P7, 90R4, 90R5, 87S3, 91S8, 85S8, 89S11, 91S18, 72T1, 90V2, 82V1, 83V1, 83W2, 83W3, 91Z2].

Starbursts: as will be discussed below, one of the main effects of interaction between galaxies is a starburst, the rapid formation of large numbers of massive stars; the evidence is increasing that during such phases indeed mostly massive stars are formed, with estimates ranging up to a supernova rate of a thousand per year.

Warps: warps in galaxies can clearly be the result of tidal interaction, but also represent stationary states of orbits in triaxial systems [R92B2, 82A1, 92Q1, 84S6].

Tidal bridges and tails: ever since the seminal paper by the Toomres [72T1] the effect of tidal torques has been found through bridges and tails in many examples, with the shapes of the galaxies reminiscent of antennae, superantennae, mice and the like. Often the original nuclei of the two partner galaxies are still recognizable.

Shells: interaction between rather unequal partners with little cool gas produces easily shells and arcs around elliptical galaxies. These shells may persist for quite some time [R85A1, 88C2, 87D7, 90H3, 92H2, 87H3, 87L5, 84Q1, 90T2, 91T6].

Polar rings: interaction with gas-rich galaxies can produce a galaxy with two different angular momentum vectors in the gas/star distribution; one extreme form of this are polar rings [87B3, 90S1, 86S5].

Ring galaxies have been viewed as the product of the near center collision of two galaxies, when one partner with an extended disk shows a tidally induced ring resulting in strong star formation, much like a stone thrown into water produces a ring that spreads out [R85A1].

Interaction driven spirals: as already realized early, spiral structure is not just another way to transport angular momentum out of a single disk, but is also the natural result of tidal torques acting on a disk as the result of the passage of another galaxy.

Merging: when two galaxies merge, a stellar disk component may be left in a galaxy which otherwise seems a perfect elliptical galaxy. Similarly, a gas-rich disk can be left with a strong dust fraction. Such nuclear dusty disks are sometimes related to a recent feeding event of an active nucleus previously dormant [R82B2, 82A1, 91B3, 88B1, 82C1, 88N3].

Counterrotating cores: they can result when the angular momentum vectors of two merging galaxies are nearly opposite to each other [90B2, 92S14, 91V8].

Boxy ellipticals: such bodies can be understood through the two-dimensional distribution of the population of stars in phase space, and as a natural result of cannibalism or merging [R82B2, 87B2, 88B2, 85B5, 89L6, 88N2, 89F4, 88W1].

Multiple nuclei: the high central regions of high stellar density can survive upon merging of two galaxies, an effect especially noted in a dense environment of galaxies among the very bright galaxies in clusters of galaxies [87N2, 89P4]. Orbital decay of central black holes can be quite rapid [92F4].

Dissipative collapse: during merging the gas undergoes a strongly dissipative collapse which leads through a strong starburst to the stellar distribution typical of an elliptical galaxy.

Spheroidal stellar component versus disk: merging clearly leads to thick or nearly spherical systems for the stellar systems, while a gas-rich disk of high angular momentum may be preserved and then forms a flat disk around a spheroidal component of possibly quite different angular momentum vector [R82B2].

Bar formation: the interaction and slow accretion between two components can lead to the formation of bars, and may not lead to a simple flattened ellipsoid as a standard case [R85A1, 91B4].

Formation of globular clusters: merging of galaxies with gas easily leads to the new formation of globular clusters; this may explain the globular cluster population in large ellipticals [92A6, 92D5].

9.3.3 Groups of galaxies

9.3.3.1 Definition

New tree algorithms have led to new lists of groups, based on much more complete catalogues of galaxies with redshifts. One problem with any such algorithm is that we observe only one velocity component out of three, and at the same time have to suspect that the phase space distribution of galaxies in groups is not typically isotropic and is also not really well approximated as being stationary with time; this latter argument is especially important, since the application of the virial theorem to derive masses of groups or clusters critically depends on the assumption that the entire system is stationary - the hypothesis that the evolutionary time scale may be close to the Hubble time for groups or clusters would invalidate many arguments on the mass to light ratio, but would not necessarily lower the implied mass [92D4, 83G1, 92G4, 89M1, 88M8, 92P3, 89R1, 87T2].

One implication is that it becomes difficult to argue what are field galaxies [90B6].

That coupled with small number statistics implies that any such results can only be trusted when the observational methods have been tested against N-body code calculations describing through some model the true three-dimensional distribution and evolution of galaxies in a group.

9.3.3.2 Structure

Small groups of galaxies, apparently observable through absorption lines in quasars in their early stages, show evidence of strong interaction between their respective partners leading to feeding of activity - both starburst and active galactic nuclei (AGN) - and merging, so that the dominant galaxy can be optically inconspicuous, but gravitationally totally dominant as seen in extended X-ray emission [85B3, 92D7, 91F3, 89F5, 88F6, 88G3, 83G5, 91H1, 88H2, 85K1, 89K4, 91O2, 87R1, 85S3].

The evolution also can lead to merging and growth of a dominant galaxy with a large halo extending throughout the group. The N5846 group is one well studied example for this [84B2, 85B1, 91B8, 89B6, 91B15, 91C7, 91H3, 84N3, 91Z1, 91Z2].

This interaction between group partners and the resulting feeding of activity may also explain the observation that radio sources and AGN in their clustering properties are between groups and clusters [R82B1, 92B3, 91C8, 87M2, 90M5].

9.3.3.3 The Local Group

Still new members of the Local Group are occasionally discovered, while important new data about known Local Group members are assembled [91C13, 92L1, 92S7, 91W2].

Also, the two large Local Group galaxies, M31 and our Galaxy, both show evidence of a central black hole; also in the tidally truncated galaxy M32 there is such evidence [92K7].

The Local Group also provides evidence of the presence of dark matter in dwarf galaxies, where single stars can be studied [87A1, 85S5].

9.3.4 Clusters of galaxies

From EINSTEIN and ROSAT data as well as from new (especially southern) optical data many new clusters have been identified. Also, for other X-ray satellites with good spectral capabilities like GINGA or TENMA extensive data on known clusters have been obtained [89A1, 91B17, 92B13, 92E2, 91F1, 90G1, 90M9, 89M3, 87U1].

There are also many new optical and radio surveys [86A1, 88A1, 91C15, 88D4, 89F3, 90H5, 87J1, 91J5, 84L1, 83L1, 91L6, 82O1, 91O5, 92O1, 92P5, 92P6, 90R2, 89R2, 90S7, 85S6, 87S9, 87S10, 87S11, 91S17, 85T4, 89V1, 91V6, 91W1, 90Z1].

The extensive X-ray data have revealed that in clusters, different from single galaxies, the dark matter is most concentrated, less concentrated are the galaxies, and least concentrated is the hot gas, in mass larger than the galaxy population. The dark matter is consistently inferred from integrating the hydrostatic equation from the hot and extended gas measurements, and also from the gravitational lensing of background galaxies leading to the conclusion that near 90 % of the gravitational mass in clusters is in dark matter [R82F1, R88M1, 92A1, 92A5, 92B10, 87C5, 89D1, 90E1, 91E1, 91E2, 91E3, 86F2, 89F2, 92G3, 88H3, 89H8, 92I1, 84J1, 88S4].

The intergalactic gas in clusters has been enriched by recycling through early starbursts and star formation in galaxies [92A1, 91A4, 92A4, 91B15, 90B8, 91D1, 86N5, 88O1], which presumably leads to a direct ejection of hot gas from the energy input by the many young supernovae - as seen in, e.g., M82, see below. This extended hot gas cools through the observed radiation and thus slowly accretes towards the center in many clusters, producing a cooling flow [92A1, 91A6, 91B6, 92D6, 82F1, 82F2, 92H3, 90J2, 86M3, 89N3, 84N3, 90P4, 85R2, 92S3, 91T9, 91W5, 91Y4].

The structure and its evolution, as well as the luminosity function of galaxies in clusters yield important clues on their history and formation [R82B1, R88B2, 91B8, 91B15, 89C3, 91D4, 91E9, 91H6, 86K2, 90K1, 90K4, 91P4, 91P8, 89S5, 85Y1, 86Y1, 92Y3].

Cannibalism and merging as well as slow continuous star formation in the central dominant galaxy can lead to giant ellipticals with extended stellar halos, extending throughout the cluster, the cD galaxies [85B3, 85C1, 91J5, 91K3, 84L1, 83M4, 90R3, 91V2].

The hot gas in clusters is capable of stripping the outer gas from traversing galaxies leading to a deficiency in HI but a weaker deficiency in the molecular gas more centrally concentrated in each galaxy [92B2, 92B5, 91C4, 90C4, 87G1, 85G3, 88G5, 86H3, 91J1, 88M2, 84T2].

Dynamos strengthen weak seed magnetic fields in the intergalactic gas in clusters to measureable and quite appreciable strengths [92B5, 91C6, 87D4, 90K5, 91K5, 92R3, 89R5, 92T1, 91T10, 90V1, 91V4].

Substructure of the galaxy distribution both in real space as in velocity space can lead to an appreciable overestimate of the true velocity dispersion when averaging over different substructure elements [92D4, 91F1, 92G1, 91R4, 88W7].

The strong interaction, partial merging and stripping of galaxies may explain the alignment that is sometimes apparent in the orientation between galaxy forms [90K2, 91P11, 87V1].

Arcs of not understood origin may be sometimes gravitational lenses, light echos, sometimes gaseous features, and, occasionally, stripped parts of the stellar population of galaxies like the shells and ripples seen around ellipticals [91E8, 89H2, 89H3, 87K1, 88K1, 87M5, 91S9, 87S8, 88S10].

Special studies have been dedicated to nearby clusters like Virgo [R88B2, 84B5, 85B4, 91B12, 90C4, 88G2, 88G5. 86H3, 86H5, 89H7, 89I1, 91J2, 88K4, 89K2, 87K3, 91K9, 82K2, 88P2, 91R2, 91S4, 84S4, 85S2, 86S6, 89T1, 85T1, 85T2, 91T2, 88W3, 88W4, 88W5, 88W6], and Coma [91D4, 83G3, 88H3, 89H8, 90K3, 90R1, 91R2, 91T10].

9.3.5 Superclusters and large-scale structure

9.3.5.1 Superclusters

The discovery of the fundamental plane of the properties of elliptical galaxies (interpreted as a consequence of the virial theorem), related to their structure and also globular cluster population, has made it possible to study the spatial distribution of galaxies with higher accuracy than possible with spectroscopy alone [R90B1, 87D1, 87D2, 92D5, 87D6, 89F1, 86L5, 91L6, 90N2, 90R1, 91R2].

There are, as a result of the extended surveys, now catalogues of superclusters, as well as a large body of data on known superclusters [R83O1, 91A3, 84B1, 86B1, 87C4, 91D3, 84E1, 86E1, 87E1, 88E1, 89E1, 91E5, 91E6, 91E7, 91F2, 86F5, 85G2, 86G1, 86G2, 89G3, 89G4, 88G4, 86H2, 88H1, 91H4, 82M1, 90P3, 92P5, 91R1, 88S8, 84T1, 88U1, 91V4, 91W4, 90W3].

9.3.5.2 Large-scale structure beyond superclusters

Thus the many surveys in number counts on the sky and in spectral lines as well as the studies of the distribution of clusters have shown that the universe has structure on rather large scales; observations like redshift surveys, source counts at various wavelengths, simple interpretative modelling [R88B1, R91G1, R83O1, R88O1, R88R1, 89B2, 88B6, 87C3, 92C4, 91C10, 90C5, 89C4, 86C3, 88C7, 89C5, 91C14, 89C6, 90C7, 91D2, 88D5, 91D6, 90E2, 91E4, 83E1, 88E2, 90F1, 92F2, 91F7, 90F2, 88F3, 89G2, 89H1, 87H1, 91H3, 89H6, 83H1, 90H6, 91I2, 91K1, 86K3, 89L1, 86L1, 88L3, 89L2, 91L1, 86L4, 88L4, 90L4, 92L4, 90M1, 90M2, 90M3, 90M4, 92M1, 92M3, 91M7, 89M4, 89M5, 86M4, 88M8, 91O4, 91P2, 86P1, 88P1, 89P1, 91P6, 86P2, 91P10, 86P3, 92P5, 87R2, 92R5, 92R6, 86R2, 86R3, 91R5, 92S1, 87S2, 89S2, 90S2, 92S2, 90S3, 89S4, 86S4, 92S20, 90S13, 92S22, 92S23, 88S12, 91S19, 88T1, 88T2, 92V1, 91W3, 91Y1, 91Z4], theory [85B2, 91C9, 87D3, 89D4, 90G4, 86K1, 91L2, 91M2, 92P4, 92S5, 84W1, 91W6, 91W7, 91Y2].

The structure is maybe best described as a multitude of bubbles or voids, with clusters of galaxies making up the walls and superclusters the filaments when three bubbles touch in such an analogy [91B2, 90B6, 91B14, 89D2, 85H1, 91K2, 90M8, 90O1, 92P1, 91P3, 92P2, 92R1, 91S6, 92S6, 86T1, 91V7].

This structure is clearly related to the physics of galaxy formation, possibly also to the early activity of quasars [91B1, 91B11, 91B13, 84D2, 84D4, 86D1, 88D3, 90D3, 92I2, 89K3, 91K7, 86R1, 92S4, 89S5, 91Y3, 88Y1].

Locally the structure is best described as large scale streaming in a certain direction, also sometimes referred to as motion towards a great attractor [90B10, 87D5, 87D6, 88D5, 91D5, 91H5, 88L6, 92M1, 92S11].

Many scientists favor models in which the X-ray and Gamma-ray background is dominated by AGN, and their clustering properties then reflect presumably the early evolution of galaxies; the heavy elements observed through emission lines in quasars are clearly the product of intense star formation in the inner part of the host galaxies [R92F1, 92B10, 92B13, 91C3, 92D1, 91H2, 91P12].

The recent measurements on the microwave background fluctuations and anisotropy [R92R1, 92B7, 92B8, 92B12, 92S13, 92S24, 92W1] have led to an increasing narrowing of the range of possible models [R92C1, R92D1, R91K1, R81K1, R91P1, R87T1, 92A7, 82B1, 92C1, 92C2, 83D2, 84D3, 84D4, 88D1, 88D2, 89D3, 92G5, 92L2, 91L4, 91M4, 91M10, 86N2, 86N3, 89N2, 90P1, 86S7, 92T1, 91V3, 92W2, 92W4, 87Z1]. Simple cold dark matter models appear to be ruled out.

A final judgement is still out, and one of the fundamental difficulties clearly remains that there is no clue what the nature of dark matter really is.

9.4 Evolution of galaxies

Subsections 9.4.1 - 9.4.4 review the literature up to 1992. An update covering the literature up to 1997 is given in subsection 9.4.5.

9.4.1 Formation of galaxies

The formation of galaxies has to be seen in the context of the limitations now set by the anisotropy measurements of the microwave background, discussed above. It appears that gravitational instability coupled with strong dissipation first leads to spheroidal systems, possibly driven by interaction with neighboring systems, and then to disk formation much later [R90B1, R82B2, R92D1, R91P1, R87T1, R91Z1, 91B1, 87B1, 91B5, 89B5, 91B8, 91B9, 90B5, 82B2, 85B5, 86B2, 91B13, 88B7, 90B9, 92B14, 90C1, 86C1, 89C2, 86C4, 92D2, 90D7, 92F5, 89G1, 92G5, 91H7, 91I1, 92K3, 88L1, 88L2, 91L5, 91O3, 91P1, 90P2, 82P2, 85R1, 86R1, 90R4, 92S13, 88S11, 88T1, 91U1, 92W1, 91W6, 92W4, 90X1, 92Y1].

These disks slowly accrete gas towards the center, and thus can produce exponential disks, central starbursts, and also, central feeding of an AGN [R82B1, 91B1, 90D4, 92H1, 89H5, 92J3, 90L1, 87L3, 87L4, 84N1, 91O1, 90S8, 83S3].

The gravitational potential of the dark matter has a core radius of similar scale as the turnover radius of the present rotation curve, and the dark matter appears to be "pulled" in by the deeper gravitational well of the dissipative matter [86B3, 86F1, 88F5, 92J1, 86K4, 92R4, 88S7, 86S3].

Elliptical galaxies, in addition, can have global accretion both from a cooling flow in gas (see above), and from merging with smaller satellite galaxies, leading in extreme cases to the central cD galaxies in clusters, and also to the activity associated with a well-fed AGN at the center [R90B1, R82B2, 92B6, 89B5, 82B2, 85B5, 86B2, 91F9, 92F5, 85G1, 83G4, 91H7, 92K8, 91L7, 85M4, 86M2, 85M5, 91N3, 91N4, 84N2, 84N3, 87P1, 90R3, 92S15, 91T4, 86T3, 90V2, 83W3].

9.4.2 Evolution of galaxies

The general topic is dicussed in depth in [R92K1, R87S1, R83S1, R91Z1, 92B6, 91B17, 91C2].

The partitioning of the stellar population into bulge and disk through the formation of galaxies can lead later to different evolutionary patterns, since the bulge to disk ratio appears to be a prime parameter to order galaxies [R84G1, R92K1, 91A5, 90B7, 92C4, 90C5, 90C6, 92D5, 89G1, 86I1, 90K6, 87M4, 86S1].

Accretion from outside may influence their evolution over much of their age [92A3, 91G4, 88K3, 91S11, 92Y2].

Galaxies evolve by consuming gas, thus changing the chemical abundance distribution in the interstellar matter (ISM), by slow overall accretion throughout the disk, as well as by recycling disk gas through the halo [89B7, 91D1, 88D6, 88D7, 88D8, 92F3, 88F3, 89F6, 91F10, 89G5, 87G3, 91K10, 86K6, 86L2, 87L2, 90L4, 92L4, 91M3, 92M5, 92M7, 91O3, 89P3, 90S11, 91S13, 92S19], possibly by a general galactic wind driven by cosmic rays [91B16], by interaction with other galaxies (see above), and finally by merging with other galaxies (see above). The inner regions of galaxies are usually most sensitive also to the effect of a central AGN [R82B1, R88B2, 85A4, 90G3, 89H5, 87H5, 92K7, 90R5, 89S1, 91T4], while a central starburst can eject matter at high velocity from the galaxy [90M6, 89R4]. A central starburst may lead unescapably to the formation of an AGN [91J3, 91J4, 87K4, 90L1, 88N4, 85T3]. An instability of the disk to the formation of spiral and circular patterns - in addition to spirals and rings being caused by bars and interaction with other galaxies [86A2, 82E1] - can increase star formation [91B15, 84M4].

9.4.3 Starbursts

Starburst galaxies are galaxies in which the star formation rate is at present far above the long-time average. Often such a starburst is confined to the central region in a galaxy (see subsect. 9.4.4.2]. The extreme far-infrared luminous galaxies detected by IRAS may be a combination of starbursts and AGN energy input, with the quasar hidden at normal wavelengths by dust clouds, thus a "shrouded quasar" [89C7, 89C8, 89H4, 89I1, 89I2, 92J2, 84J3, 85J2, 92K2, 92L3, 92M4, 88N4, 88N5, 88N6, 89P5, 87S1, 88S2, 88S3, 89S1, 91S15]. At present the judgement is still out up to which level of infrared luminosity a galaxy can be interpreted as a starburst, but scaling from nearby starbursts, like M82 [85A2, 90H7, 85K3, 90K9, 88L5, 86N1, 87N1, 89P2, 91P13, 91S7, 91S10, 91T3, 91T7, 90T3], up to a supernova rate of 1000 supernova events per year have been estimated, consuming an enormous amount of cool gas. The energy input of such an extreme population of young stars - we note that massive stars put as much energy into the interstellar medium through their winds as later by their supernova explosion - is such that the interstellar energy densities can be several orders of magnitude higher than in the rather quiescent solar neighborhood. This extremely high energy often leads to a break-out of the hot component of the interstellar gas perpendicular to the disk, as seen in M82, where the X-ray emission extends many kpc up and down from the disk, sometimes referred to as a superwind [91B18, 87H2, 90H2, 92H4, 89N1, 89S12, 88Z1], although this phenomenon resembles more an explosion in a stratified atmosphere. On a small scale such break-outs appear to be to quite common even in normal galaxies, whenever the local star formation energy input surpasses a critical level, when hydrostatic equilibrium can no longer be maintained. Clearly, cosmic rays contribute strongly to the hot gas component breaking out, and may cause an additional acceleration of the hot gas far above the disk by dissipating their energy through reconnection and wave dissipation. Starbursts are often used successfully as a paradigm for central starformation in galaxies, with starbursts and quasar-activity often competing [88N4, 91S3, 88Z1].

9.4.4 Star formation activity in normal galaxies

9.4.4.1 Tracers of star formation

Star formation and the excitation of the ISM by the young stars, the explosion of stars and the subsequent acceleration of energetic particles leading to nonthermal radioemission, lead to the well established correlation between the nonthermal radioemission, the far-infrared dust emission and the X-ray emission from strongly star forming regions in galaxies and entire galaxies [R87S1, R83S1, R88T1, R91Y1, 85A1, 91A3, 90A2, 88B6, 91B19, 87C1, 89C1, 88C5, 92D1, 87F1, 88F1, 92F1, 90H7, 89I2, 90J1, 85J1, 89K1, 87K3, 90K7, 90K8, 90K9, 89L4, 90M7, 91M5, 91M6, 91N2, 91P7, 88S3, 91S5, 89S3, 91S8, 91S10, 90S10, 92S21, 88W2, 90W1, 88W8]. Although this general correlation is well understood, the detailed physical steps leading not only to a correlation but also to a tight connection are not finally clear [87L1, 92M2, 88P3, 89U1, 89V3].

Tracers of star formation are thus molecules and atoms in excited states tracing out high-density regions in clouds (emission [R91H1, R82M1, 91B7, 92K2, 88L5, 91M1, 88M5, 88M6, 88M7, 89M6, 90M11, 89P2, 91P9, 86S2, 87S1, 88S1, 89T3, 86W1, 89W1], absorption, and masers [85N1, 85N2], far-infrared dust emission from dust particles heated by massive young stars [89K1, 88K5, 88K6], infrared and optical line emission from dense gas excited by young stars, and the nonthermal and thermal radio continuum emission from the hot phase of the ISM). These arguments seem to hold to a fair degree in normal galaxies as well as irregular and blue compact galaxies.

9.4.4.2 Star formation in the nuclear regions of observed galaxies

Star formation is usually concentrated in the inner region of a galaxy, and manifests itself in a centrally peaked distribution of all the indicators of star formation [R91H1, R87S1, R88T1, R91Y1, 84B3, 90B5, 91C1, 90C3, 88C2, 92C3, 92D3, 92E1, 91G1, 91G6, 92H2, 90H4, 90H8, 92K4, 88K5, 88K6, 88N4, 91S1, 91S2, 86S2, 92S12, 88S9, 89S6, 91S11, 92S16, 92S18, 91S15, 89S11, 86T2, 87T1, 91V2, 91W9, 91W11, 86Y2]. Early-type galaxies often show a central hole in star formation. Most interesting is the finding that many galaxies show evidence of central rings on which star formation is rather intense [R82M1, 88A2, 92C5, 90D2, 91G2, 87N1, 87S6, 89S7, 90S9, 91S12, 92S17, 91T1, 91T3, 90W1]. The origin of such a ring can be traced to the forcing of a putative bar [89A2, 88G1, 91G3, 90H1, 86H1, 87H4, 89K1, 91L3, 88P5, 85S4, 89T2], often known to be present, to a turnover in the rotation curve and the pile up from normal accretion throughout the disk on galactic time scales [90D1, 90L2, 91R6, 87S5]. Such a ring is also found often in AGN galaxies, where the star formation activity in such a nuclear ring can dominate the emission at some wavelengths through the starburst-driven wind (e.g. N1068) [89B1, 87C1, 87C2, 87G2, 90H8, 92K2, 92M4, 90P5, 92W3, 91W8]. This nuclear ring has to be considered as the inner edge of a disk in molecular gas.

Disk components are often visible in the stellar distribution, as dust lanes, emission lines and, in some cases, as molecular gas, also in elliptical galaxies [R91H1, 91I3]. Since such dust lanes are indicative of cool molecular clouds, it can be expected that stars form and that thus the stellar population changes and evolves [92Q1, 87R3].

9.4.4.3 Theoretical interpretation

Galaxy-wide accretion after the disk has been formed is now seen as a prime mechanism to produce the exponential disk in the gravitational potential given by the dark matter as well as the spheroidal component of the stellar population. The gradual increase in primary nucleosynthesis elements is now well documented, with the initial increase with time often dominant. During mergers new globular clusters can form, hence leading to a number of globular clusters which increases faster than linear with stellar luminosity. It is now well recognized that an AGN at the center of a galaxy is being fed from the surrounding regions, usually accompanied with strong star formation. Even many radio galaxies, usually elliptical galaxies, have prominent dust lanes usually perpendicular to their radio symmetry axis, which contain star forming regions (the best known example is Cen A).

9.4.5 1997 Update to 9.4

The advent of data from the satellites COBE (Cosmic Background Explorer), then the Hubble Space Telescope (HST), the Infrared Space Observatory (ISO), and now Hipparcos have modified our view of the Universe considerably. In ground-based observations, the micro-lensing observations of the multitude of stars in the Large Magellanic Cloud as well as the central region of our Galaxy above the disk have shown that there is an otherwise invisible population of compact objects, quite possibly a population of very faint stars. These space and ground-based observations all have deep implications for our understanding of the evolution of the universe and its constituents. Although we have not yet converged to a clear understanding of how galaxies form and evolve, now we can see many more facets of this process.

9.4.5.1 Progress in our understanding

COBE [96B1, 96B2, 96F1, 96G1, 96H1, 96H2, 96K1, 96K2, 96K3, 96L1, 96W2, 97B1] has demonstrated together with several ground experiments, that the fluctuations in the microwave background radiation are really there at the expected level, and has thus provided a clear view of one very early stage of structure formation in the universe. Together with the galaxy counts, which trace structure on very large scales, there appears to be no simple theory to match both sets of data. The reference model, the socalled CDM (Cold Dark Matter) model [96D2] proposes that all matter, visible or not, is non-relativistic at the time of decoupling. In such a model, a small fraction of the density of the universe is baryonic, and most appears to be in a form of non-baryonic matter, of which we see only the gravitational effects, both through giant arcs in clusters of galaxies and in microlensing by compact objects in galaxy halos.

Already we have the well-known discrepancy between the baryonic fraction of the density of the universe inferred from nucleosynthesis, and that much smaller baryonic fraction derived from direct observations of stars, galaxies, and interstellar and intergalactic gas (in clusters of galaxies). The observations of the faint glow around some galaxies [94S1] as well as the micro-lensing observations [94R1, 96A2, 96A3, 97A1] suggest that this discrepancy is due to faint stars distributed in the form of an isothermal sphere around galaxies.

The rotation curves of galaxies, as well as the lensing observations of clusters of galaxies [94R1, 94W1, 96W3, 97B2] clearly demonstrate that clusters have a much larger mass than can be accounted for with baryonic matter [94C1]. This dark matter leads to cluster masses of the order of magnitude of 10^{15} $M_{\odot}$. Mass determinations for clusters of galaxies are done in several ways: a) The virial theorem uses the motions of galaxies; b) the giant lensing arcs are used, which directly give the mass; and c) the X-ray observations are used to integrate the hydrostatic equilibrium equation. This last method needs an assumption about the total pressure in the gas. Allowing for a population of energetic particles and magnetic fields in clusters in analogy to the interstellar medium in galaxies basically triples the total pressure in the gas in the central region of the cluster, and also brings methods b) and c) into consistency. This then leads, for instance, to a lower limit to the density of the universe of 0.4 $h_{50}^{-1/2}$ of the critical density [97E1], where h_{50} is the Hubble constant in units of 50 km s^{-1} Mpc^{-1}. Allowing for hot dark matter may well push the total count of baryonic and dark matter, hot and cold [95P1], to unity in terms of the critical density, so desired by cosmological purists.

The Hubble Space Telescope, in its very long observation of what is called the "Hubble Deep Field" [96A1, 96C1, 96C2, 96C3, 96D1, 96F2, 96G3, 97L2, 96M1, 96M2, 96O1, 96S3, 96V1, 96W1, 97C4, 97F2, 97H1, 97S1, 97V1, 97Z1, 97C1, 97C3, 97G2, 97L1] has observed a large number of young galaxies and what appear to be galaxy fragments with ISO [97G1, 97M1, 97O1, 97R1, 97S2]. Radio observations of this field with the VLA (the Very Large Array, in New Mexico, USA) as well as infrared observations with ISO have shown that many of these objects are very young, that they emit a large fraction of all their power in the infrared, and that galaxy formation appears to be a prolonged affair. Metal formation appears to peak between redshifts of 1 and 2, in agreement with CDM models.

Finally, HIPPARCOS and the recalibration of stellar distances, and so stellar ages have now demonstrated that the age of globular clusters is much lower than we used to think, only 11.5 ± 1.3 Gyr [98C1]. This allows quite possibly a convergence of the constraints for the age of the universe and the determination of the Hubble constant to numbers compatible with a negligible cosmological constant Λ. This suggests the density to be unity in terms of the critical density $\Omega = 1$, the Hubble constant H_0 to be near 65 km s^{-1} Mpc^{-1}, an age of the universe τ near 11 Gyr and is compatible with $\Lambda = 0$. Then the baryonic fraction is in the few percent range, and little information about the dark matter is available. Dark matter around galaxies and clusters seems to follow isothermal spheres of non-interacting particles (therefore non-dissipative).

Low surface brightness galaxies are actually dominated throughout their structure by dark matter halos, while high surface brightness galaxies have an inner region where the baryonic matter dominates gravity. All early Hubble type galaxies also appear to have a central black hole of a mass proportional to the spheroidal mass with a factor of order 1/500 [94M1, 94M2, 95M1, 95M2, 95K1, 96S2, 97F1]. Central activity [93A1, 95K1, 96G1, 96S1] should therefore be common in all galaxies with a spheroidal component throughout some of their evolution.

9.4.5.2 Web-connections

The reader will be well advised to check the web for the latest publications based on observations with HST, ISO, HIPPARCOS, other satellites or ground instruments. Also, many reviews are available on the web. The Space Telescope Science Institute has made the Hubble Deep Field data available [96W1] spawning large scale followup work which can be found under "Science Resources" at http://www.stsci.edu/. One conference at the SpaceTelescope Science Institute has been dedicated already to the Hubble Deep Field [97L1].

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References for 9.3 and 9.4

The references are structured in three sections, with the first listing important conference proceedings, the second one separately published review articles, and the third section references to the standard literature, with a strong bias to recent literature, which can serve as a guide to locate other work. There has been no attempt to achieve completeness.

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9.5 Quasars and active galactic nuclei

9.5.1 Definition

Active galaxies are distinguished from other galaxies in that they show indications of having energy output not related to ordinary stellar processes. The activity is centered in a small nuclear region and associated with strong emission lines. The nuclei of such galaxies are named Active Galactic Nuclei (AGN). The luminosity emitted by such objects ranges from 10^{41} to 10^{47} erg s^{-1}.

In this chapter an object is classified as an AGN if at least one of the following is observed:

1. Compact nuclear region, brighter than the corresponding region in galaxies of similar Hubble type.
2. Nonstellar nuclear continuum emission.
3. Nuclear emission lines indicating excitation by a nonstellar continuum.
4. Variable continuum and/or emission lines.

Throughout this section we assume a Friedman universe with q_0 = 1/2, H_0 = 70 km s^{-1} Mpc^{-1} and zero cosmological constant. The luminosity distance for this model is

$$D_L = \frac{2c}{H_0}[1+z-(1+z)^{1/2}] \approx 8.563\cdot 10^3[1+z-(1+z)^{1/2}]\ \mathrm{Mpc}, \qquad (1)$$

where $z = \dfrac{\lambda-\lambda_0}{\lambda_0}$ is the redshift.

9.5.2 Classification

AGN are classified into subgroups according to their luminosity and spectrum. Such a division is not unique and there is some overlap in properties between the groups. The following is a typical classification scheme. Examples are given in Table 1.

9.5.2.1 Quasars and Seyfert 1 galaxies

These are the most luminous AGN, showing all the above four characteristics. They are easily recognized by their strong, broad permitted emission lines and their nonstellar continuum. The typical line Full Width at Half Maximum (FWHM), if interpreted as being due to Doppler motion, is 3000…5000 km s^{-1}, with extreme cases of up to twice that. All Seyfert 1 galaxies, and some quasars, show also strong narrow (400…1000 km s^{-1}) permitted and forbidden lines. This has resulted in a subdivision of Seyfert 1s, according to the relative strength of the broad and narrow lines. Thus, a Seyfert 1.5 is a Seyfert galaxy in which about 20 % of the total Hβ flux is due to the narrow component of the line. Several examples of quasar spectra are shown in Fig. 1.

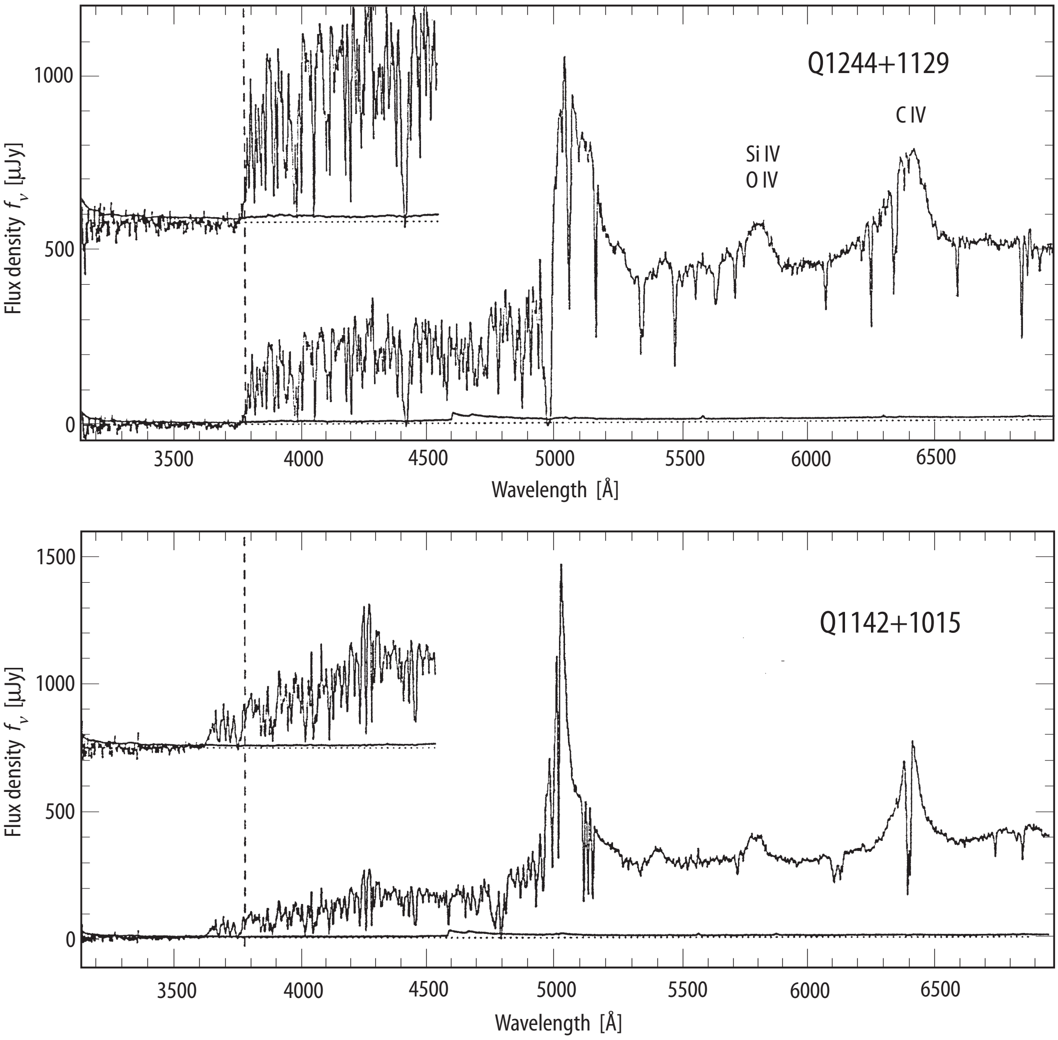

Fig. 1. The spectrum of two high redshift quasars (courtesy of C. Steidel) showing the strong emission lines of Lyα, SiIVλ1397, OIV]λ1402 and CIVλ1549, as well as numerous narrow absorption lines short of the Lyα line wavelength.

9.5.2.2 Broad line radio galaxies (BLRGs)

Some powerful radio galaxies show a typical Seyfert type 1 spectrum. These are sometimes classified as a separate group under the name of broad line radio galaxies (BLRGs). Besides the strong radio emission, there are some subtile spectral differences between BLRGs and Seyfert 1 galaxies, mainly to do with the broad line profiles.

9.5.2.3 Seyfert 2 galaxies

Seyfert 2 galaxies are less luminous than Seyfert 1 galaxies and quasars and show extremely week or no broad emission lines. Their narrow lines are similar in width and excitation to the narrow lines of Seyfert 1s but their equivalent widths, relative to the nonstellar continuum, are much larger. Much of the differences between Seyfert 1 and Seyfert 2 galaxies are due to the fact that the central continuum, and the broad line region in Seyfert 2s, are obscured from direct view (see subsect.

9.5.10.6). The optical, ultraviolet and soft X-ray continua are seen by reflection, which makes it difficult to determine their shape. The only parts of the spectrum where direct view of the central source is possible, in some Seyfert 2s, are the far infrared and the hard X-ray bands.

9.5.2.4 Low ionization nuclear emission line regions (LINERs)

These are the least luminous AGN. Their nonstellar continuum is very weak, compared with the stellar continuum, and there are only a few good observations of its shape. The strongest emission lines are of low ionization species and are somewhat narrower than the narrow lines of Seyfert galaxies. LINERs are recognized by their low excitation narrow lines but some LINERs show also very weak, broad emission lines.

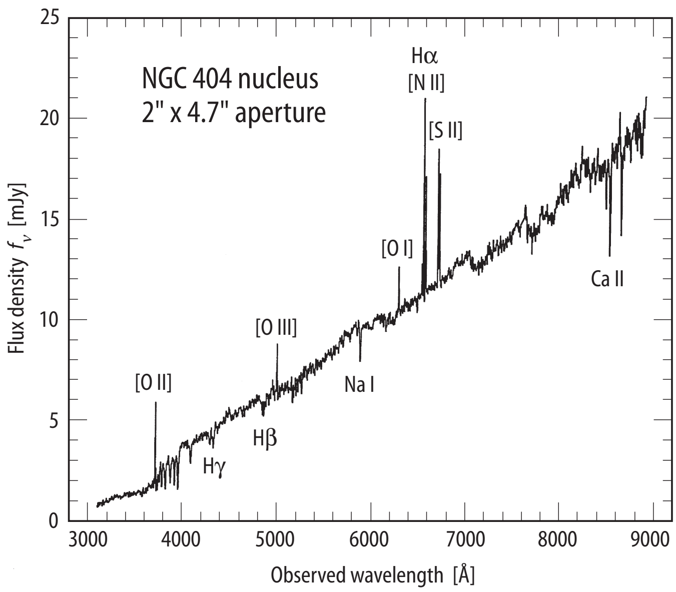

Fig. 2. The spectrum of the LINER NGC 404 (courtesy of A. Filippenko). Note the strong low excitation lines of [OII]λ3727 and [OI]λ6300.

9.5.2.5 Narrow line X-ray galaxies (NLXGs)

The name NLXGs was invented to describe some narrow line galaxies with unusual X-ray properties. The more luminous objects of this class show strong narrow lines, similar in width and excitation to the narrow lines of Seyfert 1 and Seyfert 2 galaxies. The NLXGs are strong X-ray emitters, with optical-to-X-ray continuum luminosity ratio similar to Seyfert 1s. The ultraviolet spectrum of most NLXGs is weaker than that of Seyfert 1s and there are indications that this may be due to reddening. In several NLXGs there are weak, very broad wings to Hα. Some NLXGs show much lower excitation lines, and are more similar to LINERs.

9.5.2.6 Narrow line radio galaxies (NLRGs)

Some powerful radio galaxies show a characteristic Seyfert 2 type spectrum. These have been named narrow line radio galaxies (NLRGs) and are sometimes classified as a separate subgroup of AGN. Here they are referred to as either Seyfert 2 galaxies or NLXGs, depending on their X-ray luminosity.

9.5.2.7 BL Lac objects and OVV quasars

Some AGN do not show any emission lines. These are the BL Lac objects, identified by their highly variable nonthermal continuum. Information on the redshift of BL Lac objects is obtained from study of their host galaxy, or absorption lines on the line of sight to the source. The time variability and other continuum properties of some quasars, known as optical violent variables (OVVs), are similar to those of BL Lac objects. The emission lines of OVVs are broad and their strength, relative to the nonstellar continuum, varies from extremely weak to average. The combined group of BL Lac objects and OVV quasars has been named BLAZARs.

Table 1. Names, positions, redshifts and approximate apparent visual magnitudes of several well studied AGN.

Object	α (1950)	δ (1950)	z	appx. m_v	Comments
QSOs					
Q0002-422	$00^h\ 02^m\ 16^s$	–42° 14'	2.758	17.4	
PHL938	$00^h\ 58^m\ 20^s$	01° 55'	1.95	17.2	
OH471	$06^h\ 42^m\ 53^s$	44° 55'	3.39	18.5	
Ton 1530	$12^h\ 22^m\ 57^s$	22° 52'	2.046	15.5	
3C273	$12^h\ 26^m\ 33^s$	02° 20'	0.158	12.8	RL
Q1246-057	$12^h\ 46^m\ 29^s$	–05° 43'	2.212	17.0	BAL*)
PKS2212-299	$22^h\ 12^m\ 25^s$	–29° 59'	2.71	17.6	RL
3C345	$16^h\ 42^m\ 39^s$	39° 50'	0.585	15.5…16.5	OVV
3C446	$22^h\ 25^m\ 47^s$	–04° 57'	1.404	16…17	OVV
Seyfert 1 galaxies					
Mkn 335	$00^h\ 03^m\ 45^s$	19° 55'	0.025	14.2	
I Zw 1	$00^h\ 51^m\ 00^s$	12° 25'	0.061	14.3	
3C109	$04^h\ 10^m\ 55^s$	11° 15'	0.033	14.6	BLRG
Mkn 79	$00^h\ 38^m\ 47^s$	49° 56'	0.020	13.5	
NGC 3516	$11^h\ 03^m\ 24^s$	72° 50'	0.0093	13.1	
NGC 4151	$12^h\ 08^m\ 01^s$	39° 41'	0.0033	12.0	
Mkn 279	$13^h\ 51^m\ 52^s$	69° 33'	0.0307	15.4	
Mkn 486	$15^h\ 35^m\ 21^s$	54° 43'	0.039	15.0	
3C390.3	$18^h\ 45^m\ 39^s$	79° 43'	0.0569	15.4	BLRG
NGC 7469	$23^h\ 00^m\ 44^s$	08° 36'	0.0167	13.6	
Seyfert 2 galaxies					
Mkn 1	$01^h\ 13^m\ 19^s$	32° 50'	0.016	16.6	
NGC 1068	$02^h\ 40^m\ 07^s$	–00° 14'	0.0036	10.7	
Mkn 612	$03^h\ 21^m\ 10^s$	–03° 19'	0.0202	16.5	
3C98	$03^h\ 56^m\ 10^s$	–10° 18'	0.031	14.8	NLRG
III Zw 55	$03^h\ 38^m\ 38^s$	–01° 28'	0.0246	14.0	
Mkn 3	$06^h\ 09^m\ 48^s$	71° 03'	0.0137	13.8	
Mkn 34	$10^h\ 30^m\ 52^s$	60° 17'	0.051	14.8	
Mkn 270	$13^h\ 39^m\ 41^s$	67° 55'	0.009	15.0	
3C327	$15^h\ 59^m\ 56^s$	02° 06'	0.1039	16.3	NLRG
Mkn 533	$23^h\ 25^m\ 24^s$	08° 30'	0.0287	16.0	
NLXGs					
NGC 2110	$05^h\ 49^m\ 46^s$	–07° 28'	0.007	14.3	
NGC 2992	$09^h\ 4^m3\ 18^s$	–14° 06'	0.007	14.0	

Object	α (1950)	δ (1950)	z	appx. m_v	Comments
NGC 5506	$14^h\ 10^m\ 39^s$	–02° 58'	0.007	14.1	
NGC 7582	$23^h\ 15^m\ 38^s$	–42° 39'	0.005	14.3	
BL Lac objects					
AO0235+164	$02^h\ 35^m\ 53^s$	16° 24'	>0.85	15…16	
PKS0548-323	$05^h\ 48^m\ 50^s$	–32° 17'	0.069	15…16	
OJ287	$08^h\ 51^m\ 57^s$	20° 18'	0.306	14…15	
Mkn421	$11^h\ 01^m\ 41^s$	38° 29'	0.0308	13…14	
Mkn501	$16^h\ 52^m\ 12^s$	39° 50'	0.0337	13.5…14.5	
BL Lac	$22^h\ 00^m\ 40^s$	42° 02'	0.069	14…15	
LINERs					
Mkn 1158	$01^h\ 32^m\ 07^s$	34° 47'	0.0151	16.2	
NGC 1052	$02^h\ 38^m\ 37^s$	–08° 28'	0.0048	13.2	
NGC 2841	$09^h\ 18^m\ 35^s$	51° 11'	0.0022	13.5	
NGC 3031	$09^h\ 51^m\ 30^s$	69° 18'	0…0.0001	12.4	
NGC 4036	$11^h\ 58^m\ 54^s$	62° 10'	0.0046	14.0	
Mkn 298	$16^h\ 03^m\ 18^s$	17° 56'	0.0345	16.2	
NGC 6764	$19^h\ 07^m\ 01^s$	50° 51'	0.008	15.5	

*) BAL: Broad Absorption Lines (see subsect. 9.5.9.1).

9.5.3 Discovery and surveys

The first known AGN have been discovered in a non systematic way, by means of their unusual optical and radio properties. More systematic searchs for AGN have later been conducted at almost all wavelengths, using a variety of techniques.

9.5.3.1 Radio surveys

Several radio surveys have led to the discovery of a large number of radio-loud (RL) quasars. The original 3C survey, at 178 MHz, with a flux limit of 9 Jy, is typical of the low frequency surveys. The fraction of steep spectrum radio sources (subsect. 9.5.6) in such surveys is very large and they are characterized by having a large fraction of their radio power emitted in the extended radio component. Some 25 % of all objects in this sample are AGN. High frequency radio samples, at 2…5 GHz tend to find flatter continuum quasars that are dominated by their compact unresolved radio core. An obvious limitation of radio discovery techniques is the small fraction (≈ 10 %) of all AGN that are strong radio emitters [e.g. 81K3, 89K2, 96H].

9.5.3.2 Infrared surveys

The InfraRed Astronomical Satellite (IRAS) completed its full sky survey in 4 infrared bands (12, 25, 60 and 100 μm) and discovered some 10^5 sources. Several of the most luminous IRAS sources have, subsequently, been identified with quasars and Seyfert 1 galaxies. In comparison with previously known AGN, that were also detected by IRAS, the newly discovered AGN are much more infrared luminous, with clear indication of dust emission that peaks at around 60 μm [88S1, 92G and references therein].

9.5.3.3 Optical surveys

Several techniques have been used to detect AGN in the optical band. Color selection makes use of the unusually blue (compared with stars) UBV colors of low redshift AGN [e.g. 83S, 88B]. UV excess objects, discovered in two dimensional (*U-B*, *B-V*) color diagrams are, therefore, prime candidates for follow up spectroscopy in attempt to identify them as quasars. The *U-B* color of high redshift ($z \geq 2.2$) quasars is substantially redder and similar to the color of many stars. More sophisticated methods, employing up to 5 optical colors, are used to detect such objects [e.g. 88K1].

Objective prism surveys [82O1, 91M3] have been used extensively to look for strong emission and absorption line objects. Most quasars known today (≈ 10000 objects in 1996) are the result of such surveys. CCD grism surveys [86S] have been used very successfully to find very high redshift quasars by their emission lines properties.

AGN variability provides yet another way for discovering such objects [88K2, 89T2] by repeated observations of a certain field. Finally, proper motion surveys, at high galactic latitudes, have been used to identify quasars by the lack of proper motion [81K2]. All optical surveys suffer from various selection effects. For example, steep continuum weak emission line quasars will be hard to detect in any of the methods described above.

9.5.3.4 X-ray surveys

Several X-ray satellites have been used in their survey mode to detect AGN via their unusual X-ray properties. Examples are the Extended Medium Sensitivity Survey of the Einstein Observatory [90G, 94D], the EXOSAT High Galactic Latitude Survey [89G] and the ROSAT whole-sky survey. Such surveys can clearly separate AGN from star. They suffer from the non-uniform flux level, AGN variability and their relatively low X-ray brightness. X-ray selected AGN samples tend to have lower radio-loud fraction and steeper continuum, perhaps because of reddening.

9.5.4 AGN evolution

The mean $<V/V_{\rm m}>$ for quasars, where V is the volume corresponding to the object location and $V_{\rm m}$ the maximum volume set by observational constraints, is about 0.7, significantly greater than the uniform distribution value of 0.5 and suggesting strong evolution. There are clear indications that the evolution is luminosity dependent and that very luminous AGN are more common at high redshifts. The luminosity function (L) of quasars and other AGN has been studied at different redshifts [83S, 86S, 88B, 90B2, 95P]. The number density of quasars, $\rho(L)$, can be fitted by a double power-law expression of the form

$$\rho(L) \propto L^{-\mathrm{S}},\ S \approx \begin{cases} 3.9 & M_B < -23 \\ 1.3 & M_B \geq -23 \end{cases}, \qquad (2)$$

with luminosity evolution of the form

$$L(z) \propto L(0)[1+z]^{k_L}, \qquad (3)$$

with $k_L \approx 3.2$. The normalization is such that the cumulative number of quasars brighter that $B = 21$ mag is about 37 per deg^2. There are strong indications for a large deficiency of objects with large redshifts $z \geq 2.5$ and the luminosity function at those redshifts is highly uncertain.

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9.5.5 The host galaxy of AGN

Many of the nearby Seyfert 1s are spiral galaxies and so are most Seyfert 2s and many LINERs. The BLRGs and the NLRGs are luminous elliptical galaxies. The situation regarding quasars is less certain. While weak emission from the host galaxy is found in almost all cases where the observations are done under the required conditions, its classification is hampered by the presence of the bright nuclear source.

Study of radio loud quasars indicates that the host galaxy is most likely an elliptical galaxy with magnitude similar to those of many powerful radio galaxies. There are also weak indications of somewhat bluer colors for those galaxies [84M1, 85B3, 86S, 89R2, 90V]. As for the radio quiet quasars, little direct evidence is available for classifying the host galaxy. There are several claims that spiral host galaxies have been detected but the deduced magnitudes, especially for the more luminous objects, are in the general range of the more luminous ellipticals. The host galaxy of some high redshift quasars is a strong emitter of a narrow Lyα line [91H] which is excited, presumably, by the strong ultraviolet central source. Much improved results from HST observations [97B1] suggest that the host galaxies of luminous, low *z* quasars, are significantly brighter than field galaxies of the same type. They also show that many radio-quiet quasars are located in elliptical galaxies and suggest that gravitational interaction plays an important role in triggering the AGN phenomenon.

There were several investigation of galaxy interaction and its effect on the AGN phenomenon, with inconclusive results [84D1, 88F, 89M]. There are many cases were the AGN galaxy is morphologically disturbed, or there is a near companion. The statistical significance of this is not clear and there are definitely cases of bright AGN in well isolated galaxies.

9.5.6 AGN continuum

AGN continuum emission spans a large energy range, $10^{12} < \nu < 10^{18}$ Hz, and its origin is mostly nonstellar. Throughout this chapter it is referred to as *the nonstellar continuum*.

The shape of the nonstellar continuum is different at different energies. Over a limited frequency range it can be described as a power-law in frequency,

$$F_\nu = C\nu^{-\alpha}, \tag{4}$$

where F_ν is the observed flux in erg s^{-1} cm^{-2} Hz^{-1} and α is the spectral index. This simplified description fails when a large energy range is considered, as discussed below.

Differences in continuum shape from one subgroup to the next are not very large, except in the radio band, where orders of magnitudes difference are observed. Fig. 3 shows an average spectrum as obtained from a large sample of medium and high luminosity objects.

9.5.6.1 Radio continuum

AGN are traditionally classified into *radio quiet* and *radio loud* sources. The difference between the groups is several orders of magnitude in radio luminosity. Even the radio-loud AGN do not emit a large part of their bolometric luminosity at radio wavelengths.

Another tradition is to classify the radio loud AGN into *steep spectrum* ($\alpha \geq 0.5$) and *flat spectrum* ($\alpha < 0.5$) radio sources. This division is also related to the morphology of the radio source: the steep component is in many cases extended and resolved while the flat component is emitted by a compact unresolved core. A useful parameter that is related to the physics of such sources is the ratio of the flux in the two component,

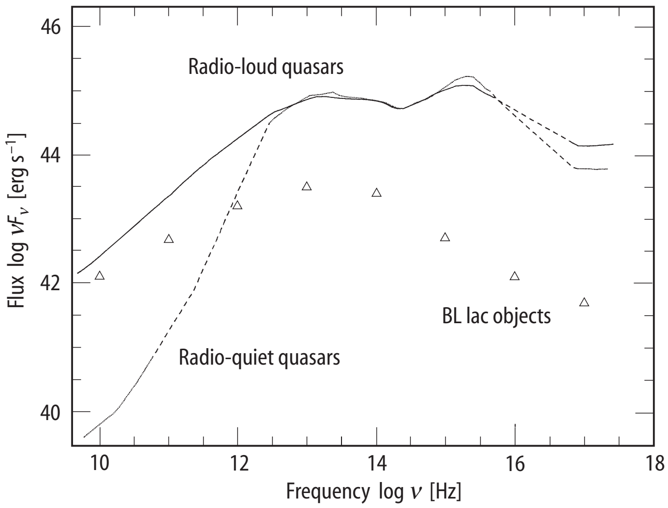

Fig. 3. The observed continuum of radio loud (uppermost curve) and radio quiet AGN, normalized to a bolometric luminosity of 10^{46} erg s^{-1}. A typical BL Lac type continuum is shown for comparison. (Courtesy of A. Laor).

$$R(\text{radio}) = \frac{\text{compact radio source flux}}{\text{extended radio source flux}} \; . \tag{5}$$

Most Seyfert galaxies show steep radio spectra [82W2, 84M2, 84U, 85W6], while many radio-loud quasars are dominated by a strong, flat, compact radio source [e.g. 89K2]. Much of this dichotomy is a result of the radio frequency used in the discovery surveys. Radio cores are more common in Seyfert 2 galaxies [94R].

9.5.6.2 Infrared continuum

The far infrared emission of most AGN rises sharply between 1000 µm and 100 µm, peaking around 20…70 µm [85M3, 86E, 87C1, 88A, 88S1]. The infrared continuum cannot be described by a single power-law. There are indications of thermal emission at almost all infrared frequencies and a broad feature at around 3…5 µm. There is also a local luminosity dependent minimum at around 1 µm. (This region of the spectrum is dominated by star light in the less luminous objects, which has been a source of much confusion.) The near infrared spectrum, between 1 and 3 µm, is the only range where a single power-law, with $1.7 > \alpha > 1$, is a reasonable fit to the data. Polarization observation at this frequency suggest a nonthermal origin for the 1…3 µm continuum, at least in some objects.

As in other wavelength bands, the infrared continuum of BL Lacs and OVVs is very different from the one described above and is entirely consistent with a single power-law component (Fig. 3).

9.5.6.3 Optical-ultraviolet continuum

The 0.1…0.7 µm continuum is much harder than the near infrared continuum, with a typical spectral index of 0.4…0.8. Deviations from a single power-law fit are clear in some, but not all objects. There is little information about the optical nonstellar continuum of low luminosity AGN, because of the stellar background.

Excellent ultraviolet continuum measurements are now available up to, in some cases, a rest energy of 2…3 Ry. There is a clear steepening of the ultraviolet continuum below 1000 Å which can be attributed, in some high redshift objects, to the numerous absorption systems [84B, 88O]. Extrapolation of the observed continuum into the far UV suggests a peak in νF_ν at an energy of ≈ 3…10 Ry. The little evidence there is on the ultraviolet continuum of Seyfert 2s and NLXGs [91K] indicates a similar shape but much lower luminosity compared with Seyfert 1s. There are good reasons to believe that much of the ultraviolet flux in those objects is due to star formation, and not the obscured nonstellar source.

The optical-ultraviolet continuum of BL Lac objects and OVV quasars is, again, very different. It is easily fitted with a single power-law component which is a simple extrapolation of the infrared continuum.

9.5.6.4 Extreme ultraviolet continuum

Observations with the EUVE satellite discoved only a small fraction of all known AGN. This is greatly due to the large amount of galactic obscuration at the EUVE wavelengths.

9.5.6.5 X-ray continuum

X-ray observations at energies above about 0.2 keV suggest a multiple component continuum. Below ≈ 1 keV the intrinsic monochromatic luminosity is decreasing with energy, with a spectral index of about 1.5 (e.g. [87W, 93W1]), confirming the evidence from the ultraviolet data that the peak in νF_ν is in the unobserved, far UV part of the spectrum. The very low X-ray energy range is difficult to observed because of the poor resolution of existing X-ray detectors and the absorption along the line of sight. There is also evidence for substantial extended soft X-ray emission (presumably starburst regions) away from the nucleus. Above about 2 keV, the continuum is flatter and $\alpha = 0.7…0.9$ is a good fit up to about 20 keV [83R, 92W]. Some AGN have much steeper ($\alpha \approx 3$) soft X-ray slopes (e.g. [96B1]). This property is correlated with variability and with emission line width and intensity.

Absorptions at low X-ray energies is common to many low luminosity Seyfert 1 galaxies ([98G, 97R] and references therein). This indicates obscuration of the central X-ray source by highly ionized gas. A different kind of absorption, by large columns of neutral gas, are seen in Seyfert 2s and NLXGs. There seem to be less soft X-ray absorption in luminosity AGN [85R, 91A, 92M1].

A parameter which has been used to describe the relative flux in the optical and X-ray band is α_{ox}, which is the energy spectral index connecting the 2500 Å and 2 keV continuum. Its value ranges from about 1.2 to 1.8. Seyfert 1 galaxies and some NLXGs are the strongest (per optical luminosity) X-ray emitters, with the smallest value of α_{ox}. Radio-loud quasars emit more hard X-rays than radio-quiet ones (per given optical luminosity) and are characterized by a small to medium value of α_{ox}. Radio quiet quasars, especially the highest luminosity ones, have the largest value of α_{ox}. An equivalent way of expressing the same relation is to correlate the optical and X-ray (1…2 keV) luminosities by an expression of the form

$$L_X \propto L_{OPT}^{\beta}. \tag{6}$$

The parameter β depends on the optical wavelength used and is between 0.7 and 0.9. The near infrared luminosity seem to be better correlated with the X-ray luminosity (i.e. β closer to 1).

GINGA discovered strong Kα lines at around 6.4 keV, mostly due to low ionization iron, and weak absorption edges near 7.1 keV. There is also evidence for hardening of the X-ray spectrum above the iron edge due, perhaps, to Compton reflection [88L, 91G, 91M2]. Given this hypothesis, the intrinsic X-ray continuum slope, between 3 and 20 keV, may be steeper ($\alpha \approx 0.9$) than observed ($\alpha \approx 0.5…0.7$).

9.5.6.6 γ-ray continuum

Most AGN are weak γ-ray emitters. This is not the case for the OVV, Blazers and several flat-continuum radio quasars that were discovered by systematic monitoring of the Gamma Ray Observatory (GRO). These objects undergo large outbursts doubling their intensities on time scales as short as a day [83B, 92G1 95M2 and references therein]. GRO has found that the hard X-ray continuum (50…200 keV) continuum of most AGN extends, with the same slope as the 1…10 keV continuum, up to about 100 keV, where there is a noticeable drop in flux. The highest energy observed so far, in any AGN, is at the TeV range (a couple of BL Lac objects).

9.5.6.7 Continuum variability

There seem to be a distinction between the continuum variability of the *violent variables* (BL Lac objects and OVVs), *moderate variables* (Seyfert 1 galaxies, most quasars and BLRGs and some NLXGs) and *non-variables* (Seyfert 2 galaxies and LINERs). The moderate variables vary at all wavelengths. While good statistics about the entire population is not available, it seems that all luminous AGN that have been systematically monitored show some continuum variation. There is some evidence that the degree of variability objects depends on luminosity, being larger in lower luminosity objects [e.g. 74G, 78U, 90E]. There is no clear evidence that it depends on radio properties [96N2].

There is a well documented correlation between the wavelength band and the variability time scale and amplitude for the moderate variables. At longer wavelength the variability time scale is longer and the relative flux change small, while at short wavelengths the opposite is true. An extreme example is the X-ray flux of several Seyfert 1s showing huge flux variations over very short (200…1000 seconds) time scale [e.g. 87L]. The X-ray variability of the more luminous AGN is not well studied but the limited available information suggest long time scales (months) and relatively small ($< 2^m$) amplitudes [84Z]. In all non-BLAZARs AGN, the radio variability is of smaller amplitude and on longer time scales.

OVVs show the largest variation of all [90B3 and references therein], with a factor of up to 10 increase/decrease on time scales of weeks to months, at all wavelengths. There are indications that the larger the average luminosity the larger is the fractional variation, in clear contradiction to the case of the moderate variables. This is consistent with the beaming hypothesis for these objects (see subsect. 9.5.10).

There were a few attempts to correlate the continuum variability at different wavelengths. The best results, so far, have been obtained for the Seyfert 1 galaxy NGC 5548. In this source, the optical (5000 Å) and ultraviolet (1300…3000 Å) continuum vary together, on a time scale of 50 days, with a time lag consistent with 0 (< 2) days. The X-ray to ultraviolet time lag for the galaxy is less than 7 days and is consistent with a zero lag [91C1, 91P, 92C]. Other cases (NGC 4151, see [96E]) confirm this result. The infrared continuum of some Seyfert 1s lags behind the optical continuum by a few months [e.g. 89C]. This is interpreted as dust emission at about 0.1…1 pc responding to changes in the energy output of the central source.

Radio observations of some OVVs and BL Lac objects, when correlated with optical observations, suggest a long delay of the order of several months. There is, however, a conflicting evidence for other AGN, where the data suggest zero lag between optical and radio variations [89B4, 91Q].

So far, there is no single evidence for periodic variations in any AGN.

Seyfert 2 galaxies, LINERs and most NLXGs do not show any optical continuum variability. Much of this is likely to be a selection effect since the optical continuum of these low luminosity AGN is dominated by starlight.

9.5.6.8 Continuum polarization

The optical continuum of luminous AGN is mostly unpolarized, with an average percentage polarization of about 1…2 %. The exception are some radio loud objects that show much higher (5…10 %) polarization at near infrared frequencies. This is attributed to the strong nonthermal source in such objects [84S2]. Other extreme example are those of highly reddened objects where dust scattering is most likely to be the source of polarized light.

Several Seyfert 2 galaxies show highly polarized (> 10%) lines and nonstellar continuum. The spectrum of the polarized radiation is very similar to the spectrum of Seyfert 1 galaxies, showing featureless continuum and strong broad emission lines of hydrogen and FeII. Such galaxies host an obscured Seyfert 1 nucleus, with a central continuum source and a broad line region (see subsect. 9.5.7.1) The light of this source can only be observed through scattering, either by dust or by thermal electrons and the scattered radiation is highly polarized [85A, 90M, 95K, 95T2].

9.5.7 AGN emission lines

A summary of the strongest emission lines observed in the spectrum of the various subgroups is given in Table 2.

Table 2. Average line intensities, relative to Hβ, in various subgroups. Some references are [75B, 77O, 78B, 78G, 78K, 78P, 80H, 80O, 81S, 83C2, 83W, 85W5, 88M2, 89B3, 91S, 92B].

Line	Quasars and Seyfert 1s broad + narrow	NLXGs and Seyfert 2s narrow	LINERs narrow
CIIIλ977	0.1…0.4		
OVIλ1035	1…3	3…8	
Lyα	8…15	30…70	15…30
NVλ1240	0.7…2	3…10	
[OI]λ1304	0.5		
CIIλ1335	0.2…0.4	0.5…2	
SiIVλ1397,OIV]λ1402	1…2	1…2	2…5
NIV]λ1486	0.5…1	0.5…1	1…3
CIVλ1549	5…8	5…20	5…10
HeIIλ1640	0.4…1	3…5	
OIII]λ1663	0.3…0.7	0…3	1…3
NIII]λ1750	0.2…0.5	0.5…2	2…4
CIII]λ1909	2…4	2…8	10…20
FeII(2200...2800 Å)	5…10		
MgIIλ2798	2…5	1…3	
[NeV]λ3426	0.1…0.3	0.2…2	
[OII]λ3727	0.2…0.7	1…4	2…5
[NeIII] λ3869	0.3…0.7	1…2	0.2…0.5
HeIIλ4686	0.05…0.5	0.1…0.5	
Hβ	1.0	1.0	1.0
[OIII]λ5007	0.11	8…15	1…2
FeII(4500...5400 Å)	1…3		
HeIλ5876	0.05…0.2	0.05…0.15	0.05…0.1
[OI] λ6300	0.03…0.1	0.6…1.5	2…4

Line	Quasars and Seyfert 1s broad + narrow	NLXGs and Seyfert 2s narrow	LINERs narrow
Hα	3…6	2.7…3.3	2.7…2.8
[NII]λ6583	0.1…0.3	0.6…1.5	2…4
[SII]λ6716	0.1…0.3	0.5…2	2…3
[SIII]λ9069	0.05…0.2	0.3…1	0.2…0.6
Pα	0.3…0.6		
L(Hβ) [erg s^{-1}]	$10^{42…46}$	$10^{40…42}$	$10^{38…41}$
EW(Hβ) [Å]	100	5…30	1…10

9.5.7.1 Broad emission lines

Most luminous AGN emit broad, strong emission lines, with a typical FWHM of 5000 km s^{-1}. Fewer objects show strong, but much narrower lines (1000 km s^{-1}) and there are many intermediate cases. The region emitting the broad emission lines has been named the broad line region (BLR).

All the strong broad emission lines are due to permitted and intercombination transitions. Thus the density in the line emitting region must exceed about 10^8 cm^{-3}. However, in some cases the [OIII]λ5007 profile has broad extended wings, comparable in width to the broad line profiles.

9.5.7.1.1 Broad line intensity

The average intensity of the broad emission lines (Table 2) give a fair representation of the entire population. There are some obvious trends with luminosity. For example, the CIVλ1549/Lyα line ratio decreases with increasing continuum luminosity. The suggested trends are weak and the scatter in intrinsic properties very large. The lines that seem to have the largest scatter of all are the optical FeII lines that can range from very weak to extremely strong. The blending of the ultraviolet FeII lines with the Balmer continuum emission forms a noticeable emission bump between 2000 and 4000 Å that has sometime been confused with continuum emission [85W5]. The highest ionization lines discovered so far are due to NeVIII [95H].

9.5.7.1.2 Broad line profiles

The broad emission line profiles of most AGN are smooth and symmetrical and span a large range of FWHM, from about 600 to 6000 km s^{-1}. The lines can be fitted, in many cases, by a logarithmic function, $I_\lambda \propto \log(\lambda - \lambda_0)$. However, there are claims that $I_\lambda \propto \lambda^{-2}$ gives a better fit to the far wing of the lines. There are also attempts to separate the broad line profiles into very broad and intermediate width components. [78B, 82O2, 82W1, 85M1, 86C, 86W1, 89S2, 94B]. Some broad profiles are definitely asymmetric. Others show distinct components, or *bumps*. Such irregular line profiles are much more common in BLRGs. Double peak lines, such as those expected from a flat (disk-like) geometry, are seen in some, mostly radio-loud, objects [e.g. 79M, 88H]. In some objects all emission lines have similar profiles while in others the line widths and shape clearly change with the degree of ionization.

The mean redshift, as derived from line centers (or peaks) can differ from one line to the next [82G, 89E, 90C]. This phenomenon is more common in high luminosity objects. The tendency is for the higher ionization lines to be blue shifted with respect to the low ionization lines by up to 1500 km s^{-1}. In such cases the low excitation lines of MgIIλ2798 and Hα agree with the systemic velocity while lines like CIVλ1549 are blue shifted with respect to it.

9.5.7.1.3 Broad line variability

Emission line variability is common in many Seyfert 1 galaxies. This has been studied in great detail in several objects [e.g. 88P3, 89C, 90E, 90N2, 91C1, 91M1, 91P, 93P]. The best available data sets are the result of large scale international campaigns to monitor the line and continuum variability in NGC 5548, NGC 3783, NGC 4151 and NGC 7469. Correlated line and continuum variations have been found in all four sources, as illustrated in Fig. 4. Cross correlation analysis confirm that in all low luminosity sources, the emission lines lag the continuum by a few days. The lag is not the same for all emission lines, and the higher ionization species (e.g. HeIIλ4686, CIVλ1549) react faster to continuum variations compared with lower ionization species (e.g. CIII]λ1909, MgIIλ2798 and Hα). In addition, there seems to be a correlation between the variability amplitude and the degree of ionization in the sense that the higher ionization lines exhibit larger amplitude variations. This has been interpreted as evidence for a thick, stratified BLR.

The analysis of the entire sample of AGN with variable lines (about 15 objects in 1996) suggests longer lags, and larger BLRs, for the more luminous objects. The BLR size, based on the measured Hβ lag, is

$$R_{\mathrm{BLR}} \approx 0.15\, L_{46}^{1/2}\ \mathrm{pc}\ , \tag{7}$$

where L_{46} is the ionizing luminosity in 10^{46} erg s^{-1}.

The emission line variability of some OVVs is extremely fast and not in accord with the above relation [e.g. 88P2]. It indicates, perhaps, a special geometry, such as an emission line region along the relativistic jet.

9.5.7.2 Narrow emission lines

The narrow emission lines are coming from the narrow line region (NLR). This region is clearly resolved in low redshift objects [91E, 91L, 96M1] with dimensions of 100…1000 pc. Well studied cases show condensations, or clouds, moving with relative velocities of hundreds of km s^{-1}. The term NLR is somewhat ill-defined and more extended, galactic scale emission line regions are sometimes included in this category. In particular, some radio galaxies show extended, high excitation regions, several kpc from the nucleus, along the radio-jet direction.

9.5.7.2.1 Narrow line intensity

The strongest lines in the NLR are due to forbidden transitions of [OII], [OIII], [NII], etc. The inferred gas density is $10^3..10^5$ cm^{-3}. The lines are listed in Table 2. A definite bias in this table is the lack of reliable information on the ultraviolet emission lines of LINERs, because of the very few such objects observed so far. We also note that the narrow emission lines of high luminosity AGN are significantly weaker, especially the ultraviolet lines [93W2].

The narrow emission lines can be classified according to their excitation and level of ionization. Seyfert 1s, Seyfert 2s and NLXGs show the highest excitation lines, with strong NV and CIV. LINERs represent the other extreme, with little or no emission of triply ionized lines [e.g. 81B, 83F, 85K]. Fig. 5. is an example of a line ratio diagram that is useful for classifying the objects to different excitation groups. On such diagrams, LINERs are clearly separated from other AGN.

The highest excitation lines are the so-called "coronal lines". Examples are lines of [FeXI], [MgVIII] and [SiIX]. Many of these are infrared transitions and are readily observed by ISO [e.g. 96M2].

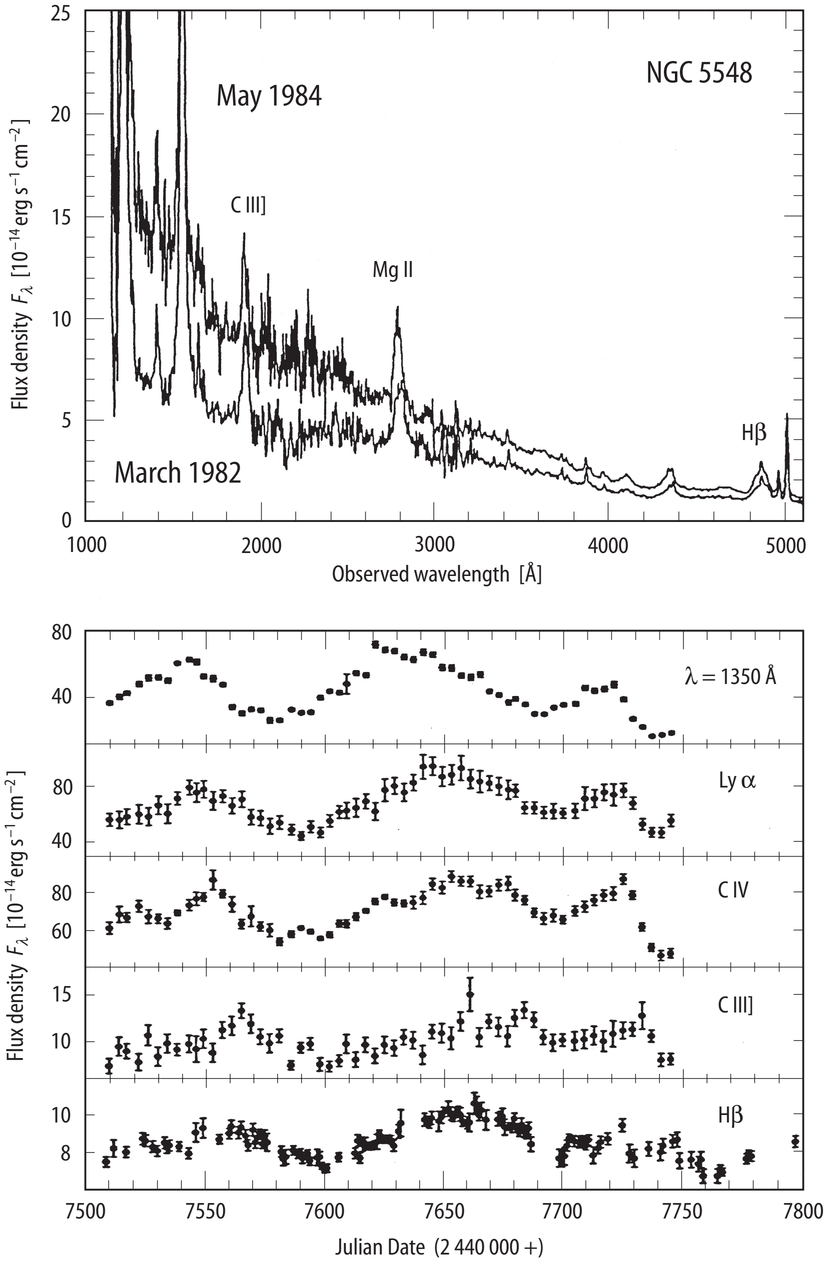

Fig. 4. The variability of the Seyfert 1 galaxy NGC 5548. Top: the ultraviolet-optical spectrum in two epochs. Bottom: line and continuum light curves from the 1989 international campaign.

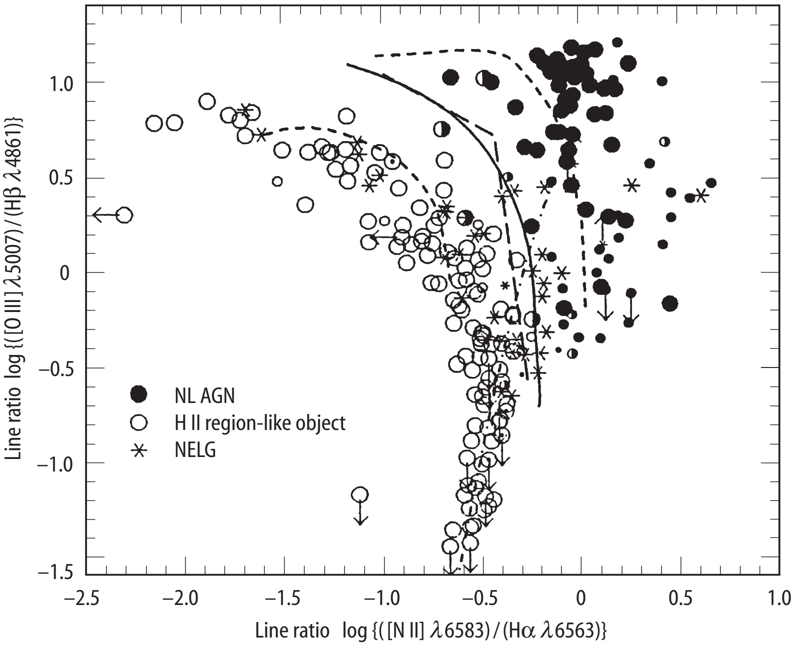

Fig. 5. Narrow line ratio diagram for different emission line objects [from 87V]. The solid line separates HII type objects (gas excited by hot stars) from AGN. The dashed lines are theoretical line ratios from photoionization calculations.

9.5.7.2.2 Narrow line profiles

Narrow emission in Seyferts and NLXGs are 400..1000 km s^{-1} wide. The typical width in LINERs is 200…400 km s^{-1}. The former is about a factor of 3 larger than the expected stellar velocity in the bulge of the host galaxy. In Seyfert 1 galaxies, and NLXGs, there is a clear tendency for lines of higher ionization species to show broader profiles, with asymmetric blue extensions. Thus lines of [FeVII] and [OIII] are broader than lines of [OII] and [NII]. The asymmetry is weak and many narrow lines profiles are symmetrical. Some narrow profiles are clearly made out of several distinct components, originating in different parts of the NLR [84D2, 85W3, 85W4, 86D, 89B5]. For example, the coronal line region is smaller than the region emitting the strong [OIII]λ5007 line.

9.5.7.3 Molecular lines and AGN masers

Infrared and millimeter studies reveal the presence of strong molecular lines in several AGN, mainly due to molecular hydrogen. Recent VLBI studies discovered powerful water vapor masers in several low luminosity AGN. The best observed source, so far, is the LINER NGC 4258. This source shows a remarkable series of water maser transitions originating in a molecular disk with inner and outer dimensions of 0.13 and 0.26 pc, respectively. The disk is very thin and slightly warped and is in nearly perfect Keplerian rotation. Precise VLBA (very long baseline array) velocity measurements allow the most accurate determination of galactic black hole, so far, $3.5 \cdot 10^7\ M_{\odot}$ [95M1, 95M3].

Models for water maser excitation include X-ray heating and mechanical (shock) energy.

9.5.7.4 X-ray lines

X-ray lines have been observed in many Seyfert 1s (e.g. [90P]). The strongest, most common feature is the iron Kα complex at 6.4 (FeI to FeXVI) to 6.9 keV (FeXXVI). The equivalent width of the Kα line is 100…300 eV in Seyfert 1s and 1…2 keV in Seyfert 2s. In the former, the lines are probably due to Auger processes in low excitation gas near the central source, most probably the central accretion disk. This idea has received much support by the discovery of very extended low-energy wings to the Kα lines, indicating relativistic velocities and strong gravitational fields [95M3, 95T1]. Seyfert 2s can be divided into two subgroups in this respect. In highly obscured sources the observed Kα flux is due to reflection presumably in a much larger region. This is consistent with the much larger equivalent width of the lines. In systems with less obscuration (column density less than ≈ 10^{23} cm^{-2}) the line is seen directly with equivalent width similar to Seyfert 1s.

Fig. 6 shows a typical X-ray spectrum of a Seyfert 1 galaxy where the soft X-ray part is highly absorbed (top panel) and the hard part is dominated by the broad 6.4 keV Kα line (bottom panel).

Soft X-ray lines, due to iron L-shell transitions, have been observed in a few Seyfert 2 galaxies (e.g. NGC 1068, [93M]). There are also identifications of H-like and He-like lines of oxygen, neon, magnesium and silicon in Seyfert 2 sources. It is not yet clear whether the line emission region coincides with the NLR, the BLR or with a third, yet unknown region.

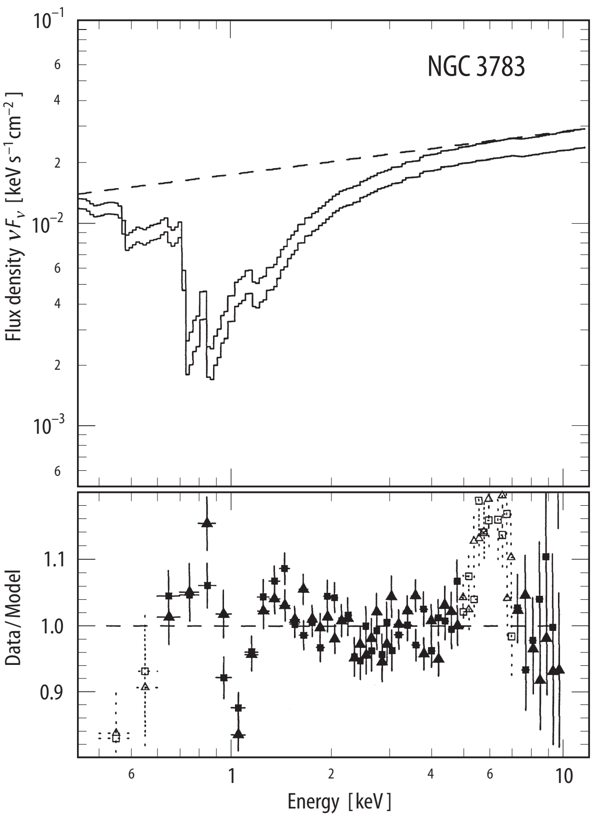

Fig. 6. The X-ray spectrum of NGC 3783 as observed by ASCA. Top: a model of the 0.5…10 keV continuum. Bottom: a comparison of the data to the continuum model. Note the strong excess at 6.4 keV due to the iron Kα line and possible excess emission at around 0.9 keV.

9.5.8 Line and continuum correlations

Many of the observed line and continuum properties are strongly correlated. An obvious example is the line and continuum luminosity for both the broad and the narrow emission lines. Another well known correlation, the so called *Baldwin relationship* [77B, 84W, 90K, 92N], is the decrease in the equivalent width (EW) of several ultraviolet emission lines with increasing continuum luminosity. Broad line widths may be correlated with continuum luminosity but this is still under study, because of various selection effects [85W1, 87J, 92M1]. A stronger, clearer inverse correlation is observed between the radio parameter R (eq. 5) and the width of some emission lines, notably Hβ [86W2].

Various suggested line and continuum correlations are shown in Table 3 where the sign of the correlation, and its reliability, are indicated. Several selection effects that are likely to influence such correlations have not been taken into account. They are related to the discovery technique and the way the data was collected from the literature.

Table 3. Line and continuum correlations for AGN with symbols as follows:
(+ +): well confirmed positive correlation, (+?): suggested positive correlation,
(– –): well confirmed negative correlation, (–?): suggested negative correlation.

Property a	Property b	Correlation
Broad line luminosity	bolometric luminosity	+ +
Narrow line luminosity	bolometric luminosity	+ +
Broad CIVλ1549 EW	L_{UV}	– –
Broad Lyα EW	L_{UV}	– –
Broad MgIIλ2798 EW	L_{UV}	–?
Broad Hβ EW	L_{opt}	–?
Broad Hβ FWHM	R(radio)	– –
Broad Hβ FWHM	X-ray continuum slope	– –
Broad lines FWHM	L_{UV}	+?
CIVλ1549/CIII]λ1909	L_{UV}	–?
blueshift of CIVλ1549	L_{UV}	+?
CIVλ1549/Lyα	L_{UV}	–?
FeII linewidth	L_{radio}	–?
L(optical FeII)	L([OIII]λ5007	– –
L(optical FeII)	X-ray continuum slope	+ +
Lyα/Hβ	$F_{1215Å}/F_{4861Å}$	+ +
[OIII]λ5007 intensity	L_{radio}	+ +

9.5.9 AGN absorption lines

9.5.9.1 Broad absorption lines

About 10 % of all quasars show strong, broad absorption lines (Broad Absorption Line (BAL) quasars). The lines appear on the blue sides of the corresponding emission lines and indicate expansion by up to 30000 k ms^{-1}. The strongest, most common broad absorption lines are CIVλ1549, NVλ1240 and SiIVλ1397. Broad MgIIλ2798 and FeII lines have also been observed but they are weaker and not as common. The broad absorption line gas is believed to be outside the BLR but its exact location and physical conditions are not well understood [85W2, 96T].

High resolution observations of the broad absorption lines reveal, in many cases, substructure on a smaller velocity scale, 500…2000 km s^{-1}. The lines are likely to be the result of scattered continuum radiation but the absorption *EW* is larger than the emission *EW*, indicating that the scattering cannot take place in a uniform spherical shell. The emission line spectrum of BAL quasars is somewhat different from the emission line spectrum of non-BAL AGN of comparable luminosity [e.g 86B]. BAL quasars are, on the average, less radio luminous, less X-ray luminous, and more highly polarized, compared with non-BAL quasars.

9.5.9.2 Narrow absorption lines

Absorption lines are very common in the spectrum of high redshift AGN. In such cases, they depress the observed continuum and make the measurement of some short wavelength lines very difficult. Most of the lines are due to intergalactic absorption or absorption in galactic halos on the line of sight. This topic is beyond the scope of this chapter.

Many Seyfert galaxies show weak to moderate absorption lines that are associated with gas inside, or just outside the BLR [e.g. 83U]. The observed velocities are blue shifted with respect to the broad lines, by up to about 1500 km s^{-1}. The lines can be considerably broader in comparison with the expected thermal width. Examples of narrow absorption lines are: Hβ and HeIλ3889 (in very few objects), and CIVλ1549 and NVλ1240 (in about 50 % of all objects).

Recent ASCA and HST observations suggest a correlation between the ultraviolet absorption lines of CIVλ1549, NVλ1240 and OVIλ1035, and the strong X-ray absorption features due to OVII and OVIII. The ultraviolet lines may originate in a highly ionized gas with a large enough column to allow trace ionization of CIV and NV (e.g. [94M, 96N1]). The location of this component is unclear and likely models include material inside the BLR as well as outflawing gas outside the BLR and even at the NLR distance.

9.5.10 AGN models

Dozens of papers are published every year on the theory of AGN and only some basic ideas will be mentioned here, dealing with the central object, the fueling of AGN, continuum emission processes and line emission. For comprehensive reviews see [90B1, 90N1].

9.5.10.1 Mass, accretion rate and fueling of AGN

The energy output of AGN is most likely due to accretion onto massive central objects, presumably black holes. A lower limit on the black hole mass is derived from the Eddington luminosity, given by

$$L_{\mathrm{Edd}} \approx 1.25 \cdot 10^{38}\, M/\, M_{\odot}\ \mathrm{erg\ s}^{-1}. \tag{8}$$

Observed upper limits on the amount of gas around the central object, mainly from variability studies, indicating that the integrated Compton depth along the line of sight must not exceed unity.

The recent reverberation measurements (see subsect. 9.5.7.1.3) allow rough estimates of the black hole mass and accretion rate. They show that the ionizing luminosity of Seyfert 1s and quasars is a few percent of their Eddington luminosity. Thus the central mass of the most luminous quasars is of the order of a few times $10^{10}\, M_{\odot}$ while that of the more luminous Seyfert 1 galaxies is roughly $10^{8}\, M_{\odot}$.

Spherical and non-spherical accretion models have been proposed to explain the observed emission. Spherical accretion requires a more massive central object since the Compton depth of the accreted gas exceeds unity at a small fraction of the Eddington rate. Non-spherical accretion allows much larger efficiency. The source of accreted gas is not well understood. Feeding from the host galaxy via a large disk, tidal disruption of stars and interaction with nearby galaxies have been proposed.

9.5.10.2 Accretion disks

Accretion disks of various types have been suggested to explain the optical-ultraviolet continuum emission of AGN and the collimation of their radio jets. Thick accretion disks (or, more precisely, *accretion tori*) are more efficient, with accretion rate as large as the Eddington rate. Their structure is hard to calculate and little detailed calculations are available. Thin disks accrete less efficiently and have several appealing properties. The viscosity in such systems results in an outward transfer of angular momentum and inward motion of the gas. Such disks are geometrically thin and optically thick. Their surface temperature is a slowly decreasing function of the radius and the emitted radiation spans about two decades in frequency. The 0.1…1.0 μm continuum of most luminous AGN can be fitted reasonably well by radiation from thin accretion disks. Such models cannot explain the observed infrared and hard X-ray emission and other mechanisms must be invoked. Present day disk models are rather simple. They do not yet combine full atmospheric and general relativistic treatment and avoid complications such as the disk corona. The hard X-ray emission is most likely due to a separate source, either near the center of the (hypothetical) disk or a hot extended corona. Its effect on the disk structure has not yet been seriously investigated. Several comprehensive references on accretion disks are:[73S, 85B1, 87C2, 88M1, 89L, 89S4, 90B1, 90L, 94S, 96S].

9.5.10.3 Nonthermal processes

Synchrotron radiation, inverse Compton and their combination have been considered. Synchrotron emission must dominates at radio frequencies. There is also evidence, from near infrared polarimetry, that the 1…5 μm continuum of radio loud sources is of a nonthermal origin. A model that combines it all is a synchrotron self-Compton model in which relativistic electrons in strong magnetic fields produce the optical continuum and in weak fields the radio-infrared continuum. The up-scattering of these photons by the electrons produce the observed X-ray continuum [85S, 90B1]. There is certainly some confusion in terminology between thermal and nonthermal processes with regard to the high energy spectrum, in particular regarding the Comptonization of high energy photons (e.g. [94T]).

9.5.10.4 Combined models, reprocessing and dust emission

Some theories attempt to explain the overall continuum emission by combining several of the above components. One such model include a central nonthermal source that emits throughout the infrared-X-ray bands. Part of this radiation is absorbed by cold gas, in the vicinity of the black hole, and re-emitted as a big bump in the optical-ultraviolet part of the spectrum. Free-free emission is important at those intermediate energies and much of the reprocessed radiation is due to that [88F1, 88G, 91C2]. A somewhat different idea involves the reprocessing of the nonthermal radiation by a central accretion disk. For example, the central X-ray radiation can be processed by the disk and re-emitted as ultraviolet radiation. The role of dust has also been considered. It is suggested that much of the observed infrared radiation in radio-quiet sources is due to dust. The dust extends from just outside the BLR, where its temperature is close to the condensation temperature (≈ 1500 K) to hundreds of parsecs, where the temperature is considerably lower. This can produces a very broad band infrared continuum [e.g. 89S]. One idea ([93N]) is that the border-line between the BLR and the NLR is at the sublimation radius of the dust.

9.5.10.5 Emission line models

The formation of the broad emission lines is believed to take place in a large number of relatively small ($\approx 10^{13}$ cm), fast moving clouds. The clouds are photoionized by radiation of the central source, their chemical composition is solar, to within a factor 3, and their average electron temperature is 10000…20000 K. Current models are quite successful in explaining the relative intensity of most, but not all the broad emission lines. The results of the various reverberation campaigns suggest a geometrically thick (thick shell?) geometry for the BLR and a range of densities and ionization parameters. Notable failures of the models are the observed intensity of the strong FeII lines and the relative strength of the Lyman and Balmer hydrogen lines [77D, 79D, 81K4, 86O, 88C, 88K3, 89F, 89R1, 90N1, 92F, 95N].

Modeling of the narrow emission lines is rather similar but range in intrinsic properties is larger. In particular, the intensity ratio of high and low excitation lines can vary by an order of magnitude from Seyferts to LINERs. This has been interpreted as being due to a monotonic decrease of mean ionization parameter from luminous to less luminous AGN. Alternatively, shock excitation of the narrow line gas may be more important in low luminosity AGN [83F, 83H, 84S, 85B2, 86F, 89V].

The cool BLR and NLR clouds must be confined or else disappear after a short time. Possible confinement mechanism are magnetic fields and hot inter-cloud gas. The idea of a two-phase model, whereby the hot ($\approx 10^8$ K) and the cool ($\approx 10^4$ K) gas coexist in pressure equilibrium, received much attention. It helps to solve the confinement problem but there are difficulties with the deduced Compton temperature, the drag on the clouds and the Compton depth [81K1, 87M, 87R]. A different idea is that the BLR clouds are the atmospheres of super giant stars, in a central cluster around the black hole [88P1, 88S2, 88V, 89K1, 94A]. Cloud formation in magnetically driven winds have also been considered [85P, 94K].

The gas dynamics in the BLR and the NLR has been investigated by fitting the observed line profiles. The possible explanations for the origin of the motions range from gravitationally bound system of clouds, to free fall and to acceleration by radiation pressure [74M, 79B, 79F, 82M, 83C1, 85M2].

9.5.10.6 Unified models

There have been several attempts to construct unified models for AGN in which a single parameter determines the type of object to be observed. In the radio range it is most natural to think of the relativistic beaming factor as the above single parameter. In this scenario, differences between radio-loud and radio-quiet, steep spectrum and flat spectrum sources depend solely on the observers viewing angle.

A similar idea has been suggested to explain the optical and ultraviolet differences between Seyfert 1 and Seyfert 2 galaxies. In this model, a thick ($\approx$ 1 pc) torus of molecular gas is situated around the central engine, blocking some lines of sight to the source. The opening angle is about 60 degrees and only those objects viewed from unobscured directions show broad emission lines and strong nonstellar continuum. In this scheme, Seyfert 2 galaxies are those objects where the line of sight to the center is blocked, at least at optical and ultraviolet energies, but the NLR is seen because of its much larger dimension. Seyfert 1s are those objects seen in direct view through the opening of the torus. The scheme gains support by the observation of broad emission lines in scattered light, in several Seyfert 2 galaxies [85A, 88K2, 90M, see review in 93A]. There have been several direct measurements of the column density of the obscuring gas in the infrared (e.g. [97V]) and in the X-ray wavelength band.

Combination of the above two schemes has been proposed too. This may explain differences between radio galaxies (strong extended radio source, indirect view of the center) and radio loud quasars (direct view of the center) [e.g. 89B2]. All such schemes are somewhat simplified and cannot explain the variety of observed AGN properties.

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9.6 Extragalactic radio sources

The article had been completed in its original form in 1992. For the results from the years thereafter some additions were made, mainly in the form of references.

9.6.1 Observational methods

Single dish observations

The extension to short mm-wavelengths observations requires dishes with surface accuracies typically smaller than 100 µm. The quality of mm receivers has substantially improved due to the development of High Electron Mobility Transistors (HEMT). Some mm- and submm-telescopes are referenced in Table 1.

Table 1. mm- and submm-telescopes.

Telescope (location)	Diameter [m]	λ_{min} [mm]
Effelsberg (Germany)	100	3.0
Nobeyama (Japan)	45	1.3
Kashima (Japan)	36	1.0
IRAM, Pico Veleta (Spain)	30	0.8
SEST, La Silla (Chile)	15	0.3
HHT, Mt Graham (Arizona)	10	0.3
Onsala (Sweden)	20	2.6
FCRAO, Amherst (Massachusetts)	14	1.3
Yebes (Spain)	14	2.6
NRAO, Kitt Peak (Arizona)	12	0.8
Metsaehovi (Finland)	14	2.6
Bangalore (India)	10	2.6
Shanghai (China)	13.7	2.6
Itapetinga (Brazil)	14	3.4
Caltech, Mauna Kea (Hawaii)	15	0.7
JCMT, Mauna Kea (Hawaii)	10	0.3

Interferometry

The theory of radio interferometry is extensively discussed in [k, p, m, o]. Techniques and applications of VLBI-observations are discussed in [n, a, b, z3].

The experiences with conventional interferometry and the VLBI technique led to the construction of the Very Long Baseline Array (VLBA), which comprises ten 25 m-telescopes. The configuration is intended to optimize uv-coverage (coverage of the spatial frequency plane), gain effects and phase stability [m].

The best angular resolution is at present achieved by mm-VLBI observations. Such observations reach spatial resolutions down to some tens of microarcsec (Fig. 1). Several interferometers and VLBI-networks are listed in Table 2.

In order to get higher resolutions, space-VLBI projects were proposed. The VSOP satellite (Japan) [h, m] was launched in early 1997 and renamed HALCA. Radioastron (Russia) is in the construction phase [88K].

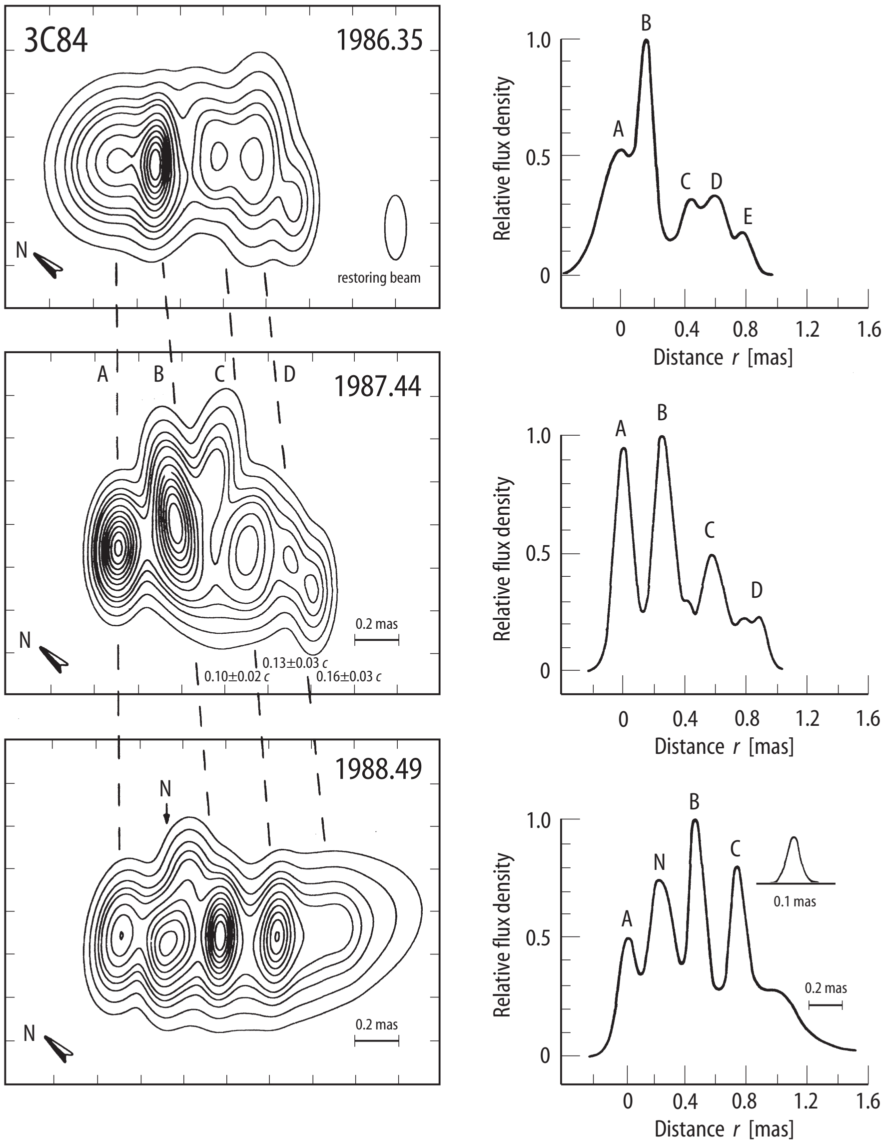


Fig. 1. 43 GHz-observations of the northern core region in 3C84 at 3 epochs [92K1]. On the right the peak flux density profiles of the jet are shown.

Table 2. Interferometers and networks (associated telescopes for the European VLBI net EVN are in brackets). N_T: number of single telescopes.

Interferometers	Telescopes [$N_T \times$ diameter]	Location
WSRT	14×25 m dishes	Netherlands
GMRT (under construction)	30×45 m dishes	India
Nobeyama	5×10 m dishes	Japan
Plateau de Bure	5×15 m dishes	France
Owens Valley mm-Array	3×10.4 m dishes	California

Interferometers	Telescopes [$N_T \times$ diameter]	Location
Hat Creek mm-Array	3×6 m dishes	California
CVN	$5 \times 14 \ldots 47$ m dishes	China
AT	6×22 m dishes	Australia
VLA	27×25 m dishes	New Mexico
MERLIN	Cambridge, Darnhall, Defford, Jodrell Bank, Knockin, Tabley, Wardle	England
VLBA	Brewster, Fort Davis, Hancock, Kitt Peak, Los Alamos, Mauna Kea, North Liberty Owens Valley, Pie Town, St. Croix	USA
EVN	Effelsberg, Jodrell Bank, Medicina, Noto, Onsala, Westerbork, Shanghai, Urumqi (Metsahovi, Yebes, Simeiz, Torun, Wettzell)	Europe
Global Array	EVN, VLBA, VLA	worldwide

9.6.2 Surveys

9.6.2.1 Radioastronomical sky surveys

Various radio surveys, of which many have been completed in the last 15 years, are listed in Table 3.

Table 3. Radio surveys observed at different frequencies (R* and RR* are first or second revisions of the Cambridge catalogues).

Name	ν [MHz]	δ [deg]	S_{lim} [Jy]	Ref.
Gauribidanur	34.5	all sky		89D1
8C	38	≥ 60	1	90R1, 95H1
Pks	85	– 25…25	3	70L
Pks	150	– 25…25	3	70L
6C	151	≥ 30	0.19	eg. 88H2, 93H1
7C	151	≥ 20	0.12	eg. 95L, 96W
3C	178	– 10…70	8	59E
3CR*, 3CRR*	178	– 5…90	9	61B, 83L
4C, 4CR*	178	– 7…80	2	65P, 67G, 80V
Texas	365	0…70	0.15	80D
MC	408	≥ – 62	0.09	see [l]
5C	408	27…54.5	≥ 0.01	see [l]
Pks	408	– 90…20	1	69E
B2	408	24…40.3	0.25	70C, 72C, 73C
B3	408	37…47	0.1	85F2
MPIfR/JBNK/Pks	408	all sky	3	81H
Dwingeloo	820	– 7…85		72B
Green Bank	1400	– 5…82	0.15	86C2
NVSS	1400	≥ 40	0.0025	in progress, see *)

Name	ν [MHz]	δ [deg]	S_{lim} [Jy]	Ref.
FIRST	1400	10^4 sq.deg. of NGP cap	0.001	eg. 95B1, 96G, 97W
Stockert	1420	≥– 19	0.8	86R
PksF	2700	– 80…25	0.2…0.6	79B2
Zelenchuk	4000	0…14	?	89A
Ratan 600	4000	5 ± 20'	0.075	91P1
MPIfR/NRAO	5000	– 5…90	0.25…0.8	81K1, 81K2
MIT/Green Bank	5000	0…35		84B2
MIT/Green Bank II	5000	17…39.15	0.041	90L1
Green Bank	5000	0…75	0.02	89C1, 91G3
MPIfR	5000	45.2…51.7	0.017…0.03	84M1, 84M2
Green Bank	5000	≥ – 42	0.03	91C4

*) Information on http://www.cv.nrao.edu/˜jcondon/nvss.html

9.6.2.2 Radio surveys and catalogues for specific classes and properties of sources

Surveys for sources selected at non-radio frequency ranges

Optically selected

The overall energy distributions of 109 optically selected quasars from the PG-list [86G3] were studied by [89S2, 89P]. Out of a total of 114 objects 84 % were detected at 5 GHz with flux densities ≥ 0.2 mJy in the Palomar Bright Quasar Survey [89K1]. Sources at the low end of the luminosity function are observed primarily by measuring radio emission from known optical objects. The most extensive surveys are those of Kotanyi [80K], Hummel [80H], Sadler [84S2] and Preuss [87P]. These normal galaxies have radio luminosities between 10^{29} and 10^{32} W. They are primarily ellipticals, but spirals are also detected.

For normal spiral galaxies most of the radio emission comes from the disk, but significant emission sometimes arises in a region less than 1 pc across. The discovery of flat-spectrum compact and variable sources in the nuclei of M81 and M104 gave the first evidence for radio-activity in the nuclei of normal galaxies. Seyfert galaxies are also not strong radio sources, but a few, such as NGC 1068, have prominent radio cores and jets [82W]. Their relation to other radio sources is discussed by Meurs and Wilson [84M4].

Weak compact radio sources are frequently found in the nuclei of elliptical galaxies. They are variable on time-scales of months to years. When mapped with high angular resolution, these weak radio nuclei show a similar structure (asymmetric core-jet) as observed in the more powerful radio galaxies and quasars (see Wrobel in [d], p. 134, and [91W2]).

A radio optical study of blue compact dwarf galaxies has been carried out by [91K2].

A radio survey of clusters of galaxies may be found e.g. in [88A1, 90R2].

Cumulative catalogs of QSOs and active nuclei (which are still being updated) can be found eg. in [93H2, 96V1].

IR-selected

From the sources detected by the Infrared Astronomical Satellite (IRAS) bright Galaxies have been investigated at radio frequencies by [85A2, 86C2, 87W1, 88H1]. A tight correlation between IRAS and radio flux densities has been established. mm- and submm-observations of IRAS galaxies are reported in [86C1, 88S3, 89S1, 92S1]. The radio-FIR relation of interacting and non-interacting spiral galaxies has been investigated by [91W3].

X-ray selected

Several X-ray satellites have been launched since 1970: UHURU (1970), Einstein (1978), EXOSAT (1983), Ginga (1987) and ROSAT (1990).

Multifrequency continuum observations of more than 200 ROSAT-selected radio sources with flux densities > 20 mJy have been made by [92N]. [97L] presented 5 GHz VLA-observations of 2127 sources found in the ROSAT all-sky survey and in the Green Bank catalog (see [91G3]).

γ-ray selected

Up to 1992 no observations of radio sources selected by the γ-range have been published, but first observations with the CGRO-satellite (Schönfelder, priv. comm., [92K2]) show that the extragalactic sources detected in the γ-range are predominantly identified with flat spectrum sources reported in the 1 Jy-catalogue [81K2]. A list of AGN detected in the high-energy γ-regime up to 1994 is given in [95M1].

Surveys for variable radio sources

Table 4. Examples of variability studies of extragalactic radio sources (LP denotes whether linear polarization has been measured (+) or not).

Variability type	λ [cm]	N_{sources}	LP	Ref.
Long-term var.	2; 3.7; 6	> 200	+	92A1, 92A2, 92H3
	3.7; 11	82	+	76A
	3.7; 11	33		87F2
	21; 34; 50; 70; 93	30		84A
	6	22	+	84K
	0.3; 0.7; 1.3; 2.5	63		87S4, 92T1, 92T2
	0.3; 0.9; 1.3; 2; 3.7; 6; 11; 21	20	+	85R
	6	15	+	75S
	0.1; 0.3	155		96T1
	0.1; 0.2; 0.3	118		88S3, 93S
Flickering	6; 11	300		84H
Fast blazar var.	8	13		92P2
Intraday var.	6; 11	49	+	91W4, 92Q

Flux density information for 25 years has been collected by the Michigan Group [92A1, 92A2, 92H3]. Monitoring programs covering more than 10 years have been carried out by [87S4, 92T1, 92T2] and [88S3, 93S] for the high frequency range. Table 4 lists mainly ongoing projects for the investigations of the variability of radio sources, see also [z3], p. 607.

Surveys for polarization

Information of linear polarization of extragalactic radio sources is available over a wide frequency range (≈ 0.4…100 GHz) [88S1]. Almost all polarization data published up to December 1978 are collected in the catalogue of [80T]. A list of typical polarization studies is shown in Table 5.

All-sky surveys of the rotation measure (RM) distribution have been made by [80S]. The depolarization of a sample of 47 double radio sources with one-sided jets has been studied by [91G1]. VLBI-polarization maps at 5 GHz are published by [92G].

Many experiments have been performed to measure the radio circular polarization (CP) of extragalactic radio sources. Observations of about 120 sources are to be found in the CP catalogue of [83W]. No entry in this catalogue lists a CP in excess of 0.5 % and, therefore, the authors consider CP > 0.1 % to be strong circular polarization.

Table 5. Examples of polarisation studies of extragalactic radio sources (N_{sources} gives the number of sources of the catalog).

Observations	N_{sources}	Ref.
RM distribution	All-sky	80S, 81S3
LP catalog	1510	80T
CP catalog	120	83W
VLA-pol. maps	40, 23, 47	82R, 84B4, 91G1
VLBI-pol. maps	11	92G

Surveys of the structure of radio sources

Table 6 lists some recent surveys for radio source structures.

Table 6. Examples for radio source structure surveys.
S_n: flux density at n cm in [Jy]
α: radio spectral index

Catalogue	N	ν [GHz]	Selection	Instrument	Ref.
S5 VLBI-sample	13	5	$S_5 \geq 1$, $\delta \geq 70°$, $b \geq 10°$, $\alpha > -0.5$	VLBI	88W2
Caltech-sample I	65	5	$S_5 \geq 1.3$, $\delta \geq 35°$, $b \geq 10°$	VLBI	88P
Caltech-sample II	37	5	$S_{10.7} \geq 5$	VLBI	91W1
Caltech-Jodrell Bank 1	135	1.6; 5	$0.7 \leq S_5 < 1.3$, $\delta \geq 35°$, $\lvert b\rvert > 10°$	VLBI	95P, 95T, 95X
Caltech-Jodrell Bank 2	193	5	$S_5 \geq 0.35$, $\delta \geq 35°$, $\lvert b\rvert \geq 10°$, $\alpha_{8400}^{365} \geq -0.5$	VLBI	94T, 95H2
Phase-ref. calib. (JVAS)	902	1.4…8.4	$S_5 \geq 0.2$, $75° \geq \delta \geq 35°$, $b \geq 2.5°$	VLA	92P1,92P4
Lobe-dom. sources	30	10.7	$S_{0.97} \geq 0.7$, $m_b \leq 19$ mag, ang. size > 10 as	VLBI	87Z
3CR-CSS-sample	25	1.6	80 % of S_5 in the steep ($\alpha > 0.5$ above 0.4 GHz) component	VLBI/ MERLIN	89F
B3-VLA-sample	1103	1.4	5 subsamples (see Ref.)	VLA	89V1
PKS 0.5-Jy-sample	323	5; 8.6	$S_{2.7} > 0.5$, flat spectrum, $\lvert b\rvert > 20°$, $-45° < \delta < +10°$	VLA/ ATCA	97D

Optical identifications

Optical identifications, redshifts and spectra of radio sources from the 1 Jy catalogue [81K2] are presented by [86L, 87L2, 89S3, 91S, 96S1, 96S2], whereas optical polarization measurements are given by [81M, 84M3, 84S1, 88F1, 88F2, 89W, 90I, 90K3].

CCD-images of radio sources are published in [81P1, 82A, 83M, 85B, 85C 88F1, 90O].

Related source catalogues

Table 7. Source catalogues for optical identifications.

Revised Shapley Ames Catalogue of Bright Galaxies (RSA)	81S1
Veron-Cetty and Veron Catalogue of Bright Galaxies (VVC)	84V, 86V
Nearby Galaxies Catalogue	88B3
General Catalogue of HI Observations of Galaxies	89H1
3rd Reference Catalogue of Bright Galaxies	91V
A catalogue of quasars and active nuclei	96V1
A revised and updated catalogue of quasi-stellar objects	93H2
BL Lac Objects and Rapid Variable QSOs	92B3
Radio Survey of Galaxy Clusters	88A1, 90R2

9.6.2.3 Radio spectra

Individual radio spectra have been extended to mm-wavelengths (e.g. 90 and 230 GHz spectra and lightcurves are presented by [88S3, 93S]). See also eg. [92A2, 92H3, 92T1, 92T2] and references therein.

9.6.3 Basic relations

9.6.3.1 Synchrotron radiation

9.6.3.1.1 Emission by a single electron

See LB VI/2c, p. 325

9.6.3.1.2 Radiation from an ensemble of electrons

In addition to power-law distributed electrons plasma-effects may pile up the energy distribution leading to monoenergetic electrons. This effect seems to occur in mega-masers. According to [88C1] the energy distribution is given by

$$N(E)\mathrm{d}E = n(\gamma)\mathrm{d}\gamma = N_0\delta(\gamma - \gamma_0)\mathrm{d}\gamma \tag{1}$$

The emission coefficient in the thermal plasma with large scale random magnetic field is then calculated as

$$\varepsilon_r(f) = b_1 f(1+f^{-2})CS(x) \tag{2}$$

with

$$CS(x) = W_{0,\frac{4}{3}}(x)W_{0,\frac{1}{3}}(x) - W_{\frac{1}{2},\frac{5}{6}}(x)W_{-\frac{1}{2},\frac{5}{6}}(x) \tag{3}$$

and $x = (f/g_0)\ (1 + f^{-2})^{-3/2}$, $f = \nu(\gamma_0\nu_p)$, $b_1 = q_0\ N_0\ \nu_p/(8\gamma_0)$, $g_0 = 3\nu_0\gamma_0/2\nu_p$. The function $W_{\lambda\mu}(x)$ represents the Whittaker function and $\nu_0 = 2.8{\cdot}10^6$ (B/Gauss) Hz and $\nu_p = 9{\cdot}10^3(n_e/\mathrm{cm}^{-3})^{1/2}$ Hz and are the gyro- and plasma frequencies, respectively. For large ($f \gg 1$) and small ($f \ll 1$) frequencies the emission coefficient reduces to the vacuum case and the Razin-Tsytovich suppression range, respectively. The energy loss due to spontaneous radiation of relativistic electrons is obtained by integration of eq. (2) over all frequencies.

9.6.3.2 Absorption mechanisms and plasma effects

See LB VI/2c, p. 326

9.6.3.3 Energy losses and evolution of source spectra

9.6.3.3.1 Energy loss rates and time scales

See LB VI/2c, p. 328

9.6.3.3.2 Equilibrium spectra

See LB VI/2c, p. 330

9.6.3.3.3 Synchrotron and Compton losses

Several observations have demonstrated that many BL Lacs, OVVs and red quasars (see subsect. 9.5) have a sharp cutoff in their continuous emission spectrum at the near IR ($3 \cdot 10^{14}$ Hz). Since the cutoffs occur most frequently in variable, strongly polarized sources, it is generally supposed that the radiation arises from incoherent electron synchrotron emission. These cutoffs which have been observed in the jet knots were by some authors ascribed to relativistic protons accelerated in shockwaves [88B1]. The occurrence of such cutoffs therefore predicts the presence of near relativistic flows in jets.

9.6.3.3.4 Inverse Compton limit

See LB VI/2c, p. 331

9.6.3.3.5 Inverse Compton effect and X-ray observations

See LB VI/2c, p. 331

9.6.3.3.6 Adiabatic expansion

See LB VI/2c, p. 332

9.6.3.3.7 Flux density evolution of jet components

Shock waves propagating down relativistic jets have been proposed to be the origin of the variability of the nonthermal continuum in blazars [92M]. Non-axisymmetric perturbations in relativistic rotating MHD jets can reproduce the quasi-periodic lightcurves of quasars and BL Lac objects (cf. subsect. 9.6.6.4.8, [92C2]). The basic outline of the relativistic jet model was first given by [78B] and expanded by [79B1] and [85M], cf. also [92M]. Under the assumption that the jet is adiabatic, the spectral evolution of a flare arising from a shock propagating down a jet takes place in three steps (Fig. 2):

Compton-loss stage

$$S_m \propto \nu_m^{[(a-11)/2(a+1)]} \tag{4}$$

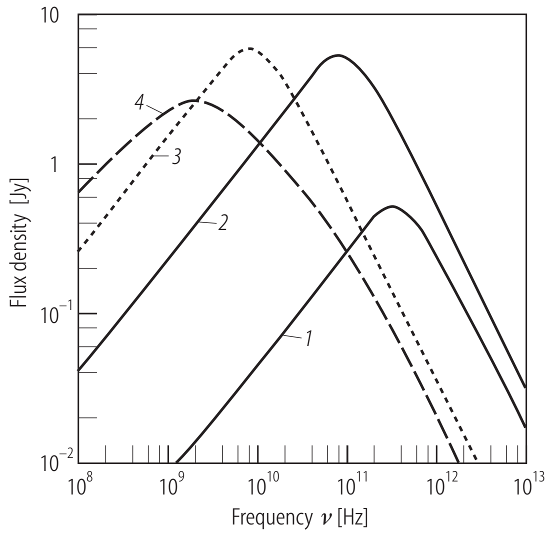


Fig. 2. Schematic spectral evolution of a flare arising from a shock propagating down a jet. The outburst progresses from the Compton-loss stage (*1* to *2*) to the synchrotron-loss stage (*2* to *3*) to the adiabatic-loss stage (*3* to *4*).

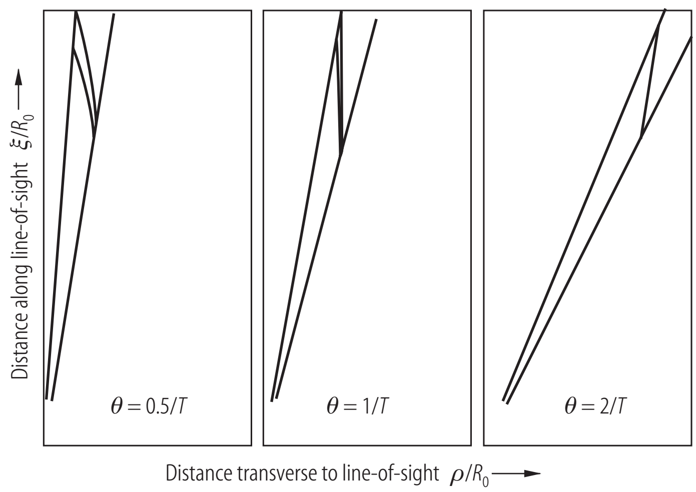


Fig. 3. Cross section of a shock moving down a relativistic jet for three different angles of inclination of the jet axis relative to the line of sight [92M].

Synchrotron-loss stage

Case (i, iii):

$$S_m \propto \nu_m^{[(2s-5)(2+3a)]/[4(s+2)+3a(s-1)]} \tag{5}$$

Case (ii):

$$S_m \propto \nu_m^{-[4(3a+2)-5s]/[2(2s+1)+3a(s+2)]} \tag{6}$$

Adiabatic-loss stage

$$S_m \propto \nu_m^{[(4s-19)+3a(2s+3)]/[2(2s+1)+3a(s+2)]}\,, \tag{7}$$

where S_m denotes the flux density at the turnover frequency ν_m. The synchrotron-loss stage is distinguished by three cases. For case (i), the line of sight penetrates first the front, then the back of the shock. For case (iii), the reverse is true. For case (ii), most of the shock is viewed nearly sideways. Typical values for the three cases are shown in Fig. 3. The parameters s and a are related to the relativistic electron distribution (with R = the distance along the jet, $N(E)$ = number density of electrons with energy E)

$$N(E,R) = K(R)\,E^{-s},\ E_1(R) < E < E_2(R), \tag{8}$$

and the decay of the magnetic field in the jet

$$B(R) \propto R^{-a},\ a = 1 \text{ behind shock, } a = 2 \text{ in front of shock with} \tag{9}$$

$$K(R) \propto R^{-2(s+2)/3},\ E_i(R) \propto R^{-2/3},\ (i = 1, 2) \tag{10}$$

The Lorentz factor of the shock is $\Gamma = 7$. ξ is the coordinate along the line of sight, l the coordinate transverse to it. The obsever is at $\xi = \infty$. R_0 is the core radius where the jet is generated. The intrinsic opening half angle is 1°5.

9.6.3.4 Energy considerations

See LB VI/2c, p. 332

9.6.4 Extended sources

The distinction of extragalactic radio sources into extended and compact radio sources refers to the observer's point of view. Various *unified schemes* [91K1] have been suggested according to which the different classes of AGN (see subsect. 9.5.2) are due to different viewing angles while they are intrinsically of the same type. Until now there is no single generic unified scheme covering all the proposed possibilities. Using the relativistic beaming model, [89B1] concludes that all radio loud quasars are beamed towards us, whereas powerful radio galaxies form the parent population. Radio-quiet quasars and powerful IR-galaxies can be unified using similar orientation effects. For detailed discussion and interpretation of such unification theories see subsect. 9.6.6.6 and [93A, 95U].

9.6.4.1 Structure of extended sources

A subdivision of extended radio objects was suggested by Fanaroff and Riley [74F], who divided extended sources into two classes, depending on whether the separation of the brightness peak was less than (FR I) or more than (FR II) half the total size of the source. In addition, [74F] discovered that the two classes were also distinguished by their radio luminosities. Following this scheme, Class I (FR I) consists of the low luminosity sources ($L_{178\ \mathrm{MHz}} < 10^{25}$ W Hz^{-1}sr^{-1}), with plume-like jets, while Class II (FR II) represents the more luminous objects ($L_{178\ \mathrm{MHz}} > 10^{25}$ W Hz^{-1}sr^{-1}) with jets terminating in hotspots and well-defined lobes (cf. subsect. 9.6.6.1.4). Since FR I sources show more complex morphologies, Class I can be divided in several subclasses including fat doubles, twin-, wide-angle-(WAT) and narrow-angle-tailed (NAT) sources.

Figure 4 shows how the subdivisions are related to the radio power, the optical galaxy classification and the occurrence of neighbour galaxies [89O].

Although the FR classification has proved its usefulness, recent high dynamic range maps show that this classification cannot be applied in all cases [92B6]. For example, some edge-brightened FR II sources appear highly noncollinear with prominent hot spots or show complex radio structures. The typical features of the different source types and correlations with other radio source characteristics have been summarized by [80M]. Examples of FR I and FR II galaxies are given in Fig. 5.

9.6.4.2 Structure of lobes

Due to the improvement of mapping techniques [84P1, 86N1] the fine structure of the lobes has been mapped in great detail, revealing structures like filaments and cocoons (see Fig. 6). In addition, complex distributions of large Faraday rotation over the lobes of extended sources (e.g. Cygnus A [87D]) were detected.

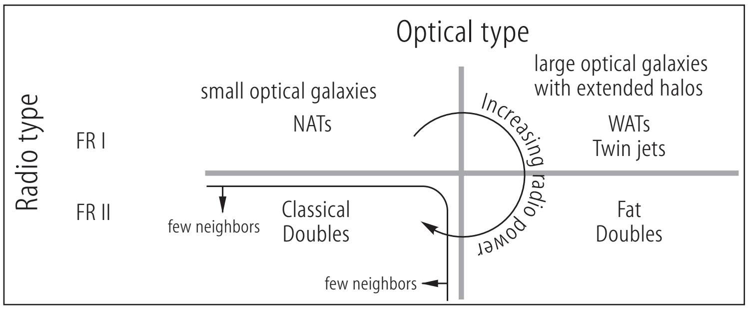


Fig. 4. Fanaroff-Riley classification with four subdivisions [89O]. Note that the least (NATs) and most powerful radio galaxies (Classical Doubles) are associated with the least powerful optical galaxies, whereas the intermediate luminosity radio sources (WATs and Fat Doubles) are associated with the most powerful optical galaxies. Furthermore, the Classical Doubles form the only class that tends to be associated with isolated galaxies.

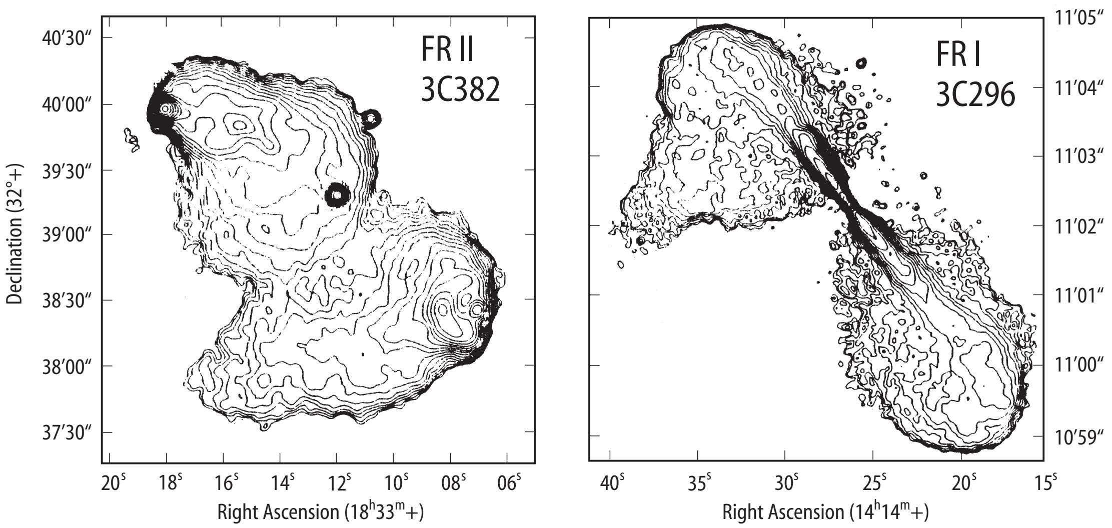


Fig. 5. Typical FR I (right) and FR II (left) radio sources [91L3].

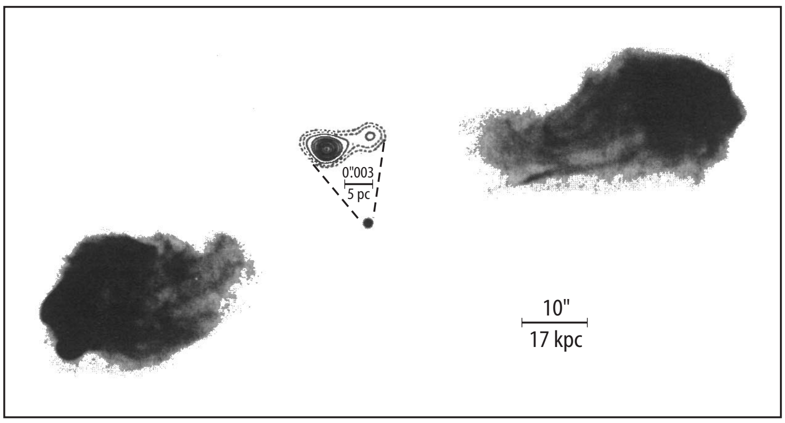


Fig. 6. Cygnus A (a classical FR II source) shows filamentary structure in its lobes and a faint radio jet which apparently feeds the outer hotspot of the eastern lobe (see [j], p. 594).

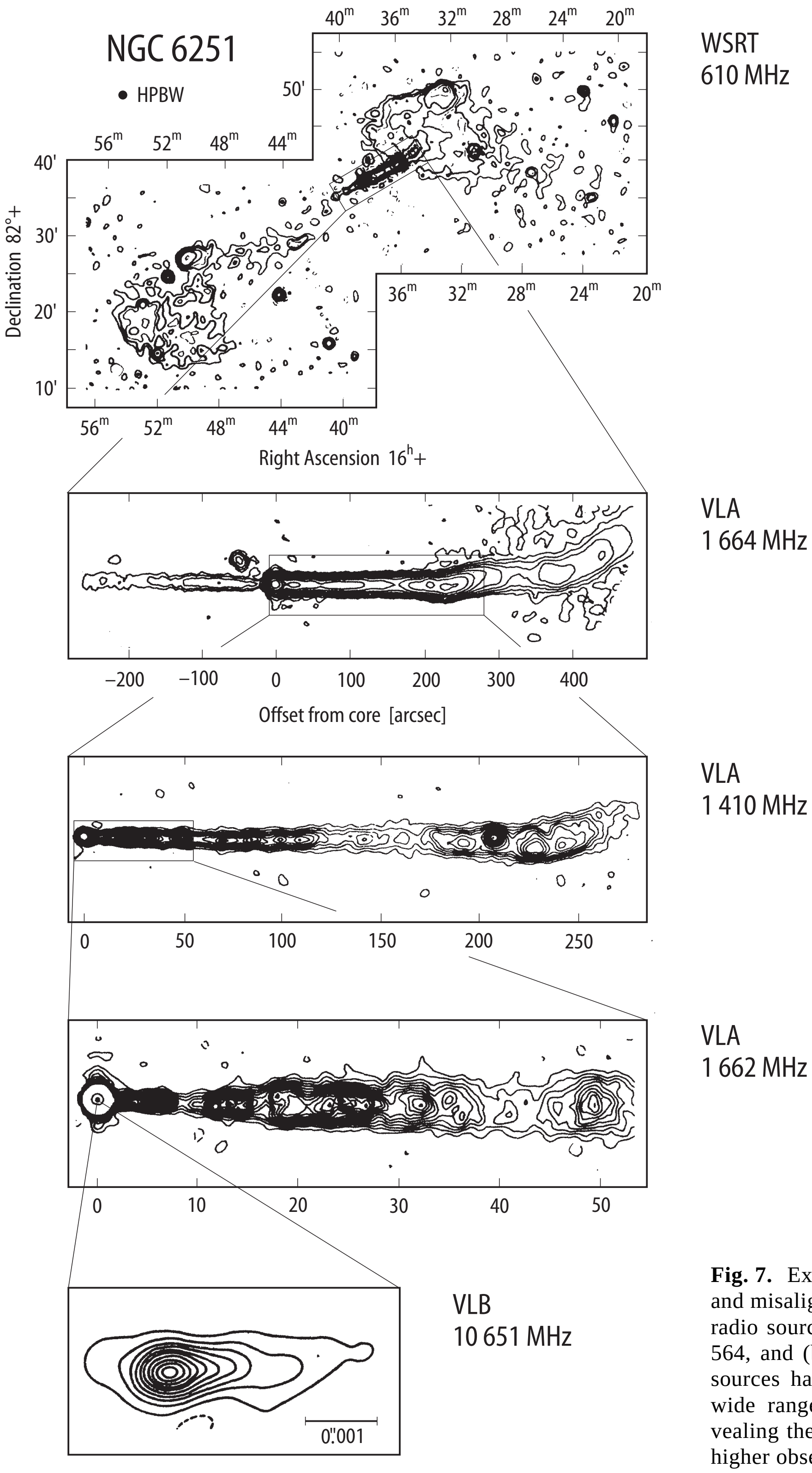
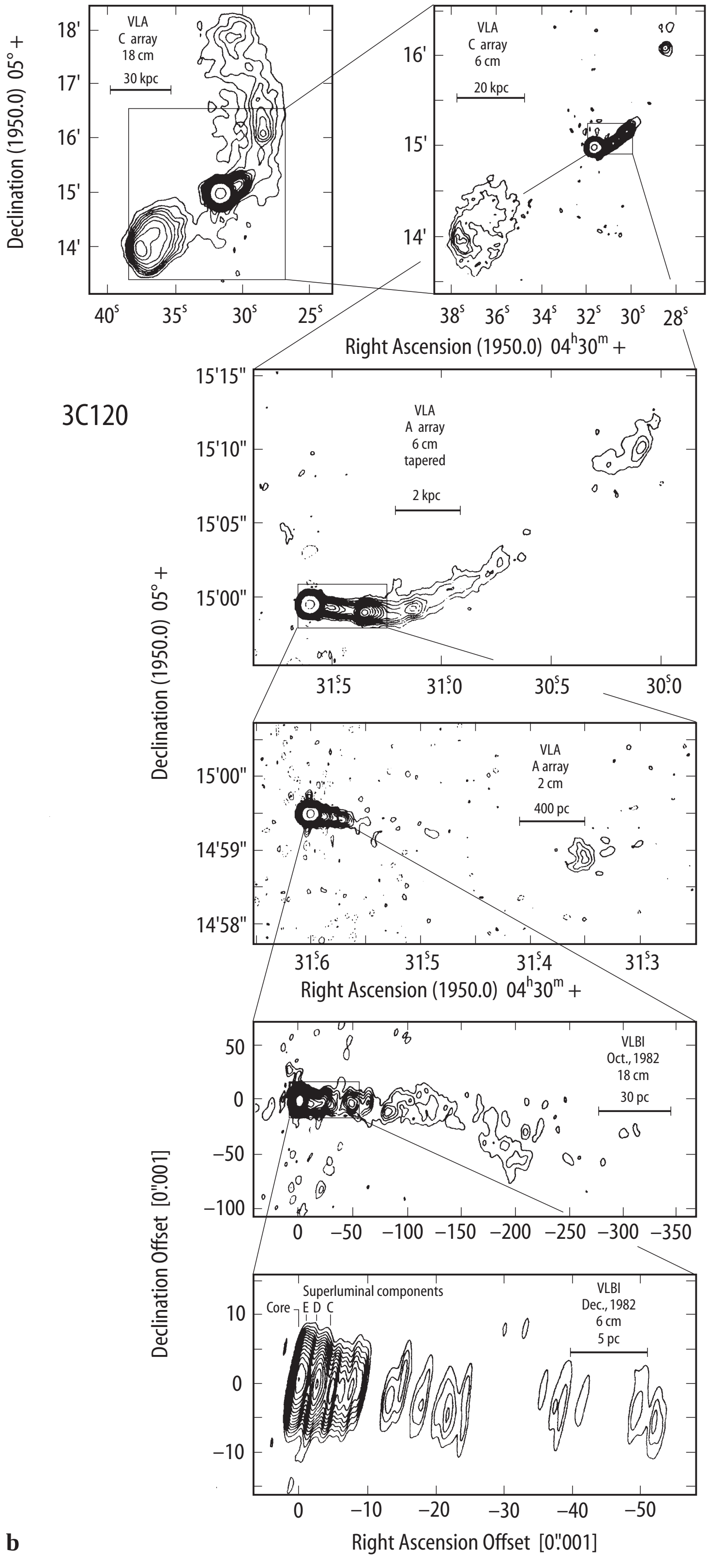


Fig. 7. Examples for align-ments and misalignments of the jets in the radio sources (a) NGC 6251 [j], p. 564, and (b) 3C 120 [84B3]. Both sources have been mapped over a wide range of angular scales, revealing the one-sidedness of jets at higher observing frequencies.

a


3C120
VLA
C array
18 cm
30 kpc
VLA
C array
6 cm
20 kpc
Declination (1950.0) 05° +
Right Ascension (1950.0) 04h30m +
VLA
A array
6 cm
tapered
2 kpc
VLA
A array
2 cm
400 pc
VLBI
Oct., 1982
18 cm
30 pc
Superluminal components
Core
E D C
VLBI
Dec., 1982
6 cm
5 pc
Declination Offset [0."001]
Right Ascension Offset [0."001]

b

9.6.4.3 Jets

A comprehensive list of known radio jets is contained in [84B3]. Jet physics and examples of various morphological types (e.g. helical jets, limb- and edge-brightened jets) are discussed in [d, e, q, u, w, y].

9.6.4.4 Properties of extended radio sources

Laing-Garrington effect

A strong asymmetry in the degree of depolarization is found between the jet and counter jet sides. Out of 37 sources with significant depolarization 34 sources show less polarization on the jet side [88G1, 91G1]. There is also a significant asymmetry in the spectral index of the two sides as the jet-side-spectral index is systematically flatter by typical $\Delta\alpha = 0.1$. Virtually no asymmetries are found in flux density, peak brightness, and separation from the nucleus [88L1]. This effect confirms that stronger Faraday depolarization occurs systematically on the counter jet side.

In Pic A a bright, highly polarized optical counterpart of the western hot spot was found by [87R].

9.6.4.5 Alignments on large scale

According to refined contour maps of radio galaxies, showing their structure over a wide range of angular scales, strong misalignments between parsec-scale and kiloparsec-scale jets are found to be quite common (see NGC 6251, [84B3]). A summary of such observations is given by [83R].

Misalignments usually increase with core prominence f_c: lobe-dominated radio galaxies with kpc-scale jets, exhibit pc-scale jets on the same side as the large-scale jets, whereas core-dominated sources bend continuously, with the sharpest curvature occurring closest to the core. This behaviour is explained by a projection effect. Short jets in core dominated sources are assumed to be close to the line of sight, therefore small bends in jets may project as large apparent misalignments [84B3]. However, because of the observed continuity in the one-sidedness from pc- to kpc-scale jets (see e.g. Fig. 7) in both core- and lobe-dominated sources it has been claimed that the large-scale jets should also be at least moderately relativistic.

9.6.4.6 Gravitational lensing effects

Since the detection of the "twin quasar" 0957+561 AB [79W] with identical redshifts and spectra, it was recognized that structures or positions of extragalactic radio sources can be feigned by gravitational lensing effects. In the following years a number of further lense candidates were published. An overview is given by [89M1]. The upper part of Table 8 shows 14 accepted cases of multiply lensed source images. On the bottom, suspected cases of gravitational lenses are listed. More recent lists of lensed objects can be found in [z2]. For an ongoing search for new cases of gravitational lenses (CLASS) see eg. [95J, 95M2]. Lensing by stars in galaxies, so-called microlensing, can affect the continuum flux density observed from compact sources. The blazar variability (see subsect. 9.6.5.2) itself may in some cases be due to microlensing [87S1], but until 1992 there was no observational evidence for this explanation.

Table 8. The upper part of the table shows presently accepted cases of multiply lensed source images. The lower part represents sources which are assumed to be gravitationally lensed ("?" = unknown redshifts). z: redshift, θ: distance.

Sources	z_{source}	z_{lens}	θ [arcsec]	Comp.	Ref.
0142–100	2.72	0.49	2.2	A,B	92B2
0218+357	?	?	0.335	Ring	92P1
0414+053	2.63	?	3.0	A,B,C,D	92B2
0957+561	1.41	0.36	6.1	A,B	79W
1115+080	1.72	?	2.3	A_1,A_2,B,C	92B2
1131+0456	?	?	2.2	Ring	92B2
1208+10	3.8	?	0.45	A,B	92B2
1413+117	2.55	?	1.1	A,B,C,D	92B2
1422+231	3.62	?	1.3	Arc	92P1
1549+3047	?	0.11	1.8	Ring	92B2
1634+1346	1.75	0.25	2.1	Ring	92B2
1830–211	?	?	1.0	Ring	92B2
2016+112	3.27	1.01	3.8	A,B,C	92B2
2237+031	1.69	0.039	1.8	A,B,C,D	92B2
0023+171	0.95	?	4.8	A,B,C	89M1
1042+178	0.92	0.5?	1.6	A,B,C,D	89M1
1120+019	1.46	0.6?	6.5	A,B	89M1
1429–008	2.08	1.6?	5.1	A,B	89M1
1635+267	1.96	0.57	3.8	A,B	89M1
1654+134	1.74	0.25	2.1	Ring	89M1
2345+007	2.25	?	7.3	A,B_1,B_2	89M1

9.6.5 Compact sources

9.6.5.1 Structure of compact sources

According to the unified theories (eg. [93A3, 95U]), the radio sources are classified in a 3D-space (see Fig. 8 [91L1]). In any horizontal plane of the cube the sources are unified.

Luminosity represents the low frequency luminosity density at frequencies $\nu \leq 200$ MHz which discards most of the Seyfert Galaxies. Pseudoluminosity is the apparent luminosity density of a beamed optical component, and depends on the speed and orientation of relativistic motion and unknown details of relativistic jets. Gas symbolically denotes the source of the emission line spectra of AGN, responsible for such different classes as referred to in Table 9.

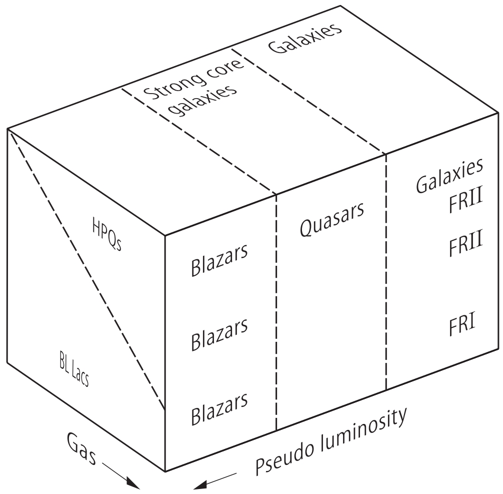


Fig. 8. Unification of different AGN families [91L1].

Table 9. Classification of AGN (see also subsect. 9.5.2).
Abbreviations:
OVV = optically violent variables
BLL = BL Lac objects
QSO = quasi-stellar (optical) object
QSR = quasi-stellar radio source
HPQ = highly polarized quasar
BLRG = broad (emission-) line radio galaxy
NLRG = narrow (emission-)line radio galaxy
NELG = narrow emission line (X-ray) galaxy
LINER = low ionisation nuclear emission region

Active galaxies	Subclass AGN		Characteristics	
	radio-quiet	radio-loud	I [W]	Emission lines
Blazars	OVV, BLL	OVV, BLL	$\geq 10^{36}$	?
Quasars	QSO	QSR, HPQ		$(10^3 \ldots 10^4)$ km s^{-1}
Emission Line Gal.	Seyfert 1	BLRG	$10^{34} \ldots 10^{36}$	broad
	Seyfert 2, NELG	NLRG		narrow
	LINER		$\leq 10^{34}$	$(500 \ldots 10^3)$ km s^{-1}
Starburst-, FIR-Gal.			10^{37}	extremely narrow
Extragal. HII-regions				≤ 300 km s^{-1}
Blue comp. Dwarf Gal.				

9.6.5.2 Variability of compact sources

Intensity variations

Intensity variations have been detected over the wavelength range of about 3 mm to about 1 m. Several types of flux density variability are observed:

Intensity outbursts of similar amplitudes occur nearly simultaneously over a wide wavelength range. This behaviour can be explained by prolonged injection (or acceleration) of relativistic particles into an optical thin synchrotron source (intensity increase) and subsequent adiabatic expansion or radiation losses (intensity decrease).

Intensity outbursts occur first at short wavelengths and propagate with decreasing amplitudes towards longer wavelengths. This pattern can be explained by adiabatic expansion of an initially opaque synchrotron source.

Low frequency flux density variations without adequate strong high frequency variations on time scales of days to months are called *flickering*. These variations depend on the galactic latitude and therefore they can be explained by extrinsic phenomena (free-free absorption, refractive and diffractive interstellar scintillation) effected by interstellar matter located between the observer and the source, e.g. supernova remnants. The extreme scattering events of 0954+658 [87F1] taking place in well defined 'absorption intervalls' (e.g. 50 days) are induced by clouds with corresponding sizes.

Intraday Variability (IDV) taking place on time scales of hours is almost common in one third of all flat spectrum radio sources (the spectral index between 6 and 11 cm: $\alpha_6^{11} > -0.5$, $S \propto \nu^{\alpha}$) exhibiting variability amplitudes of up to 30 %. Simultaneous lightcurves over a range from 3.6 to 20 cm wavelengths have been investigated by [91Q3] (see Figs. 9, 10). In the case of the BL Lac 0716+714 clear hints to simultaneous variations in the optical excluding extrinsic reasons for this kind of variability have been found [91Q2]. The most promising explanations for this variability type are the shock-in-jet models discussed by [85M, 91Q1, 92M], but also refractive interstellar scintillation and coherent processes [92B1] are discussed to solve the problem of high brightness temperatures (10^{18} K) exceeding the inverse Compton limit (10^{12} K).

Polarization variability

Polarization variability can be classified into similar variability types as already discussed for the total intensity. The time scales for significant changes in polarization degree and angles appear to be shorter than those for intensity variations, whereas the variability amplitude exhibits commonly higher values. Due to the improvement of polarimetry, correlations and anticorrelations of polarization and intensity variations have been found in some sources. For example, the sources OJ 287 and 0917+624 show polarization angle swings of up to 180° during a minimum of polarized flux density which are assumed to be the result of shocks propagating in helical jets.

Structural variability

As more multi-epoch VLBI maps of the radio cores of active galactic nuclei became available, it was becoming increasingly clear that superluminal motion is a common feature of flat spectrum radio sources $\alpha_6^{11} > -0.5$ [88W2]. Causal connection between the emergence of superluminal components from the cores and the flux density outbursts has been demonstrated by several authors (recently also at mm-wavelengths for 3C273 [90C2, 90K2]). First results from mm-VLBI show that strong jet curvature near the cores might be more common than expected and that curvature increases with increasing resolution. Some examples of repeated VLBI-measurements of superluminal sources are given in Fig. 11.

The features of structural variability can be classified by

1) stationarity
2) superluminal motion along non-curved trajectories with constant velocities
3) superluminal motion along curved trajectories with variable velocities
4) coexistence of superluminal and stationary components.

The classification of radio sources following this scheme depends on the available data. For example more observational data may shift a source from 1) to 2) or from 2) to 3). A representative list of sources with measured velocities is shown in Table 10. More recent tables and additional references can be found in [e, z1].

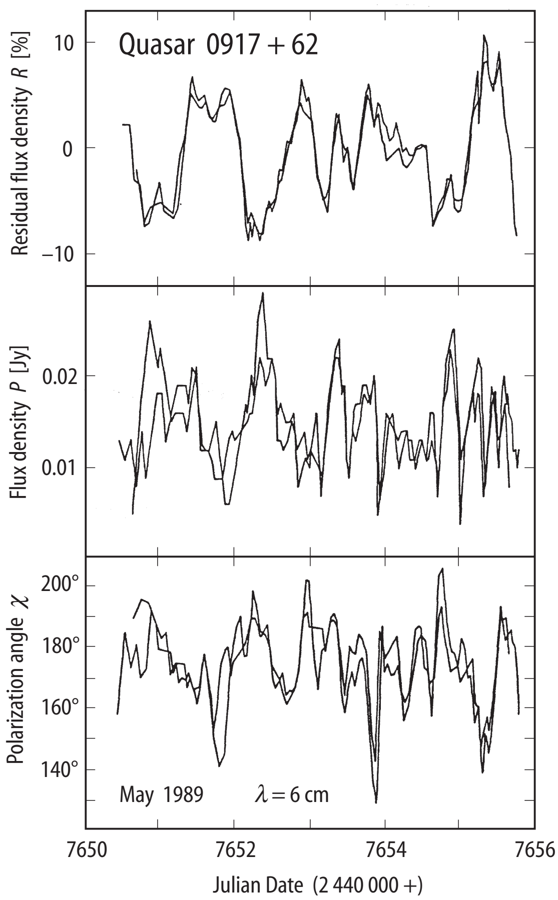


Fig. 9. The reliability of short time variations, being independent from atmospheric effects, has been demonstrated for the quasar 0917+624 by a simultaneous measurement of the Effelsberg 100m telescope and the VLA (R = residual flux density, P = polarized flux density, χ = polariza-tion angle) [91W4].

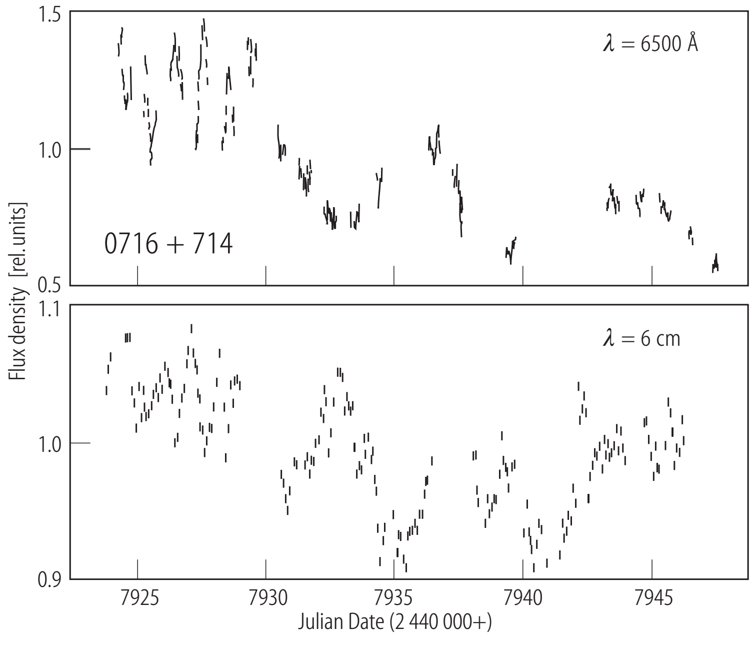


Fig. 10. Light curves of 0716 + 714 in the radio and the optical range. A change of the variability mode with a timescale from 1 to 7 days can be simultaneously seen in both regimes (at JD = 2447930) [g], p. 139.

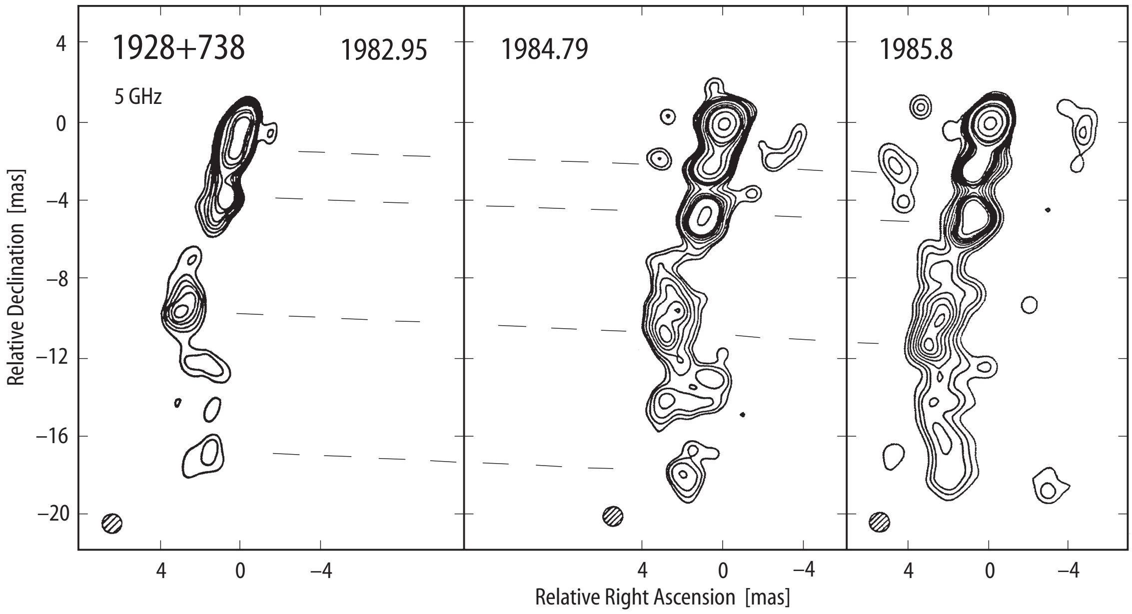


Fig. 11. 5 GHz observations of the superluminal flat spectrum source 1928+738 [90S].

Table 10. Superluminal sources and stationary or subluminal sources [see 89M4].
H_0 = 100 h km s^{-1} Mpc^{-1}; μ = proper motion; β_{app} = apparent velocity

Source	Other names	z	Id	μ [10^{-3}arcsec/yr]	$\beta_{app}h$
Superluminal sources					
0212+735		2.367	BL	0.09	3.9
0333+321	NRAO140	1.258	Q	0.15	4.8
0430+052	3C120	0.033	G	1.35…2.66	2.1…4.1
0723+679	3C179	0.846	Q	0.19	4.8
0735+178		0.424	BL	0.18	2.8
0836+710		2.16	Q	0.13…0.25	0.2…10.4
0850+581		1.322	Q	0.12	3.9
0851+202	OJ287	0.306	BL	0.28	3.3
0906+430	3C216	0.669	Q	0.11	2.4
0923+392	4C39.25	0.699	Q	0.16	3.5
1040+123	3C245	1.029	Q	0.11	3.1
1137+660	3C263	0.652	Q	0.06	1.3
1150+812		1.25	Q	0.13	4.1
1226+023	3C273	0.158	Q	0.76…1.20	5.1…8.1
1253–055	3C279	0.538	Q	0.11…0.50	2.0…9.2
1641+399	3C345	0.595	Q	0.3…0.48	5.9…9.5
1642+690		0.751	Q	0.34	7.9
1721+343	4C34.47	0.206	Q	0.36	3.1
1901+319	3C395	0.635	Q	0.64	13.2
1928+738		0.302	Q	0.6	7.0
1951+498		0.466	Q	0.07	1.2

Source	Other names	z	Id	μ [10^{-3}arcsec/yr]	$\beta_{app}h$
Superluminal sources (continued)					
2200+420	BL Lac	0.0695	BL	0.76	2.4
2230+114	CTA102	1.037	Q	0.65	18.5
2251+158	3C454.3	0.859	Q	0.35	8.9
Stationary or subluminal sources					
0153+744		2.33	Q	< 0.03	< 1.3
0316+413	3C84	0.0172	G	0.24	0.2
0710+439		0.517	G	< 0.04	< 0.7
0711+356		1.62	Q	< 0.05	< 1.8
1228+127	M87	0.004	G	< 0.3	< 0.01
1637+826	NGC2651	0.023	G	< 0.3	< 0.3
1803+784		0.68	BL	< 0.07	< 0.74
1934–638		0.683	Q	< 0.4	< 3.1
2021+614		0.2266	Q	< 0.04	< 0.04
2134+004		1.936	Q	< 0.091	< 0.4

9.6.5.3 Correlation of radio spectra with other properties

See LB VI/2c, p. 341

9.6.6 Physics of extended and compact radio sources

9.6.6.1 Extended sources

9.6.6.1.1…9.6.6.1.3

See LB VI/2c, p. 396 ff

9.6.6.1.4 Elements of radio galaxies

Normal spiral galaxies are near the low end of the radio luminosity function with radio luminosities ≈ 10^{30} W. Seyfert galaxies, starburst galaxies and the nuclei of active elliptical galaxies are up to 1000 times more luminous in the radio band. Radio galaxies and radio-loud quasars are powerful radio sources at the high end of the luminosity function with luminosities up to 10^{39} W (see Woltjer in [c], p. 12).

The extended radio sources have an energy content up to 10^{54} Ws. Long and thin jets extend away from a compact central core toward the outer radio lobes which are the landmarks of extended radio sources. The standard beam model (see subsect. 9.6.6.1.3 in LB VI/2c, [82N, s]) postulates the presence of a beam which transports the relativistic plasma, energy and magnetic fields from the active core to the extended radio lobes. With the advent of the Very Large Array (VLA) and MERLIN telescopes in the early 80s many jets have now been detected in powerful extragalactic sources ([84B2], Perley in [89M2], p. 1, Muxlow and Garrington in [u], p. 52).

Maps produced by interferometers such as the Cambridge 5 km gave rise to a simple division into *extended, steep spectrum and compact, flat spectrum* objects. Extended sources were essentially collinear double sources with two lobes of radio emission extending out to hundreds of kiloparsecs on either side of the optical nucleus. Compact objects were at that time unresolved point sources treated as a separate class and studied with VLBI arrays [a, d, e]. Subsequently, more sensitive and higher resolution interferometry has lead to the classification into *core-dominated* and *lobe-dominated* sources. It now appears that all radio galaxies and radio-loud quasars with luminosities at 1 GHz exceeding 10^{25} W Hz^{-1} possess flat spectrum cores and steep spectrum jets and lobes [d, e].

The following structural elements are distinguished within radio sources ([84B2, 89M2], Muxlow and Garrington in [u], p. 52):

Cores
Radio cores are compact flat spectrum components associated with the central source in the nucleus of a radio galaxy or quasar. When resolved with VLBI instruments, they are often resolved and show a core-jet structure on the milliarcsecond level [d]. The innermost core may be the optically thick base of the jet (for 3C 273 and 3C 345, see [91B1, 92B4]).

Jets
Radio (and optical) jets are linear features linking the core to the outer extended structure [y]. They may be visible over all or only part of their inferred length, they may be one- or two-sided, smooth or knotty, center-brightened or edge-brightened. Criteria have been formulated by Bridle and Perley [84B3]. The jets have typically spectral indices around 0.6.

Hotspots
These are the bright knots located at the outer edges in powerful extended sources [89M2] with linear sizes less than 1 kpc and spectral indices in the range of 0.5…1.0. The emission is highly polarized, and the inferred magnetic field direction is predominantly perpendicular to the source axis. A few hotspots are known to be sources of highly polarized optical synchrotron emission [89M2, 91R, ac, ah, ai]. In the hotspots the beam hits the ambient medium. Thereby a significant fraction of the beam energy is converted into relativistic particles. The structure of hotspots has been studied in numerical simulations [89L3, 90K4, ac]. Many sources show a primary and secondary hotspot with a more complex structure. The primary hotspot could be the site of current beam impact, the secondary hotspot a "splatter-spot" formed by the deflected beam [85W].

Lobes
Lobes is the general term to describe the extended radio emitting region, which contain the plasma spread out from the hotspot [89M2, u, ac, ah]. In weak radio sources lobes are plume-like, their outer boundary is ill-defined since the surface brightness decreases with increasing distance from the galaxy. Other lobe structures are tail-like, which are believed to be deflected by interaction with the external medium. Some lobes show bridges of high luminosity ([89L4], Leahy in [d], p. 174). In extremely weak sources one just finds haloes of low surface brightness which contain considerably aged plasma [87A].

9.6.6.1.5 Radio emission of spiral galaxies

Sources at the low end of the luminosity function are observed primarily by measuring radio emission from known optical objects. The most extensive surveys are thos of Kotanyi [80K], Hummel [80H], Sadler [84S2] and Preuss [87P]. These normal galaxies have typically a radio luminosity between 10^{29} and 10^{32} W. They are primarily ellipticals, but spirals are also detected.

For normal spiral galaxies most of the radio emission comes from the disk, but significant emission sometimes comes from a region less than a parsec across. The discovery of flat spectrum compact and variabel sources in the nuclei of M81 and M104 gave the first evidence for activity in the nuclei of normal galaxies. Seyfert galaxies are also not strong radio sources, but a few, such as NGC 1068, have prominent radio cores and jets [82W]. Their relation to other radio sources is discussed by Meurs and Wilson [84M4].

9.6.6.1.6 Radio emission from nearby elliptical galaxies

Weak compact radio sources are also frequently found in the nuclei of elliptical galaxies. They are variable on time-scales of months to years. When mapped with high angular resolution, these weak radio nuclei typically show the same asymmetric core-jet structure which is observed in the more powerful radio galaxies and quasars (see Wrobel in [d], p. 134, [91W2]).

9.6.6.2 Large-scale jets and beams

9.6.6.2.1 What are radio sources made of ?

The medium surrounding radio sources is a fully ionized, collisionless plasma. This has been studied for the Coma cluster, in which several radio sources are embedded. The electron density is about $4{\cdot}10^3$ m^{-3} and the temperature $1.0{\cdot}10^8$ K [88H3]. Density and temperature in the Coma cluster are probably within a couple of orders of magnitude of the environments of most kpc-scale radio sources. Density and temperature determine the plasma parameters, such as the Debye screening length, plasma frequency and the electron speed (see Table 11).

Table 11. Plasma parameters for the centre of the Coma cluster, H_0 = 100 km s^{-1} Mpc^{-1} has been used.

Observed parameters			
Electron density	n_{th}	$4{\cdot}10^3$	m^{-3}
Temperature	T	$1{\cdot}10^8$	K
Magnetic field	B	0.1	nT
Cluster core radius	R_c	150	kpc
Radius of typical jet	R_j	2	kpc
Derived parameters			
Thermal pressure	$P_{th} = 2n_{th}k_BT$	$1{\cdot}10^{-11}$	Pa
Magnetic energy density	$u_B = B^2/2\mu_0$	$4{\cdot}10^{-15}$	J m^{-3}
Plasma parameter	$\beta_P = P/u_B$	$4{\cdot}10^3$	
Thermal sound speed	c_s	$2{\cdot}10^6$	m s^{-1}
Alfvén speed	$v_A = \sqrt{2u_B / n_{th} m_p}$	$3{\cdot}10^4$	m s^{-1}
rms electron speed	$v_e = \sqrt{3k_BT / m_e}$	$7{\cdot}10^7$	m s^{-1}
Plasma frequency	ω_p	$3{\cdot}10^3$	rad s^{-1}
Debye screening length	$\lambda_D = v_e / \sqrt{3}\omega_p$	$1{\cdot}10^4$	m
Coulomb logarithm	$\Lambda_C = \ln[2\lambda_D/(h/m_e v_e)]$	37	
Effective collision frequency	$v_{eff} = n_{th}e^4\Lambda_C / (4\pi\varepsilon_0^2 m_e^2 v_e^3)$	$4{\cdot}10^{-13}$	Hz
Electron mean free path	$\Lambda_e = v_e/v_{eff}$	6	kpc
Larmor frequency	$\omega_e = eB/m_ec$	20	rad s^{-1}
Electron Larmor radius	$r_{ge} = \sqrt{2/3}v_e / \omega_e e$	$4{\cdot}10^6$	m

Far less known is the physics of the synchrotron emitting plasma which is found in radio jets and radio lobes. Even the composition is a matter of debate. Jets may contain in general four components:

a normal plasma consisting of ions and electrons injected from the plasma of the central accretion disk (see subsect. 9.6.6.5.5);

magnetic fields, visible in the synchrotron emission and the polarization of the central core of the jet, in VLBI knots, large-scale jets and lobes;

relativistic electrons responsible for the synchrotron emission with Lorentz factors up to 10^6 [96M2];

a possible electron-positron load injected from the immediate vicinity of the black hole [92P3, 95B2]; there is no evidence for electron-positron annihilation in the gamma-ray spectra of radio-loud AGN [92H1, 95R1].

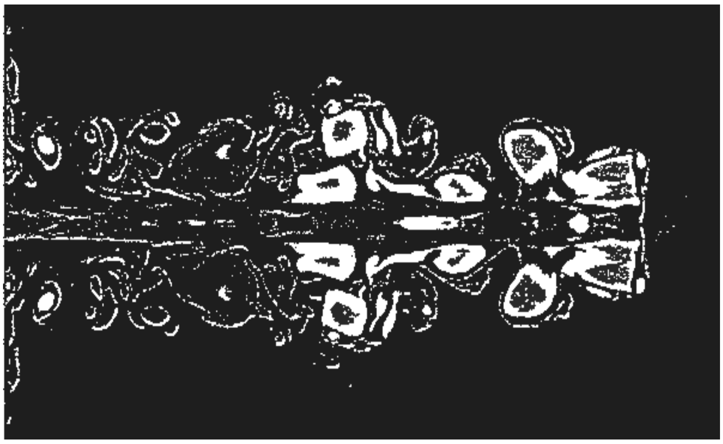
In any jet model, normal plasma from the disk is the basic substrate of the jet matter [97M2, 97O]. The origin of the magnetic fields, however, remains quite often unclear, in particular in pure hydrodynamic models. Many authors assume that these fields are completely turbulent with arbitrary turbulence scales. Jets could amplify the magnetic fields by dynamo action if the plasma streamlines are helical ([88G2, 88R], Eilek in [z1]). Magnetic fields are also an essential component of the dilute plasma found in radio sources. Magnetic fields up to 50 nT have been derived form observations of the optical jet in M87 and of the order of 40 nT in the optical hotspots of Pictor A and 3C273 (Meisenheimer in [x], p. 525, [ac], p. 159, [ai], p. 230).

9.6.6.2.2 Numerical models of extragalactic radio sources

According to the standard model [s, ak, al], the jets are interpreted as collimated supersonic outflows of plasma including magnetic fields, relativistic particles and thermal plasma initially formed in the nucleus of the galaxy. The hot spots are seen as the point of impact of the jet as it plows out through the intergalactic medium. Numerical simulations with supercomputers allow to study a wide range of nonlinear physics inherent in the hydrodynamic and magnetohydrodynamic equations (see e.g. Birkinshaw in [u], p. 278). These numerical studies provide some important insights into the physics of radio jets and of the structures observed in radio maps. The computer code ZEUS [91B2] and similar codes [89L3, 90K4, 97Z] only allow to study nonrelativistic bulk flows. Some of the results obtained from both two-dimensional and three-dimensional numerical simulations for the formation and evolution of extended radio morphologies are described in [91B2, 91N3].

The first calculations carried out in 1981 yielded a wealth of new information on the internal shock structures and nonsteady flow dynamics of a low-density supersonic gas stream penetrating a higher density external medium [82N]. The jet material splashes back from the leading edge in a vigorous backflow to inflate a "cocoon" surrounding the jet. It is believed that this cocoon corresponds to the broad radio lobes observed in radio galaxies. In Fig. 12 the results of a simulation (top) together with a schematic sketch (below) are reproduced [91N3].

In the next step, magnetic fields were added to the fluid [86C5, 89L3, 90K4, 91N3, 96M1, 97M2, 97O]. The essential difference between the hydrodynamic and MHD jet dominated by a toroidal magnetic field is that shocked gas accumulates in a foreward "nosecone" rather than flowing back into the cocoon (Fig. 13). The addition of longitudinal fields weakens this effect however [89L3, 90K4].



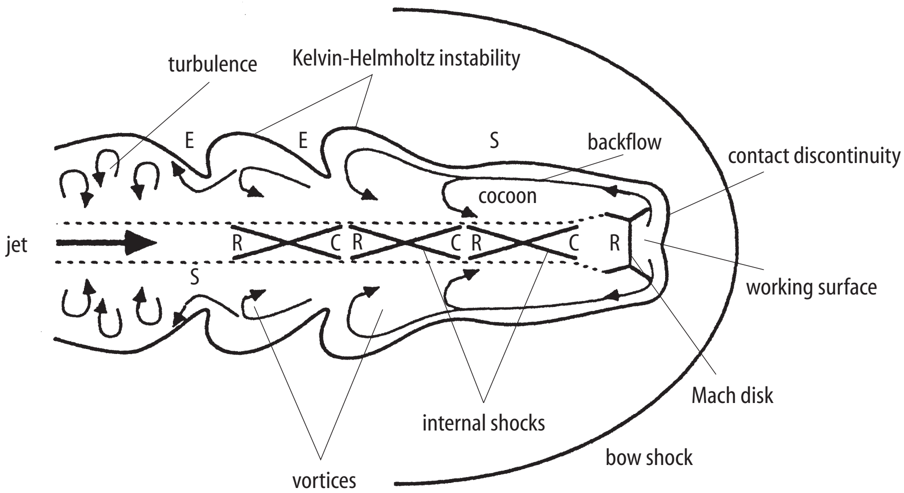


Fig. 12. An axisymmetric supersonic gas jet boring through a denser background medium. Upper: simulation; lower: an illustration of the observed structures [91N3]. The computation used a cylindrical coordinate grid of 600×400 zones. R and C are rarefaction and compression zones, respectively; S denotes a shear surface, E a turbulent eddy.

In the 90s, two-dimensional simulations will be extended to three dimensions thanks to enhanced computer capabilities [91N3, 97H]. While the basic structures revealed by two-dimensional simulations persist in these calculations, a wealth of eddy structures shows up in three dimensions [91N3]. The evolution of the magnetically-confined jet in three dimensions shows for the first time the well known "fire-hose" instability of plasma columns. Laboratory studies of magnetically-confined plasma columns show that they are violently unstable in three dimensions. In particular, the "nose-cone" is susceptible to this instability. The nose-cone material is periodically sloughed off to one side of the jet. This might be the origin of the complicated hotspot structure found in double-hotspot sources. Future improvements include a realistic description of the magnetic diffusivity and the extension into the special relativistic domain [94D, 95M4, 97M1] Aperture synthesis observations together with supercomputer simulations will provide a powerful tool to probe the origin and evolution of extended extragalactic radio sources.

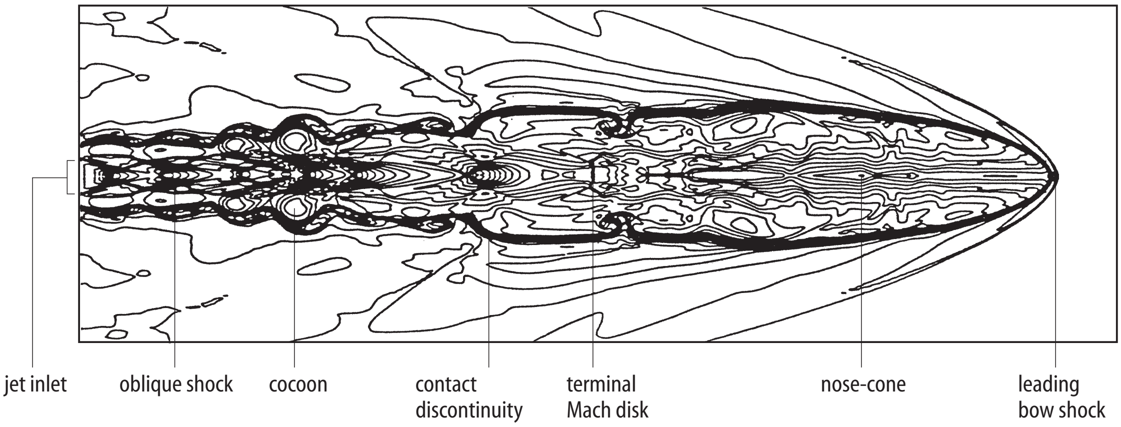


Fig. 13. Structure of a magnetically-confined, axisymmetric supersonic jet [91N3]. This simulation differs from the hydrodynamic one in the absence of the cocoon and the presence of a "nose-cone" in front of the terminal Mach disk. The computation used a cylindrical grid of 600×150 zones.

9.6.6.2.3 Instabilities in jet flows

Astrophysical plasma beams must be capable of exceptional stability, since these flows survive from the generating engine to the hotspot. For weak radio sources, less stability is necessary. Most of the early work on the linear stability of jets concentrated on the hydrodynamical Kelvin-Helmholtz instability [81D, 81P2, 91B3, 95H3, 96M1]. MHD flows with a homogeneous axial magnetic field were considered by [81R, 84F, 89B2]. The addition of a toroidal magnetic field has a great influence on the stability [88A2, 92A3]. Current-carrying jets are found to be more stable than gasdynamic jets, and even more stable than a configuration with only longitudinal magnetic field [92A3].

9.6.6.2.4 Electron accelerations in jets and hotspots

The local dynamical evolution of relativistic particles in jets, hotspots and radio lobes is determined by their transport and by in situ dynamics [r, 92E, 89L2]. Shocks would primarily accelerate protons to high energies [84W]. In hotspots of FR 2 radio galaxies the highest observed energies of cosmic rays ($10^{17}\ldots10^{20}$ eV) could be formed and escape to sustain the observed cosmic ray flux at the Earth [87B2]. Protons must reach very high energies to satisfy the threshold conditions for secondary particle production [87S2, 90B3].

9.6.6.2.5 Laing-Garrington effect

The interpretation of the depolarisation asymmetry in double radio sources (cf. subsect. 9.6.4.4) is found in [91G2].

9.6.6.3 Compact radio nuclei

9.6.6.3.1…9.6.6.3.4

See LB VI/2c, p. 399

9.6.6.3.5 Correlations between radio, optical and X-ray fluxes

For spiral and irregular galaxies, there is a well-established correlation between the total radio and FIR luminosity [84D, 85H, 85S, 86G2, 87W2, 88W1, 91C3]. This correlation is explained by a model in which the FIR emission rate and the production rate of relativistic electrons are both proportional to the supernova rate [89V2]. The explanation of the non-unity slope between radio and FIR luminosity has been given in [89D2] in terms of a model including dust heating by star formation and the interstellar radiation field. Spiral galaxies are characterized by an infrared disk with a shorter scale length than that of the radio continuum disk [90B4]. The radio continuum disk is proposed to be smeared out as a result of cosmic-ray propagation [90B4]. The spectral index distribution between the radio and IR has been investigated for a large sample of galaxies by Condon et al. [91C4].

In a sample of 179 quasars 74 were detected in at least one of the IRAS bands [86N2]. A correlation between the IR luminosity and X-ray luminosity has been studied in [87E2]. In the IRAS wavelength range the continuum energy distributions found for Seyfert 1 galaxies are modified by the presence of dust and of the host galaxy [87C2, 87W1]. Core-dominated sources exhibit flat radio spectra upto 1.3 mm with luminosities comparable from the mm through the X-ray regimes as well as flux-density variability [87C3, 88C3]. For the radio-FIR relation of interacting and noninteracting spiral galaxies, see [91W3], and for a radio-optical study of blue compact dwarf galaxies, see [91K2]. The very highest infrared luminosities are nearly all associated with AGN [88S4, 89L1]. Hard X-ray selected AGN also show some correlation with mm-fluxes [91L2]. The mid-FIR emission (12…100 μm) is found to be much stronger on average (about four times) in the quasars than in the radio galaxies [92H2].

9.6.6.3.6 Models for optical, UV, and X-ray emmisson from compact sources

See LB VI/2c, p. 401

9.6.6.4 Compact jets

The actual formation of jets in radio galaxies is fundamental for the understanding of the emission from these objects as well as for the astonishing ability of these jets to stay together over a very large range of distance scales. On their way from the black hole in a galactic nucleus to hot spot and the radio lobe, cosmic jets cover a stupendous factor of 10^8 in length scale.

The actual initiation of jets is still a subject of controversy. Though VLBI observations can now provide structural information on scales of ≤ 0.1 pc for extragalactic sources [91K3, 91B1, 92B4], the processes that govern the initiation of the jets occur on still smaller scales. The mm-VLBI can resolve the parsec-scale structure implying some constraints on possible models for the knots on this scale. Another difficulty has to do with the complexity of the physical processes which are involved in producing jets. Soon after the discovery of powerful radio galaxies and quasars, it was argued that their power is ultimately gravitational in origin. It is assumed that supermassive black holes with a mass M_H between 10^6 and 10^{10} $M_\odot$ reside in the center of the parent galaxy [ag]. They are surrounded by an accretion disk extending to a few thousand Schwarzschild radii (see subsect. 9.6.6.5.3 in LB VI/2c). Magnetic fields are important for the jet formation mechanisms. This all means that general relativity, magnetohydrodynamics, plasma physics and radiation transport must be included in the various processes.

9.6.6.4.1…9.6.6.4.6

See LB VI/2c, p. 402 ff

9.6.6.4.7 Gasdynamic jet production – collimated funnel winds

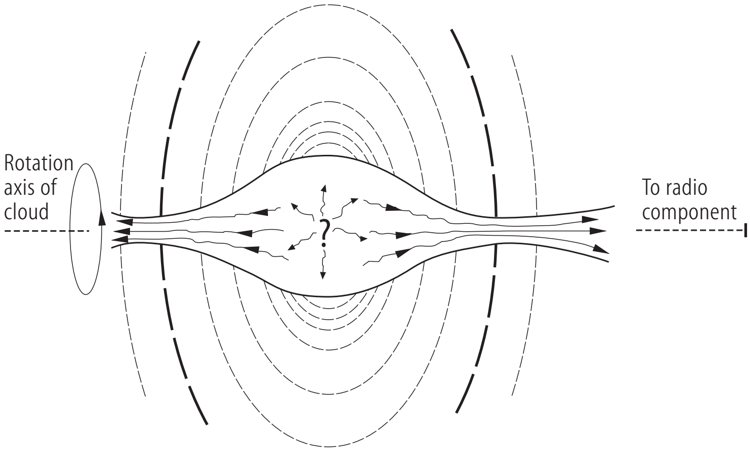


Fig. 14. Twin-exhaust model for the collimation of jets in radio sources [c], p. 242. The hot outflowing gas is in pressure equilibrium with the surrounding gas cloud which is confined by the gravitational potential well generated by the galactic nucleus.

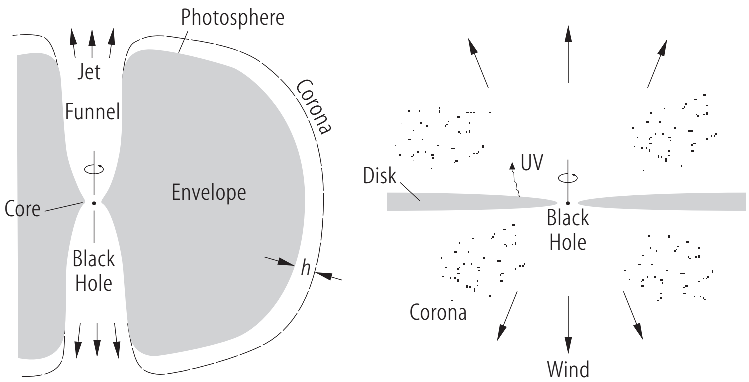


Fig. 15. Radiation pressure driven outflows which are collimated by funnels in a radiation-pressure supported torus around a Kerr black hole (left). Radiation pressure driven outflows from geometrically thin disks (right) [c], p. 243.

In early models for jet formation, magnetic fields are neglected for the extraction of energy from the central object. They are unimportant in the acceleration and collimation of beams [s]. In the *twin-exhaust* model (Fig. 14), two anti-parallel channels are supposed to propagate adiabatically in anti-parallel directions out of the galactic nucleus forming thereby nozzles. In the supersonic part of the flow, the jet will expand in the transverse direction as the external pressure decreases. This mechanism is no longer believed to be responsible for collimating the jets in powerful radio sources, since according to VLBI observations collimation must occur on scales ≤ 1 pc. This would require a too high gas pressure on this scale. Jets in low-luminosity radio galaxies could however be formed in this way.

Although thin accretion disks define obviously a preferred direction for the ejection of matter that could then be collimated into beams, there are no well-developed models for jet production in the absence of dynamically controlling magnetic fields. Disk winds are certainly a generic phenomenon for geometrically thin disks, but the collimation mechanisms are unclear in this case.

More promising for a hydrodynamic production of jets is a *geometrically thick disk* with steep funnel walls (Fig. 15). Since quasars are extremely luminous objects with accretion rates close to the Eddington limit, radiation pressure may be sufficient to overcome gravity along the funnel walls [80J]. Since the radiation field is not sufficiently anisotropic, the outflowing gas is accelerated only to mildly relativistic speeds, much less than necessary to explain superluminal motion [81S2].

The time evolution of axisymmetric supercritical accretion disks around Newtonian quasi-black holes have been investigated by Eggum [88E]. The solutions have in general four distinct zones: Centered on the disk midplane is a thick, dense region of turbulent convection. In a thick disk, both entropy and angular momentum contribute to the buoyancy of matter. Above the convective core is an accretion zone in which low angular momentum matter rapidly flows onto the black hole. This accretion zone is bounded by a photocone, in which matter becomes optically thin. The photocone is the source of both the mass and the radiation which drive an outflow near the rotational axis. Inside the photocone, a broad outflow of expelled matter is found with poor collimation.

These outflows are conical in shape, with opening half-angle of 25°…35°. The density in the outflow is low, and the optical depth to infinity is less than one. The corresponding mass ejection rate $\dot{M}_j \cong 0.01 \ldots 0.004 \dot{M}$. The velocity of the outflow increases from zero in the jet formation region near the central object to a maximum value of ≅ 0.5 c. This speed must be corrected for relativistic effects, resulting in a maximum outflow speed of about one-third of the speed of light. If these radiation-driven bipolar outflows are to become highly collimated, a collimation mechanism must act externally to the radiation acceleration region - the action of magnetic stresses is the most natural mechanism [91F]. The total disk luminosity always remains sub-Eddington, despite the super-critical accretion, typically, $L_D \simeq 0.8\ L_{ED}$.

The problem of funnel wind acceleration has to be formulated in terms of special relativistic hydrodynamics including radiation transfer. Ferrari et al. [86F1] developed models based upon results taken from solar wind theory. This model is analogous to the classical proposal of Blandford and Rees [78B], with the crucial difference that here the rapid expansion of the gas at the exit of the funnel brings the critical point inward along the funnel axis. The flows generated in this way are typically transsonic with the sonic point achieved very deep in the funnel (only at a few Schwarzschild radii above the equatorial plane). Depending on the form of the funnel walls, multiple critical points can occur [86F2, 86F3].

The stability of thick disks has received tremendous attention in the 80s [91N2]. Papaloizou and Pringle [84P2, 85P] have discovered a set of virulent instabilities for thick accretion disks. They grow on dynamical, i.e. orbital time scales. The original calculations were confined to constant entropy, incompressible tori with constant specific angular momentum [84P2, 85B, 85G, 86B, 86H]. Further analysis of this problem can be found in [85G, 85P, 86G1]. Numerical simulations have demonstrated the importance of these instabilities [86Z, 88H4]. A fully relativistic 3D treatment of supercritical accretion onto rapidly rotating supermassive black holes is still lacking. An alternative type of torus has been proposed for radio galaxies [84R]. In the ion torus, cool electrons are supposed to be supported by the pressure of a hot ion gas with temperatures up to 100 MeV. This gas would be quite optically thin and is subject to high radiative losses. It also may contain a strong magnetic field. The stability of these ion tori is even less clear than that of radiation pressure supported tori.

9.6.6.4.8 Magnetic collimation of disk winds

The other major category of jet formation models considers magnetic fields to be important [82B, 86C3, 87C1, 87L1, 92P5, 95F, 96C, 96F, 97F, 97M, 97O]. Winds that originate from surfaces and coronae of accretion disks can carry off an appreciable amount of angular momentum if they are magnetized. Extragalactic jets could be formed and collimated if they originated from accretion disks around black holes. Magnetic torques can drive external winds, if the angle θ of a magnetic field line frozen into the disk at radius R is larger than 30° [82B] (Fig. 16). The equipotentials for the sum of gravitational and centrifugal forces are drawn in Fig. 16,

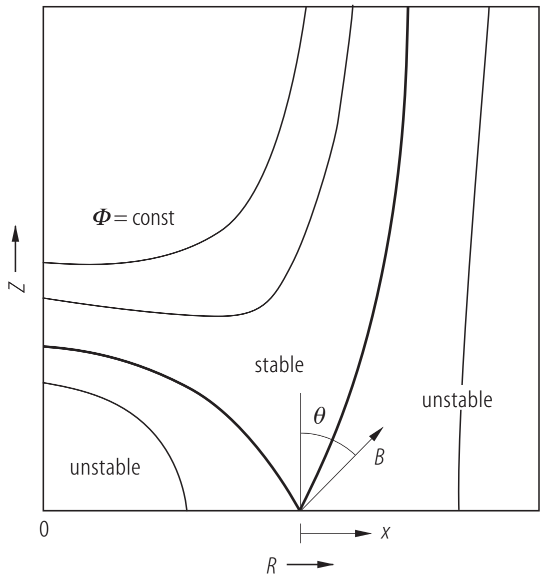


Fig. 16. Combined gravitational and centrifugal potential for plasma particles frozen onto magnetic field lines tied to a Keplerian disk, [c], p. 215.

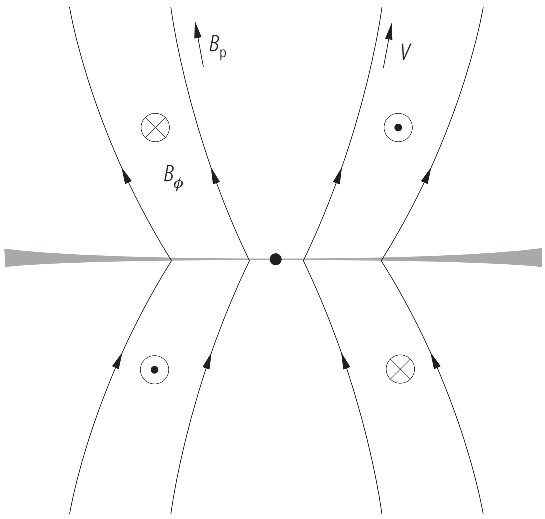


Fig. 17. Structure of a magnetically collimated disk wind in the Newtonian approximation [c], p. 244. The inertia of the escaping disk plasma produces toroidal magnetic fields B_ϕ which can collimate the jet. Plasma flows along the magnetic surfaces formed by the rotating poloidal magnetic fields B_p.

$$\Phi = -\frac{GM_H}{\sqrt{(R+x)^2 + z^2}} - \frac{GM_H (R+x)^2}{R^3} \quad . \tag{11}$$

Ionized gas frozen onto a magnetic field line at the surface of the disk will be unstable if $\theta > 30°$ and will be flung outward along the magnetic field line by centrifugal forces.

In the hydromagnetic limit, gas may be viewed as being centrifugally slung outward along rotating magnetic field lines which form axisymmetric flux surfaces for the flow (Fig. 17). The plasma will be tied to the magnetic field and its inertia causes the field lines to be bent backwards creating a toroidal component. The associated hoop stress acts to collimate the poloidal flow. The structure of the magnetic surfaces is determined by the cross-field force-balance which follows from a projection of the relativistic Euler equation

$$n(\boldsymbol{u}\cdot\nabla)(\rho\boldsymbol{u}) = -\nabla P + \rho_e \boldsymbol{E} + \frac{1}{\mu_0}(\nabla\wedge\boldsymbol{B})\wedge\boldsymbol{B} \tag{12}$$

onto the normal $\boldsymbol{n}$ of the magnetic flux surfaces [89H3, 91C1, 93A1, 93A2, 96C, 96F]

$$\kappa\frac{B_p^2}{\mu_0}\left(1-M^2-\frac{R^2\Omega_F^2}{c^2}\right)=\left(1-\frac{R^2\Omega_F^2}{c^2}\right)\nabla_\perp\frac{B_p^2}{2\mu_0}+\nabla_\perp\frac{B_\phi^2}{2\mu_0}+\nabla_\perp P+\left(\frac{B_\phi^2}{\mu_0 R}-\frac{\rho u_\phi^2}{R}\right)\nabla_\perp R-\frac{B_p^2\Omega_F}{\mu_0 c^2}\nabla_\perp(R^2\Omega_F) \tag{13}$$

where κ denotes the local curvature of the poloidal field lines, $\kappa B_p^2 = \boldsymbol{n}\cdot(\boldsymbol{B}_p\cdot\nabla)\boldsymbol{B}_p$. P is the plasma pressure, ρ its total mass-energy density and $\boldsymbol{u} = \gamma\,\boldsymbol{v}$ its velocity given by ideal MHD [86C3, 86C4, 96C, 97B1]

$$\boldsymbol{u} = \frac{\eta}{n}\boldsymbol{B} + \gamma R\Omega_F \boldsymbol{e}_\phi \tag{14}$$

Ω_F is the angular velocity of the field line which is constant along the field line. The inertia of the plasma enters over the relativistic Mach number M, defined as $M^2 = \mu_0\rho u_p^2 / B_p^2$ [86C3]. The electric field is due to the rotation of the field lines, $\boldsymbol{E} = (R\Omega_F/c)B_P\boldsymbol{n}$. Newtonian MHD [89H3] is only valid for small radii, i.e. radii much smaller than the light cylinder radius, $R \ll R_L = c/\Omega_F$ [96C].

Magnetic flux surfaces will be collimated either to asymptotically current-carrying cylindrical surfaces (perfect collimation) or to current-free paraboloidal surfaces [89H3, 91C1]. The terminal-4 velocity on a cylindrical flux surface is directly proportional to the current enclosed within that surface [89C3, 91C1, 96F, 96H].

All models of this type are based on some distribution of magnetic fields in accretion disks. Fully turbulent accretion disks are ideal set-ups for magnetic dynamos, quite similar to dynamo action in the gaseous disks of spiral galaxies [90C1, 95R2, 96K, 97B]. When the dynamo effect is neglected in a disk, the strong differential rotation just amplifies the toroidal field. The poloidal flux is, however, only redistributed in the disk by advection and diffusion (there is no source term). In this case, one can find stationary solutions for the distribution of the disk fields under various assumptions for the magnetic diffusivity in the disk [87L1, 89K2, 90C1, 92K2, 95R2], provided there is a continuous magnetic flux injection at the outer edge of the accretion disk from the surrounding galactic disk.

As in the case of the static axisymmetric plasma confinement in the lab, the magnetic surfaces of the outflowing disk wind also provide a kind of plasma confinement, eq. (13). If the pinching force of the toroidal field and the electrical field is sufficiently strong to overcome pressure gradients and centrifugal forces, the magnetic surfaces can bend towards the rotational axis resulting in a collimated outflow. The fast rotation in the disk generates electric radial fields in the disk, which drive a poloidal current system in the magnetosphere. These currents produce toroidal magnetic fields, which exert a momentum on the foot points on the disk. The magnetic structure of this hole-disk-system must then be calculated self-consistently including all the currents driven by the rotation by using Ampère's equation for the poloidal magnetic field [89C3, 90C1, 92P5, 95F, 97F].

9.6.6.4.9 Black hole driven pair winds

Several models for jets also include a relativistic beam, which is formed by electrons and positrons in pair cascades on the UV photons of the accretion disk (Phinney in [q], p. 201). In such a scheme of a two-fluid model [84C, 89S4, 92P3, 95B], the relativistic knots are considered as clouds of $e^\pm$ plasma pervading the ambient subrelativistic flow ejected by the accretion disk. These beams can be stable against the excitation of plasma waves for moderate bulk Lorentz factors (γ < 43) and for sufficiently strong magnetic fields $B > B_c$ ($\omega_B > \omega_p$) [92P3]. The Alfvén turbulence in the jet can be used to heat up the pair plasma to relativistic energies by a second order Fermi process [91H]. The pairs are cooled by inverse Compton scattering on soft photons, which would be the origin of the X- and γ-rays in quasars [95M3]. The pair production zone would be located outside the light cylinder

R_L, typically at a few hundred Schwarzschild radii, i.e. just at the position where the knots have to be injected into the jets in order to show up in mm-VLBI. According to this scheme, VLBI knots would just consist of pair clouds ejected along the magnetic surfaces of the underlying jet. These $e^{\pm}$ beams just propagate until they reach a region with $B \simeq B_c$, where they loose their energy to Langmuir waves and heat up the ambient medium (typically at a distance of $\simeq$ 1 kpc from the central source). $e^{\pm}$ beams with higher bulk Lorentz factors [86K], $\gamma \gg 43$, can only propagate in a vacuum.

9.6.6.4.10 Core-jet structure

One particular problem in the interpretation of observed compact jets is the identification of the jet feature which corresponds to the VLBI radio core and the moving VLBI knots. This core as the most compact feature in VLBI maps is most probably stationary and is situated at one end of the jet. In the standard model [79B1], the core is identified with the throat of the diverging conical jet, where density and magnetic fields are highest. This would occur in a HD jet if the mean energy per gas particle were to drop below the rest mass energy, such that the flow becomes ballistic within a short distance from the throat, provided the ambient pressure is lower than the jet pressure [88D]. Superluminal knots have been identified as clouds caught up in the jet flow [79B1], as instabilities in the flow [92A3], or as shock waves propagating down the jet [85M, 89H2, 91M1]. In the first case, the velocity of the knot is roughly that of the local jet flow. Forward shocks will slightly decelerate with respect to the background flow.

9.6.6.4.11 Relativistic beaming, superluminal motion and gamma emission

Superluminal motion is explained in terms of knots moving with speed $c\beta$ very close to the speed of light along trajectories making small angles θ with respect to our line of sight (cf. subsect. 9.6.6.4.2 in LB VI/2c). The observed apparent velocity β_{app},

$$\beta_{app} = \frac{\mu d_L}{1+z} \ , \tag{15}$$

for given angular velocity μ in mas yr^{-1} is connected to the speed of the knot by

$$\beta_{app} = \frac{\beta \sin\theta}{1-\beta\cos\theta} \ . \tag{16}$$

This dependence of β_{app} on the inclination angle is shown in Fig. 18 for various bulk Lorentz factors γ. Statistical investigations are presented by Vermeulen in [ai], p. 245.

The spectral flux density S_ν observed from an unresolved knot is strongly amplified by Doppler-beaming, $S_\nu = S'_\nu D^{2+\alpha}$, where $D = [\gamma(1-\beta\cos\theta)]^{-1}$ is the Doppler factor ($\alpha = \mathrm{d}\ln S'_\nu / \mathrm{d}\ln \nu'$). The ratio R between the jet and counter-jet emission is given by $R = (1+\beta\cos\theta)/(1-\beta\cos\theta)$ (cf. Cawthorne in [u], p. 187). Relativistic motion also accounts for beamed γ-emission of extragalactic sources [95M4, 95T2, 96T2].

9.6.6.5 The central engine models

It is generally believed that the energy outpout of AGN is due to accretion onto a supermassive object, most probably a supermassive rotating black hole. A lower limit on the accretion luminosity is given by the Eddington luminosity. In radio galaxies and quasars, also the rotational energy of a black hole could be a source of energy [v, al].

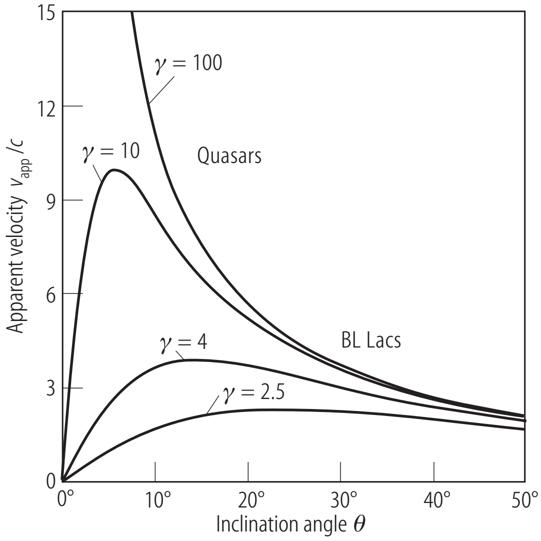


Fig. 18. The apparent transverse velocity v_{app} as a function of the inclination angle θ between the line of sight and the axis of the jet for various bulk Lorentz factors γ.

9.6.6.5.1…9.6.6.5.4

See LB VI/2c, p. 405 ff

9.6.6.5.5 Standard model for AGN

Extragalactic radio sources are a subset of active galaxies which show, by definition, a strong nuclear activity (Seyfert galaxies, QSOs, quasars; cf. sect. 9.5). All of these sources have most probably jets, or at least a kind of bipolar outflow in the nuclear region. But the power in the jets of Seyfert galaxies e.g. is many orders of magnitude lower than the overall power of the AGN, while in a typical jet source, such as 3C 273, jet power and AGN power are comparable. The difference between these two types of AGN (historically called radio-weak and radio-loud sources) must be hidden in the physics of the nuclear region of the corresponding host galaxies (cf. subsect. 9.6.6.7.5).

The standard model for AGN [90C1, c, v, al] used in the 80s assumes the existence of a supermassive rotating black hole in the center of a galaxy surrounded by a Keplerian accretion disk with an extension of a few thousand Schwarzschild radii (< 0.1 light year). This entire structure is embedded into a nuclear star cluster with mass $M_c > 10^{10}\, M_\odot$ and core radius $R_c \geq$ parsecs [ag]. This inner disk is fuelled by material present in the form of molecular clouds and gas on the scale of a few parsecs to a few hundred parsecs. In the innermost few parsecs, galactic matter is assembled in the form of a molecular torus, quite similar to structures found in our galactic centre. Direct evidence for the existence of the inner accretion disks follows from the presence of a strong optical-UVX excess in the continuum of quasars. Cold molecular gas appears as a thermal component in the far-infrared, while hot dust is the origin of the near-infrared emission in radio-weak objects [90B2].

9.6.6.5.6 Accretion disks around black holes

The specific angular momentum of gas in orbit on the parsec-scale in a galaxy is many orders of magnitude larger than the Keplerian angular momentum in the last stable orbit around a black hole. Gas that accretes onto the black hole forms therefore an accretion disk. References related to the theory of accretion onto black holes are Shakura and Sunyaev [73S], Novikov and Thorne [73N], Pringle [81P3], Frank, King and Rayne [85F3], Treves et al. [88T], Shields [89S5], as well as [al, 89B3, 89M5, 97P]. The magnetic fields carried by these disks are in general limited by the Eddington magnetic field strength

$$B_{\mathrm{Ed}} = \sqrt{(L_{\mathrm{Ed}} c^3 / G^2 M_{\mathrm{H}}^2)} = 4T\sqrt{10^8 M_{\odot} / M_{\mathrm{H}}} \ . \tag{17}$$

For accretion rates below the Eddington value, the maximally possible field strengths are however much smaller [91C2]. The magnetic pressure in the disk, $B_D^2 / 2\mu_0$, cannot exceed the disk pressure at radius R

$$P_D \approx \frac{\dot{M}}{4\pi\alpha R^2}\sqrt{\frac{GM_{\mathrm{H}}}{R}}\left(\frac{H}{R}\right)^{-1} , \tag{18}$$

where $\dot{M}$ is the accretion rate and $\alpha \approx 0.1\ldots0.01$ the turbulence parameter of standard accretion disks [73S].

9.6.6.5.7 Black hole magnetohydrodynamics

The rotational energy of rotating black holes is up to 29 % of the rest-mass energy of the black hole. This energy can be extracted without violation of the four laws of black hole thermodynamics [86T]. The most promising way to extract this energy is via a magnetic coupling between accretion disk and black hole [86T]. When the magnetosphere of the accretion disk forms a global circuit together with the black hole, the rotational energy can be tapped and dissipated as work at large distances. Phinney in [q], p. 201, has illustrated the basic analogy between a conductor rotating in a uniform magnetic field and a black hole surrounded by magnetic field and plasma. It is also argued that if the accretion disk provides sufficient energy in γ-rays, then the electron-positron pair density formed near the black hole would exceed that allowed for a force-free magnetosphere [92O]. Under these conditions, the magnetohydrodynamic approximation becomes applicable. The rotation of the magnetic structure can now drive a pair wind that carries away angular momentum and energy from the rotating supermassive black hole [95B2, 96L].

The complexity of the magnetohydrodynamic (MHD) description is quite high near a black hole. The dynamics of axisymmetric MHD winds is much simpler due to the existence of four integrals of motion [86C4, 89C3, 96C, 97B1].

The membrane technique, based upon a 3+1 split of spacetime into space + time for the treatment of black hole physics provides a reasonable framework also for the magnetohydrodynamics of black holes [82M, 86T, 92C1, 96K]. The ability of magnetospheric models to collimate and accelerate either electron-ion plasma or pair beams is strongly in favour for the magnetic origin of the jets in radio galaxies and quasars.

9.6.6.6 Large-scale distribution of radio sources and cosmological evolution

See LB VI/2c, p. 407

9.6.6.7 Unified schemes

9.6.6.7.1 The Scheuer-Readhead hypothesis

The discovery of superluminal motion in the early 1970s and the increasing evidence for bulk relativistic flow suggested that part of the radiation from compact nuclei is boosted by relativistic aberration and thus appears anisotropic. The jets emerge in opposite directions, but only the near-side jet is visible due to "Doppler favouritism". In this scheme, the sequence: radio-weak quasars, radio-loud quasars and blazars would correspond to sources of equal intrinsic strength, associated with relativistic jets viewed at progressively smaller angles between jets and the line of sight (cf. subsect. 9.6.6.4.3 in LB VI/2c).

9.6.6.7.2 The Orr and Browne scheme

In 1978 Readhead et al. showed that the core-dominated sources are smaller and their jets are less well aligned with the large-scale structure than in lobe-dominated sources [78R]. This can be naturally explained if the core-dominated sources are pointed towards us and if the parent population consists of the lobe-dominated sources. Orr and Browne suggested in 1982 that extended double radio quasars are the parent population of compact, core-dominated quasars [82O, 82K, 89H4]. In this scheme, all flat-spectrum core-dominated quasars are just lobe-dominated quasars seen close to the line of sight. On the whole, the agreement with the model is quite satisfactory. By using the angle to the line of sight as deduced from the apparent speeds in superluminal sources to deproject the large-scale structure, the superluminal sources appear, however, to be bigger than most of the parent population [83S, 87B3].

A crucial test of this scheme is based on the R distribution [82O]. The ratio R of core to extended flux density (e.g. at 1.6 GHz) depends on the angle to the line of sight of the approaching jet and the Lorentz factor of the jet. For a sample of 94 flat-spectrum radio sources mapped with VLBI the following results have been obtained [91M2, 96V2]: The R distribution cannot be fitted with a single Lorentz factor, a range of $3 \leq \gamma \leq 11$ is required. In a sample of sources selected by core radio emission, sources with high Lorentz factor are preferentially selected. The projected linear-size distribution of compact sources cannot be explained by large intrinsic bends, but requires large intrinsic linear sizes of these sources. This is in agreement with Orr and Browne, provided the intrinsic linear size is correlated with the Lorentz factor. In the quasar sample, a maximum intrinsic linear size of 600 h^{-1} kpc is required [91M2]. For these questions, see also Browne [92B5].

9.6.6.7.3 Unification of quasars and radio galaxies

Another way around the linear-size problem is to include double-lobed radio galaxies in the parent population [87S3]. Indeed, if some quasars could appear as galaxies when their radio jets lie sufficiently far from the line of sight, then some of the problems with the unified scheme disappear [89B1]. This would mean that all quasars are beamed versions of FR II radio galaxies. This strong version of the unification of radio galaxies can be subjected to various consistency tests [91K1], Browne and Jackson in [x], p. 618: The low-frequency 3CR sample has complete redshift information and should also have an almost random distribution of jet orientations. It turns out that the redshift dependence of the relative numbers and sizes of FR II radio galaxies and quasars does not conform with the predictions of this unification. The most significant difference between galaxies and quasars is in the bend-angle distribution; quasars appear much more bent and misaligned than galaxies at all redshifts. The smaller bends in galaxies imply that the ejections in quasars are intrinsically more asymmetric, or that galaxies and quasars must inhabit very different environments.

9.6.6.7.4 The parent population of BL Lac objects

Extended radio sources show a wide range of intrinsic luminosity. The inclusion of the low-luminosity BL Lac objects into the unification requires a parent population for the BL Lac objects, which has been proposed to be the low-luminosity radio galaxies of Fanaroff-Riley type I [90P, 91P2], Padovani and Urry in [x], p. 642.

9.6.6.7.5 Unification based on black hole models

Primary parameters for black hole models are the mass M_H, $10^6\ M_\odot \leq M_H \leq 10^{10}\ M_\odot$, the relative accretion rate $\dot{m} = \dot{M} / \dot{M}_{ED}$, where $L_{ED} = \varepsilon_H \dot{M}_{ED} c^2, \varepsilon_H \approx 0.1$, and the spin parameter $a_H = J_H/J_{H,\,max}$ of a rotating black hole. Blandford [c] has proposed that M_H, $\dot{m}$ and a_H are the key parameters controlling the intrinsic properties of AGN. The fourth important parameter is the viewing angle θ between the spin axis of the black hole and the observer direction. Also important is the covering factor of the AGN by dusty molecular gas on the parsec-scale (e.g. for the appearance of powerful infrared-galaxies). This last parameter is important for AGN embedded in young galaxies. The resulting classification scheme based on the first four parameters is summarised in Table 12.

Table 12. A physical AGN classification scheme [90B5] based on black hole models. Each source is specified by the value of the 4 parameters M_H, $\dot{m}$, a_H and θ by whether they are high (H) or low (L).

AGN	M_H	$\dot{m}$	a_H	θ
Extended Radio Quasar	H	H	H	H
Compact Radio Quasar	H	H	H	L
Broad Absorption Line Quasar	H	H	L	H
Radio-quiet Quasar	H	H	L	L
Narrow Line Quasar	H	L	H	H
High Polarization Quasar	H	L	H	L
Edge-Darkened Radio Galaxy	H	L	L	H
Core-Halo Radio Galaxy	H	L	L	L
Broad Line Radio Galaxy	L	H	H	H
Compact Radio Quasar	L	H	H	L
Type 2 Seyfert Galaxy	L	H	L	H
Type 1 Seyfert Galaxy	L	H	L	L
Narrow Line Radio Galaxy	L	L	H	H
BL Lac Object	L	L	H	L
LINER	L	L	L	H
LINER	L	L	L	L

Radio-quiet quasars (QSO) and Seyfert 1 galaxies apparently form a single class distinguished by their luminosities. They have high mass accretion rates $\dot{m} \simeq 0.01 \ldots 1.0$ so that their luminosities approach the Eddington limit. Their jets are not powerful due to slowly rotating holes. Type 2 Seyfert galaxies and narrow line quasars may be similar except that the broad line region is obscured by intervening gas. These objects should be viewed close to the equatorial plane. Broad absorption line quasars should have large $\dot{m}$ and observed roughly equatorially. The absorption would be caused by dense MHD driven disk-winds. Radio-loud quasars have broad emission lines and relativistic jets due to high accretion rates and rapidly spinning holes. The steep spectrum, extended sources are distinguished from the flat spectrum, compact sources by our orientation. When the Doppler boosted optical continuum dominates the emission from the accretion disk, a High Polarization Quasar (HPQ) or an Optically Violently Variable quasar (OVV) will be seen. Edge-brightened radio galaxies have relativistic jets (rapidly spinning holes), edge-darkened radio galaxies are driven by sub-relativistic jets (slowly spinning holes). BL Lac objects are simply interpreted as narrow line radio galaxies viewed at small angles so that the Doppler boosted continuum from the relativistic jets dominates the emission lines.

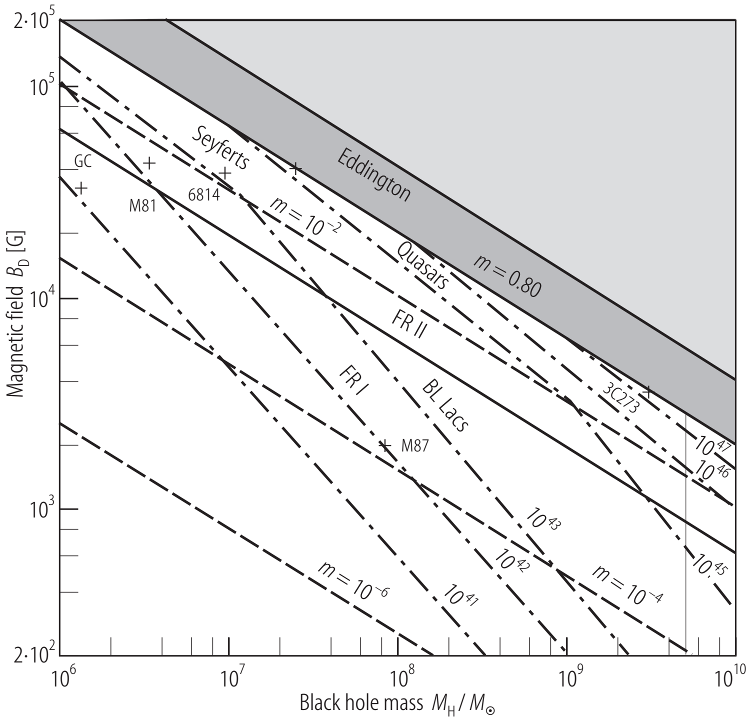


Fig. 19. Classification of AGN in terms of black hole masses M_H and the typical magnetic field B_D in the inner accretion disk [91C2]. Dashed curves have constant accretion rate $\dot{m}$, the shaded area is forbidden by the Eddington argument, disks between the solid curve and the shaded area are radiation pressure dominated. The accretion luminosity is constant along dot-dashed curves (in units of erg s^{-1}). The highly superluminal quasars 3C 273 and 3C 345 must be at the upper end of the mass and accretion scale [g], p. 205.

This scheme unifies extended and compact quasars as in [82O], but does not unify narrow emission line radio galaxies with quasars [89B1]. The latter scheme has difficulties, since the narrow line strengths of radio galaxies differ from those of quasars with similar extended radio emission strength [90J].

Observations show that Seyfert galaxies are associated with spirals and radio galaxies with giant ellipticals. This is compatible with the unification scheme if the mass of the black hole is correlated with the mass of the host galaxy or its bulge mass [95K]. Black holes residing in the center of spirals should be less massive than holes in the center of ellipticals. Based on this fact, a classification of AGN in terms of the mass M_H and the maximal magnetic field in the inner accretion disk is shown in Fig. 19 [91C2].

This unification scheme naturally explains the strong magnetic fields observed in quasar and FR II jets, and the weak magnetic fields of FR I radio sources.

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9.7 Cosmology

9.7.1 List of symbols

See LB VI/2c, p. 346

9.7.2 Friedmann cosmologies

See LB VI/2c, p. 346-350

9.7.3 Observations supporting basic assumptions

9.7.3.1 and 9.7.3.2

See LB VI/2c, p. 351

9.7.3.3 Evidence for cosmic evolution

The Hubble Space Telescope (HST), as well as the Keck telescope and other large ground-based telescopes have increased the ability to study directly the evolution of galaxies at high redshift. Number counts versus magnitude and redshift surveys are used [92K1]. Unknown cosmological parameters and uncertain evolutionary effects make deductions difficult [88S1]. HST provides information on the morphology of distant galaxies [95S1].

Faint blue galaxy excess

The number counts of blue galaxies increase with magnitude $B > 22^{m}$ more rapidly than for red galaxies, and more rapidly than expected, if the local population at redshift $z = 0$ had just undergone passive evolution with comoving density and mixture of types preserved for $z > 0.3$ [88B1, 92K1, 93L1]. The interpretation is difficult, because of uncertainties in the faint end slope and normalization of the local luminosity function [92L1, 94M1, 96E1, 96L1]. There is evidence from ground-based photometry that the luminosity function of red galaxies shows little evolution for $z < 1$, while the blue luminosity function brightens by about one magnitude and steepens at $z > 0.5$ [95L1].

Faint blue galaxies might be a population of dwarf galaxies undergoing starbursts and then fading away [96B1], or they might be starforming fragments of galaxies that merged into bright galaxies at $z < 1$ [92B1]. Their abundance now seems quite consistent with galaxy formation models based on hierarchical clustering [93L2, 94K1]. The morphology of the excess faint blue galaxies has been revealed by HST [95C1, 95D1, 95G1, 95S1, 96A1], especially in the Hubble Deep Field images [96A1]: a high percentage are late-type spirals, irregulars and peculiar (possibly merging) galaxies. Blue irregular galaxies seem to be an intermediate step in the galaxy formation process, since they appear to be missing in the nearby universe.

Absorption lines

Absorption lines along the line of sight to background quasars probe the gas clouds and/or protogalaxies present at high redshift. The "Lyman-alpha forest" (Lyα) consists of the numerous optically thin absorption lines (with HI column densities $\leq 10^{17}$ cm^{-2}) seen at wavelengths shorter than rest-frame Lyα (1216 Å) in the spectrum of a quasar.

"Lyman limit systems" are absorbers with N (HI) exceeding 10^{17} cm^{-2}, so that the medium is optically thick in the Lyman continuum (rest-frame $\lambda \leq 912$ Å), resulting in strong continuum extinction. "Damped Lyα systems" have $N\,(\mathrm{HI}) \geq 10^{20.2}$ cm^{-2} and thus show damping wings in the Lyα line, and opaque Lyman continuum.

High HI column densities are associated with young galaxies [86W1, 95W1]; lower HI column density systems may show MgII absorption [91B1, 94S1], and other metal lines [94S1, 94P1]. The total amount of baryons in the damped Lyα systems at $z \approx 3$ is consistent with the amount of baryons seen in galaxies today [95L2, 95W1].

The Lyα forest can be identified in numerical simulations as the web of structure forming in hierarchical clustering models [94C1, 96H1]. The observed N (HI) distribution is close to a power law from 10^{12} to 10^{21} cm^{-2} [95H, 95W].

Lyα absorbers with $N\,(\mathrm{HI}) > 3{\cdot}10^{14}$ cm^{-2} also have measurable CIV lines and a medium metallicity of 1 % of the solar [95C2]. This has led to the speculation of star formation in subgalactic clumps [96H2].

9.7.3.4 and 9.7.3.5

See LB VI/2c, p. 352 and 353

9.7.3.6 The cosmic microwave background (CMB)

9.7.3.6.1 The CMB spectrum

The CMB spectrum has been measured with unprecedent accuracy by the satellite COBE [90M1], (Fig. 1). Within observational uncertainties the measurements are fitted by the Planck spectrum of a black body with a temperature of

$$T_\gamma = 2.728 \pm 0.002 \text{ [96F1].}$$

Strong limits can be derived on possible distortions away from the perfect black-body shape. Possible energy releases in the early universe occurring between redshifts 10^3 and $5{\cdot}10^6$ must be less than $2{\cdot}10^{-4}$ of the total energy of the CMB [94M2]. This leads with 95 % CL (confidence limit) to $|y| < 1.5{\cdot}10^{-5}$ for the Compton distortion parameter y [94M2], and to $|\mu_0| < 9{\cdot}10^{-5}$ (95 % CL) for a chemical potential distortion [94M2, 96F1].

The number density of photons is $n_\gamma = 413\ \mathrm{cm^{-3}}$; the mass density $\rho_\gamma = 4.68{\cdot}10^{-34}\ \mathrm{g\ cm^{-3}} = 2.262\ \mathrm{eV\ cm^{-3}}$ [96F1].

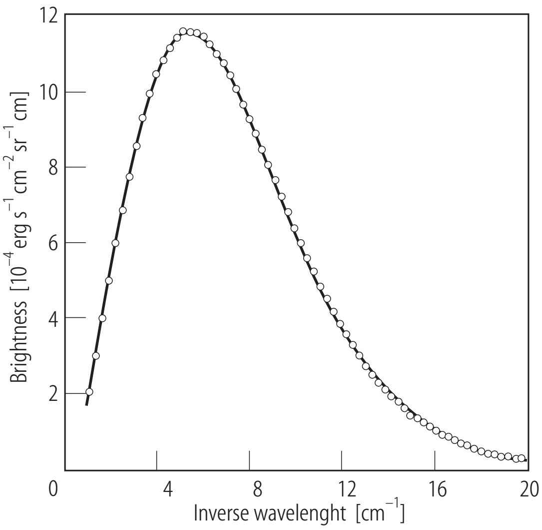

Fig. 1. The CMB spectrum as obtained by COBE.

9.7.3.6.2 Anisotropies of the CMB

COBE observations have shown that the CMB has a dipole anisotropy at $\Delta T/T \approx 10^{-3}$, and smaller scale anisotropies at $\Delta T/T \approx 10^{-5}$.

The general approach is to expand the CMB temperature on the sky in spherical harmonics

$$T(\theta,\varphi) = T_0 \sum_{lm} a_{lm} \mathrm{Y}_{lm}(\theta,\varphi),$$

and find observational limits on the various multipole amplitudes. In the direction $\boldsymbol{n}$ of an incoming photon $T(\boldsymbol{n}) \equiv T_0\,(1 + \Delta T(\boldsymbol{n}))$. T_0 is the background temperature and $\Delta T(\boldsymbol{n})$ is the possible deviation dependent on direction. The autocorrelation function $C(\theta)$ is the average value of the product $\Delta T(\boldsymbol{n})\Delta T(\boldsymbol{n}')$, where the directions $\boldsymbol{n}$ and $\boldsymbol{n}'$ enclose an angle θ : $\cos\theta = \boldsymbol{n} \cdot \boldsymbol{n}'$.

$C(\theta) \equiv \Delta T(\boldsymbol{n})\Delta T(\boldsymbol{n}')$ is expanded in terms of Legendre polynomials P_e $(\cos\theta)$:

$$C(\theta) = \frac{1}{4\pi} \sum_{e} (2l+1) C_l \mathrm{P}_l (\cos\theta) .$$

$(2l + 1)\ C_l/4\pi$ is called the power at scale l, with $l \approx 200°/\theta$.

For Gaussian random fields

$$(2l+1) C_l \ / \ 4\pi = \sum_{m=-l}^{+l} < |a_{lm}|^2 > .$$

(for a review see [94W]).

Dipole anisotropy

The dipole anisotropy (l = 1) has an amplitude of $\Delta T/T \approx 10^{-3}$. This anisotropy is interpreted as the Doppler shift caused for the terrestrial observer by the motion of the earth with respect to the almost isotropic background radiation field.

The motion of a receiver with velocity υ/c relative to an isotropic black-body radiation field with temperature T_0 produces a $\cos\theta$ behaviour of the observed temperature

$$T(\theta) = T_0 (1 - \upsilon^2 \ / \ c^2)^{1/2} (1 - \upsilon \ / \cos\theta)^{-1} \approx T_0 (1 + \upsilon \ / \cos\theta) .$$

The velocity implied for the barycenter of the solar system is υ/c = 0.001236 ± $2 \cdot 10^{-6}$ or υ = 371 ± 0.5 km s^{-1} towards (α, δ) = ($11.16^h \pm 0.01^h$, –6.7° ± 0.15°) or (l, b) = (264.14° ± 0.15°, 48.26° ± 0.15°). T_0 was taken to be T_0 = 2.728 ± 0.002 K [93K1, 96F1]. This in turn implies a velocity for the Galaxy and the Local group of galaxies relative to the CMB: υ_{LG} = 627 ± 22 km s^{-1} toward (l, b) = (276° ± 3°, 30° ± 3°).

Removal of the Doppler dipole leaves a CMB radiation field that is isotropic to $\Delta T/T \approx 10^{-5}$. This high isotropy of the CMB is at present the strongest support for the Friedmann-Lemaître cosmological models [93B1].

Intrinsic CMB anisotropies

The differential microwave radiometers (DMR) aboard the satellite COBE have provided evidence for fluctuations of cosmic origin in the CMB signal [92S1]. The rms sky variation is (30 ± 5) μK over patches of ≈ 10^0, i.e. $\Delta T/T \approx 10^{-5}$ at 10°. Since receiver noise is ≈ 80 μK, and galactic emission is present, the discovery of this signal required a careful statistical analysis [92S1, 92B2, 92W1].

Receiver noise, galactic emission, and the dipole component have to be subtracted from the full sky maps. There is still discussion on the problems of data reduction, especially with future experiments MAP and COBRAS/SAMBA in mind. In the expansion in spherical harmonics the COBE result limits multipoles up to $l \approx 20$. The power spectrum is consistent with a flat Harrison-Zel'dovich spectrum of initial density fluctuations ($P(k) \propto k^n$ with n = 1). The implications of this result for galaxy formation are obvious: The initial conditions for galaxy formation, i.e. the inital density fluctuations, are imprinted in the radiation field, and the gravitational instability picture with dark matter components has now firm support.

Fits to the data for some specific model (e.g. $P(k) \propto k^n$) over smaller angular scales are characterized by the expected value of the quadrupole amplitude $\langle Q \rangle$. In conventional notation $Q_{\mathrm{rms}}^2 \ / \ T_\gamma^2 = 5C_2 \ / \ 4\pi$. The 4 year COBE DMR data give $\langle Q \rangle = 15.3^{+3.7}_{-2.8}$ μK, and a best fit slope n = 1.2 ± 0.3. For n = 1 one gets $\langle Q \rangle (n=1) = 18 \pm 1.6$ μK [96G1].

The cosmic variance of each component C_l is $[2 \ / \ (2l+1)] C_l^2$ [94W1].

9.7.3.7 Nucleosynthesis of the lightest elements

The big bang nucleosynthesis calculations have become very precise, because the lifetime of the neutron has been measured quite accurately [89M1]. The lifetime τ_n lies in the interval

$$884\ \mathrm{s} \le \tau_n \le 890\ \mathrm{s}$$

(i.e. the neutron halflife is between 10.16 and 10.23 min.).

In addition updated nuclear cross-sections [88C1] have improved the calculations further.

On the observational side there are various new abundance determinations, and some disagreement still, especially on the deuterium (D) measurements.

The values given below are taken from [91S1, 91W1, 95C1, 96S1] with error estimates as discussed in [96S1].

The primordial value of the fractional mass abundance of the isotope ^{4}He is derived from the observations of blue compact galaxies. $Y_p = 0.232 \pm 0.03$ with a 2σ random error. Estimates of systematic uncertainties are + 0.01 and – 0.005 [90P1].

From the solar wind with corrections for ^{3}He depletion one derives [93G1]

$$\frac{\mathrm{D}+{}^3\mathrm{He}}{\mathrm{H}} \le 1.1 \cdot 10^{-4}.$$

The abundance of deuterium D/H from interstellar UV absorption has been limited to $< 2 \cdot 10^{-5}$. The primeval abundance may be different, because deuterium can only be destroyed but not created in stars and other normal astrophysical environments.

Observations of high-redshift absorption lines along the line of sight to a quasar could give D/H limits closer to the true primeval abundance. The problem is to identify an absorption line clearly as a D-absorption, i.e. to exclude an interloping hydrogen cloud with just the right velocity to mimic a D-line. There are doubts about one observation yielding a high value of $[\mathrm{D/H}] \approx 10^{-4 \pm 0.21}$]. The best value from several quasar observations is at present $[\mathrm{D/H}] = 2.7 \cdot 10^{-5}$ [96T1].

This fits well with UV measurements of interstellar deuterium absorption in the direction of Capella by the HST, which sets a lower limit $[\mathrm{D/H}] > 1.5 \cdot 10^{-5}$ [90P1].

The abundance of ^{7}Li is determined from spectroscopic measurements of old stars, as

$$^7\mathrm{Li/H} = (1.4 \pm 0.3) \cdot 10^{-10}.$$

Possible depletion in stars and addition by spallation reactions lead to an estimate of systematic uncertainties of $(+\,1.8, -\,0.4) \cdot 10^{-10}$.

Theoretial big bang nucleosynthesis gives values of these light element abundances as functions of the baryonic density Ω_B, or equivalently of the photon/baryon ratio $\eta = \frac{n_\gamma}{n_B}\Big|_0$ at the present time,

$$\Omega_B h^2 = 3.65 \cdot 10^{-3}\, (T/2.726)^3 \eta_{10}\ .$$

T is the CMB temperature in K, η_{10} is η in units of 10^{-10}. It is barely possible to achieve consistency with the measured values.

Using only the abundances of ^{4}He and ^{7}Li, the value of η_{10} is between 1 and 10, i.e.

$$0.0037 \le \Omega_B h^2 \le 0.037.$$

The D and ^{3}He values in addition limit η_{10} between 2.8 and 4.2, and give the narrow interval

$$0.01 \le \Omega_B h^2 \le 0.015.$$

The higher, and disputed D-values give

$$0.007 \le \Omega_B h^2 \le 0.014.$$

The abundance of ^{4}He can be used to obtain a bound on the number of light neutrino species [79S1]

$N_\nu \leq 3.4 + [Y_{p,\,max} - 0.245] / 0.012 - (\eta_{10,\,min} - 2.5) / 5.$

The narrow interval for $\Omega_B h^2$ required to find agreement between theory and observation is viewed by some as a triumph of big bang nucleosynthesis. The worry is, of course, that such a narrow margin may eventually give way to a real discrepancy. In fact, even now there seems to be a ^{4}He problem: the best fit from D, ^{3}He, and ^{7}Li data is $Y_p = 0.245$, while the measured values lean towards 0.232. It seems reasonable to allow for slightly larger systematic uncertainties in the experimental data and to accept a wider limit for η. This leads to a range of

$0.01 \leq \Omega_B h^2 \leq 0.025.$

The systematic uncertainties due to galactic and stellar evolution are almost impossible to estimate, so there is the attitude now [96S1] to ascribe problems with ^{3}He and ^{7}Li to the intricacies of stellar evolution.

In attempts to weaken the nucleosynthesis limits on Ω_B there have been investigations of the effects of inhomogeneous nucleosynthesis [94J1, 95J1]. After the decoupling of weak interactions, and especially, if the quark-hadron phase transition was of first order, density inhomogeneities might cause different neutron and proton density distributions. The mean free path of neutrons is much larger than that of protons. Thus in the initial high-density regions a very proton-rich environment appears, while the low-density regions are almost entirely filled with neutrons. Besides Ω_B, additional parameters occur such as the density ratio between high and low density regions, or the distance between high density zones. $\Omega_B = 1$ cannot be achieved, even with extreme assumptions, because one must be careful not to produce too much ^{4}He and ^{7}Li. It seems possible to weaken the standard homogeneous nucleosynthesis limits somewhat – by factors of 2 or 3. The models contain many ad hoc parameters, which are – for the astrophysically relevant range of values – disfavoured by the standard model of strong interactions [92I1].

9.7.4 Redshift

9.7.4.1 and 9.7.4.2

See LB VI/2c, p. 354

9.7.4.3 Peculiar motions of galaxies

9.7.4.3.1 Random peculiar motions

(1)-(6) see LB VI/2c, p. 355

(7) The pair-wise velocity dispersion of galaxies

The square root of the mean value of the square of the difference of the peculiar velocities of two galaxies at positions $\boldsymbol{x}$ and $\boldsymbol{x} + \boldsymbol{r}$

$$\left\langle \left(\upsilon(\boldsymbol{x}+\boldsymbol{r}) - \upsilon(\boldsymbol{x})\right)^2 \right\rangle^{1/2} = \sigma_p(\boldsymbol{r})$$

is one of the low-order statistics of the distribution of galaxies. Density inhomogeneities give rise to these peculiar motions which can in general only be measured statistically by an analysis of the anisotropy of the two-point correlation functions [83D1].

Recent analysis of various galaxy catalogues [93M1] gives a value σ_p (r = 1 Mpc) = (450 ± 50) km s^{-1}.

Theoretical models of the galaxy distribution usually give values higher than that.

9.7.4.3.2 Streaming motions

Measurements of a bulk motion for a sample of 200 elliptical galaxies [87D] have motivated several groups to investigate the redshift vs. distance relation. It seems to be well established that a large-scale bulk motion involving a scale of ≈ 50 Mpc around us exists [94D1].

9.7.5 The determination of the Hubble constant H_0

The problem with a precise determination of H_0 is the following: for any single galaxy it is almost certain that it does not follow exactly the overall cosmic expansion. All galaxies show peculiar motions of several 100 km s^{-1}, so

$$cz = dH_0 + \upsilon_p$$

with d = distance in [Mpc].

The peculiar velocities υ_p are comparable to dH_0 for nearby galaxies, and at distances where υ_p becomes negligible the distance determination becomes increasingly uncertain. For many years there was a split among observers voting for a large distance scale ($H_0 \approx 50$ km s^{-1} Mpc^{-1}]), and those advocating a short distance scale ($H_0 \approx 100$ km s^{-1} Mpc^{-1}). It traces back to the historic discrepancy between Sandage & Tammann ($H_0 = 50$ km s^{-1} Mpc^{-1}) and de Vaucouleurs ($H_0 = 100$ km s^{-1} Mpc^{-1}), both parties presenting their results usually with small error bars (less than 10 %).

9.7.5.1 Cepheids in the Virgo cluster

A much improved distance ladder to the Virgo cluster galaxies is available now, because Cepheid stars can be observed with the Hubble Space Telescope (HST) out to that distance. In addition, the zero-point of the Cepheid period-luminosity-correlation (PLC) could be calibrated by direct trigonometric parallax measurements of Galactic Cepheids [97F1].

$$\langle M_v \rangle = -2.81 \log P - 1.43$$

with P = period in days.

After correction for metallicity effects a distance modulus of 18.70 ± 0.10 for the Large Magellanic Cloud (LMC) was obtained. This is 0.2 mag higher than the value of 18.50 commonly used. Especially the HST project of measuring Cepheids in Virgo cluster galaxies is affected by this correction, since in building up the distance ladder Cepheids in LMC were calibrated using $(m - M)_{LMC} = 18.50$ [95M1]. Thus the distances published so far must be increased by ≈ 10 %, and the value of H_0 decreased by about 10 %.

More than 50 Cepheids have been analyzed in the spiral galaxy M100 [94F1, 96F2]. The distance is given as

$$d = (15.8 \pm 1.5)\ \mathrm{Mpc}$$

which should read $d = (17.4 \pm 1.5)$ Mpc with the new LMC distance calibration. It is a question whether this is a good estimate of the distance to the center of mass of the Virgo cluster. The spiral galaxies (as e.g. M100) may be outlying members of the cluster, and thus the distance determination may carry a large systematic error.

A cautious estimate seems to be [95M1]

$$d_{\mathrm{Virgo}} = (17.1 \pm 3.4)\ \mathrm{Mpc}.$$

Since this value already contains uncertain estimates of systematic errors, it is not clear how the LMC distance correction should be applied here.

The Virgo infall pattern is not well known, and therefore the true cosmic velocity of Virgo is also not well determined. Secondary distance indicators (Tully-Fisher, Dn-σ) are used to obtain an accurate relative distance between the Coma and Virgo cluster [95M1, 94F1]:

$$(m - M)_{\text{Coma}} - (m - M)_{\text{Virgo}} = 2.71 \pm 0.05.$$

Using $(m - M)_{\text{Virgo}} = 31.04 \pm 0.2$, the Coma value is $(m - M)_{\text{Coma}} = 34.75 \pm 0.21$, or $d_{\text{Coma}} = (89 \pm 9)$ Mpc.

From the redshift of the Coma cluster, $\upsilon_{\text{Coma}} = (7146 \pm 86)$ km s^{-1}, the Hubble constant is then

$$H_0 = (80 \pm 8) \text{ km s}^{-1} \text{ Mpc}^{-1}.$$

Taking into account systematic errors and the 10 % distance increase due to the new Cepheid calibration:

$$H_0 = (72 \pm 6 \text{ (random)} \pm 16 \text{ (systematic)}) \text{ km s}^{-1} \text{ Mpc}^{-1}$$

[95M1].

The derived cosmic velocity of the Virgo cluster, $\upsilon_{\text{Virgo}} = (1400 \pm 400)$ km s^{-1}, covers the values obtained in other astronomical observations. The mean value of 1400 km s^{-1} appears rather high compared to values of 1000 to 1200 km s^{-1} usually quoted.

9.7.5.2 Supernovae of type Ia as standard candles

Supernovae of type Ia, if they are good standard candles, can be used to directly measure the cosmic velocity field beyond the Virgo cluster. SNIa are generally thought to be thermonuclear explosions of white dwarfs consisting mainly of carbon and oxygen. ^{56}Ni is synthesized in the supernova explosion, and the optical luminosity results from the thermalization of γ-rays and positrons which are produced by the decay of ^{56}Ni to ^{56}Co to ^{56}Fe.

Intrinsic variations in luminosity at maximum are substantial [96V1]: $-17.3 \geq M_{\text{B}}$ (max) ≥ -19.61 from nine SNIa with distances determined by the Cepheid method.

Theoretical models also have room for intrinsic variations of the parameters [96H3, 96N1].

The calculation of the maximum luminosity from theoretical models is an intricate, as yet unsolved radiative transfer problem.

The lightcurve shape seems to be correlated with the maximum luminosity [95R1]: The fast decaying ones are usually fainter, and the slow ones are more luminous at maximum. The light-curve shape method gives a tight fit to the Hubble relation. The value of H_0 from presently available SNIa data is [95R1]:

$$H_0 = 66 \pm 6 \text{ (random)} \pm 7 \text{ (systematic) km s}^{-1} \text{ Mpc}^{-1}.$$

Even disregarding systematic errors, this value is consistent within the $1 - \sigma$ random errors with H_0 as determined from the Cepheid distances to the Virgo cluster. Another determination [93S1] from SNIa data arrives at values $H_0 = (71 \pm 7)$ km s^{-1} Mpc^{-1}. Other high-weight techniques need further refinement and development.

Tully-Fisher distances [94L1] yield

$$H_0 = (84 \pm 8) \text{ km s}^{-1} \text{ Mpc}^{-1};$$

planetary nebulae give $H_0 = (86 \pm 18)$ km s^{-1} Mpc^{-1} via Virgo [93M2], and $H_0 = (75 \pm 8)$ km s^{-1} Mpc^{-1} via the Fornax cluster [93M3]. Surface brightness fluctuations in elliptical galaxies lead to a mean value of

$$H_0 = (80 \pm 12) \text{ km s}^{-1} \text{ Mpc}^{-1} \text{ [92J1]}.$$

Other methods to determine H_0 make use of the Sunyaev-Zel'dovich (SZ) effect [94B] and the time delay in gravitational lens images [97K1]

$$H_0 = (66 \pm 15) \text{ km s}^{-1} \text{ Mpc}^{-1}.$$

9.7.6 The determination of q_0

9.7.6.1 Classical tests for q_0

9.7.6.1.1 The magnitude-redshift relation

The $m - z$ relation for SNIa might be sufficiently well determined to give a value of q_0 [95R1].

A value of $-1 \le q_0 \le +1$ seems to be indicated by the data at present [95R1].

9.7.6.1.2 - 9.7.6.1.4

See LB VI/2c, p. 358

9.7.6.2 The determination of the mean density

The mean luminosity density has been remeasured many times in recent years. One representative value of the blue band mean $\langle l_B \rangle$ is [88E1]

$$\langle l_B \rangle = (1.9 \pm 0.06) h\, L_\odot \mathrm{Mpc}^{-3}.$$

Then $\Omega_0 = (1450)^{-1} h^{-1} (M/L_B)_\odot$; where $(M/L_B)_\odot = (M/M_\odot)/(L/L_\odot)$ is the mass-to-light ratio in solar units. To reach $\Omega_0 = 1$, the M/L ratio of the objects considered should be $(M/L_B)_\odot = 1450h$.

The uncertainties are difficult to estimate, because systematic effects like galaxy evolution, obscuration and other photometric difficulties, might produce a much larger error in $\langle l_B \rangle$ then indicated above. Also the population of objects used to measure M/L_B may not be representative for the whole universe.

Since $\langle l_B \rangle \propto h$, and $M/L_B \propto h$, this factor cancels out, and Ω_0 is then independent of H_0.

This is not so for optical starlight from galaxies which for an average $M/L \approx 7$ gives

$$\Omega_* = 0.005 h^{-1}.$$

The rotation curves of spiral galaxies lead to an estimate of $M/L \approx 20h$, and

$$\Omega_G = 0.014.$$

The gravitational lens effect of compact objects in the halo of our galaxy on stars in the Large Magellanic Cloud (LMC) is measured by several groups in a large observational program. This so-called "microlensing" rests on the brightening of a stellar image, when the light path is close to a halo object. The "MACHO" experiment has identified 10 microlensing events. The mass of the halo objects has been estimated as $\approx 0.3\, M_\odot$ [93A1, 97A1]. This value is still quite uncertain, but it indicates the possibility that the DM in galactic halos may well be baryonic, concentrated in compact objects of low luminosity.

Clusters of galaxies offer several possibilities to estimate the mass, and consequently M/L.

A) Clusters are the largest virialized systems. Application of the virial theorem to the galaxies in the cluster, gives

$$\langle \upsilon^2 \rangle = \frac{GM}{R_\mathrm{v}}\ .$$

R_v is the effective virial radius; $\langle \upsilon^2 \rangle$ is the sum of the mass-averaged velocity squares. $\langle \upsilon^2 \rangle$ itself is not a measurable quantity. One uses assumptions such as $\langle \upsilon^2 \rangle = 3\sigma^2$, where σ^2 is the line-of-sight velocity dispersion obtained from redshift measurements. The virial radius R_v is determined from the projected number of galaxies. The mass determinations can be roughly represented by

$$M = 1.1 \cdot 10^{14} \left(\frac{\sigma}{10^3 \, \mathrm{km s}^{-1}} \right)^2 \left(\frac{\theta}{30''} \right) \left(\frac{D}{1 \mathrm{Gpc}} \right) M_\odot$$

(θ is the angular extent analysed; D the distance). This leads to M/L values between $150h$ and $400h$; and thus to estimates of Ω_m between 0.1 and 0.3. E.g. Coma: $M/L = 400h$; MS1224: $M/L = 250h$;

B) Cluster masses can also be determined from gravitational lensing. Giant arcs [96N2], as well as the statistical analysis of arclets (weak lensing) [96N2] allow to determine the mass of clusters, and their M/L ratios.

Typical estimates from giant arcs give

$$M = 1.1 \cdot 10^{14} \left(\frac{\theta_{\mathrm{arc}}}{30''} \right) \left(\frac{D}{1 \mathrm{Gpc}} \right) .$$

An example is A370 with $M/L \approx 200h$.

Some M/L ratios from weak lensing (arclets) are given in Table 1.

Ω_m for clustered matter derived from these measurements $0.13 \le \Omega_m \le 0.5$.

Table 1. Mass-to-Light ratios of several clusters derived from weak lensing [96N2].

Cluster	M/L	Remark	Ref.
MS1224	$800h$	virial mass ≈ 3 times smaller	94F2
Cl1455	$520h$	DM more concentrated than galaxies	95S2
A2218	$440h$	gas mass fraction < 4 %$h^{-3/2}$	96S2
A851	$200h$	mass distribution agrees with galaxies and X-rays	96S3

C) The cluster mass determination by X-ray observations is based on the assumptions that the hot gas emitting the X-rays is kept in hydrostatic equilibrium by the gravitational mass of the cluster.

The mass profile for a spherically symmetric cluster

$$M(r) = -\frac{kT_g(r) r^2}{m_n \mu G} \left(\frac{\mathrm{d} \log T_g(r)}{\mathrm{d}r} + \frac{\mathrm{d} \log \rho(r)}{\mathrm{d}r} \right) ,$$

where $\rho(r)$ and $T_g(r)$ are the density and temperature profile of the gas.

For rich clusters of galaxies one finds typically [95D2],

$$M_{\mathrm{grav}} \approx (5 \cdot 10^{14} \ldots 5 \cdot 10^{15}) \, M_\odot .$$

Galaxies are about 1…4 % of the total mass

$$M_{\mathrm{Gal}}/M_{\mathrm{grav}} = (0.01 \ldots 0.04) \, h^{-1} .$$

The intracluster gas is between 4 % and 30 % of the total mass $M_{\mathrm{g}}/M_{\mathrm{tot}} = (0.04 \ldots 0.3) \, h^{-1.5}$.

The gas mass M_{g} also is a measure of the mass in baryons contained in a cluster.

This can be used to derive limits on the total cosmic density under the assumption that this ratio of $M_{\mathrm{B}}/M_{\mathrm{tot}}$ in clusters is typical of the whole universe [93W1].

The nucleosynthesis limits give

$$0.01 < \Omega_{\mathrm{B}} \, h^2 < 0.025 .$$

If $\Omega_{\mathrm{B}}/\Omega_{\mathrm{tot}} \ge 0.1 h^{-1.5}$, then limits for Ω_{tot} result $\Omega_{\mathrm{tot}} \le 0.25 h^{-0.5}$.

The M/L ratios for clusters indicate $\Omega_{\mathrm{tot}} > 0.1$, and probably $\Omega_{\mathrm{tot}} \approx 0.3$.

These values apply for clustered matter, a more evenly distributed component is not accounted for in this analysis.

9.7.6.2.1 - 9.7.6.2.4

See LB VI/2c, p. 359-360

9.7.6.2.5 Limits on Ω_Λ

Statistical analysis of the distribution of gravitational lenses can give limits on Ω_Λ [93M4, 95W2].

$$\Omega \equiv \frac{8\pi G}{3H_0^2}\rho\,;\ \ \Omega_\Lambda \equiv \frac{\Lambda}{3H_0^2}\ .$$

For a flat model $\Omega_\Lambda \le 0.7$.

9.7.7 Constituents of the universe

See LB VI/2c, p. 361-362

9.7.8 The time scale of the universe

9.7.8.1 and 9.7.8.2

See LB VI/2c, p. 362

9.7.8.3 The age of the universe

The age of globular cluster stars is affected by the HIPPARCOS astrometry of galactic Cepheids [97F1]. The absolute magnitude of RR Lyrae in LMC globular clusters is M_v (RR) = 0.25 ± 0.10 at a metallicity [Fe/H] = – 1.9.

The age for the oldest galactic globular clusters is thereby reduced from $14.6 \cdot 10^9$ years [96C1] to $\approx 11 \cdot 10^9$ years. This supports new determinations of globular cluster ages which give ages of $(12 \pm 2) \cdot 10^9$ years for M68, and similar values for M15 and M92 [97S1].

This value of $(12 \pm 2) \cdot 10^9$ years should also be taken as an estimate of the age of the universe.

9.7.8.4 The history of the canonical Big Bang

See LB VI/2c, p. 363

9.7.8.5 H_0 and t_0 within a cosmological model

Figure 2 (after [89E1]) shows a family of $H_0 t_0$ = const. graphs as a function of Ω_m and Ω_Λ. The range of $H_0 t_0$ is not constrained too narrowly by the astronomical data, $0.7 \le H_0 t_0 \le 1.4$ is possible within the 2σ-limits.

9.7.9 Other cosmologies

See LB VI/2c, p. 365-366

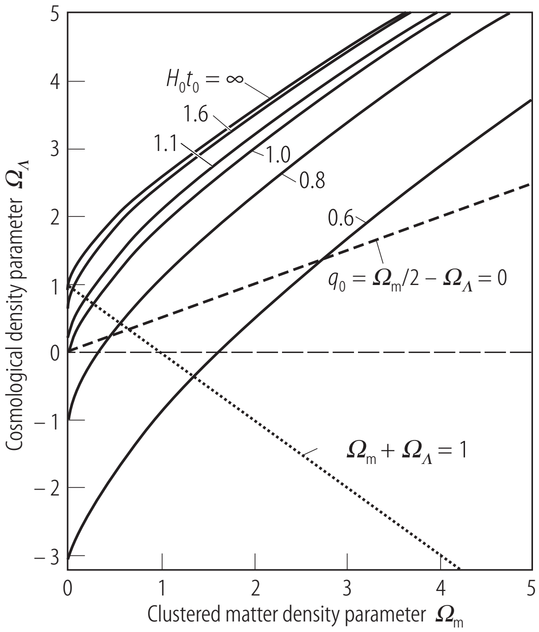

Fig. 2. Graphs of constant values of H_0t_0 are plotted showing the dependence on Ω_m and Ω_Λ.

9.7.10 Formation of cosmic large scale structure

9.7.10.1 Linear regime

Large redshift surveys [89G1, 90M2, 94F3, 96L1] reveal a wealth of interesting structures in the three-dimensional distribution of galaxies. The galaxies lie predominantly in filaments and sheets surrounding large empty regions of almost spherical shape ("voids") [89G1, 96L1], Fig. 3.

The two-point correlation function of the galaxies follows a power law

$$\xi(r) = (r/r_0)^{\gamma}$$

with $\gamma = -1.8$, $r_0 = 5h^{-1}$ Mpc [80P1, 90M2] up to scales of $\approx 10h^{-1}$ Mpc.

It is the aim of most modern theories of cosmology to explain the large-scale structure patterns as the evolution of initially small perturbations of a smooth background density which grow by the action of gravity. As long as the density contrast

$$\delta \equiv \frac{\rho(x,t)}{\rho_b(t)} - 1$$

($\rho_b(t)$ is the density of the homogeneous background) is small, $|\delta| \ll 1$, linear perturbation theory can be used [80P1, 93B1].

The Euler and Poisson equations lead to second order differential equations for δ

$$\ddot{\delta} + \frac{\dot{R}}{R}\dot{\delta} = \frac{\nabla^2 p}{\rho} + 4\pi G \rho_b R^2 \delta\,;$$

specialization to pressure-free matter eliminates the $\nabla^2 p$ term, and the general solution can be written

$$\delta(x,\tau) = A(x)D_1(t) + B(x)D_2(t).$$

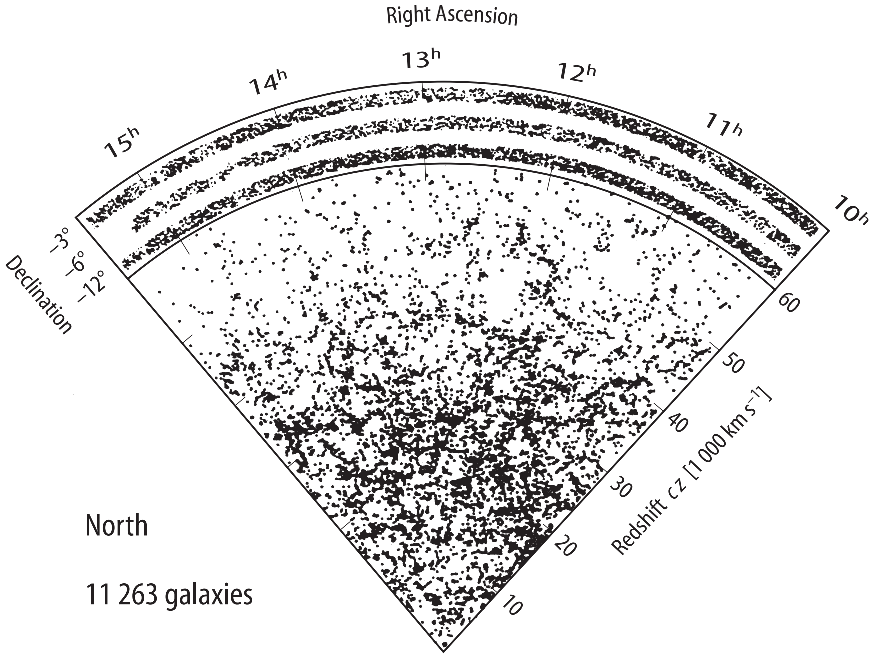

Fig. 3. The distribution of galaxies in the North galactic cap from the Las Campanas Redshift Survey (LCRS). Galaxies were observed in 3 different slices of declination which are all projected onto each other. The coordinates plotted are "right ascension" and the redshift *cz*.

For the Einstein-deSitter universe there is a simple form of a growing $\delta \propto t^{2/3}$ and a decaying mode $\delta \propto 1/t$. Detailed solutions are given in [80P1]. At the epoch of recombination all fluctuations were small, so it is sufficient to consider only the growing mode $D_1(t)$. For baryonic matter the density contrasts only grow after the time of recombination. This limits the growth factor $D_1(t_0)/D_1(t_R)$ to less than ≈ 1500. The initial amplitudes are limited by (in the adiabatic case) the COBE anisotropy measurements $\delta(t_R) = 3\left|\frac{\Delta T}{T}\right| \approx 3\cdot 10^{-5}$, and therefore δ at the present epoch is $\approx 5\cdot 10^{-2}$. Structure cannot form! These limits are strong enough to rule out a purely baryonic structure formation model.

As a way out the existence of nonbaryonic dark matter (DM) has been postulated [83B1].

9.7.10.2 Dark matter (DM)

Hot dark matter (HDM)

HDM are light, weakly interacting particles ($m \le 100$ eV) which are still relativistic when they decouple thermodynamically from the rest of the universe. The relativistic "free streaming" of these collisionless particles damps out all density fluctuations on scales smaller than the horizon scale at the epoch, when the particles have cooled down to non-relativistic velocities ($kT \le mc^2$). A typical example would be a neutrino with a hypothetical mass of a few eV.

Massive neutrinos ($m_\nu < 100$ eV) decouple when the temperature of the universe drops below 1 MeV. For each species we have today

$$n_{\nu 0} = \frac{3}{4}\cdot\frac{4}{11} n_{\gamma 0} = 109\left(\frac{T_{\gamma 0}}{2.7\mathrm{K}}\right)^3 \mathrm{cm}^{-3}.$$

The contribution to the cosmological density is

$$\rho_{\nu 0} = m_\nu n_{\nu 0} = 1090\,\mathrm{eV\,cm^{-3}} \left(\frac{m_\nu}{10\,\mathrm{eV}}\right)\left(\frac{T_{\gamma 0}}{2.7\,\mathrm{K}}\right)^3.$$

Since the critical density is $\rho_c = 10500h^2$ eV cm^{-3} we can write

$$h^2 \Omega_{\nu 0} = \rho_{\nu 0} / \rho_c = 0.104 \left(\frac{T_{\gamma 0}}{2.7\,\mathrm{K}}\right)^3 \left(\frac{m_\nu}{10\,\mathrm{eV}}\right).$$

The horizon size at $kT = m_\nu c^2$ is

$$\lambda_\mathrm{H} \approx M_{pl} m_\nu^{-2}.$$

This is the damping scale for hot DM: all fluctuations with $\lambda < \lambda_\mathrm{H}$ are damped out by the freely streaming relativistic particles. The free-streaming scale is comoving with the expanding universe, i.e., $d_\nu \propto (1 + z)^{-1}$, and at present [83B1]

$$d_{\nu 0} = 13(\Omega_\nu h^3)^{-1} \left(\frac{T_{\gamma 0}}{2.7\,\mathrm{K}}\right)^{-2} \mathrm{Mpc}.$$

Cold dark matter (CDM)

CDM are particles which decouple very early. They are either very heavy particles with mass of a few GeV (such as the lightest stable supersymmetry candidate, the "neutralino") which are nonrelativistic very early, or they appear with essentially zero random velocity (such as a Bose condensate of axions, or quark lumps). No CDM particle is known experimentally. Free-streaming is unimportant, because for CDM this scale is much smaller than any scale of astronomical interest. CDM fluctuations can only grow, when the energy density of the nonrelativistic CDM component becomes larger than the relativistic energy density. With N_ν types of light neutrinos

$$\rho_\mathrm{rel} = \rho_\gamma (1 + \tfrac{7}{8} N_\nu \left(\frac{T_\nu}{T_\gamma}\right)^4) \approx \rho_\gamma (1 + 0.227 N_\nu),$$

$\rho_\mathrm{x} = \rho_\mathrm{rel}$ at t_eq ("x" are the CDM particles)

$$1 + z_\mathrm{eq} = 4.2 \cdot 10^4 (\Omega_\mathrm{x}\, h^2)(1 + 0.227 N_\nu)^{-1}.$$

The horizon size $\lambda_\mathrm{eq} \approx \int_0^{t_\mathrm{eq}} \mathrm{d}t / R(t) \propto (\Omega h^2)^{-1}$ determines a typical scale.

The **power spectrum** of density fluctuations is defined as $P(\boldsymbol{k}) = \left\langle |\delta_k|^2 \right\rangle$, where δ_k is the Fourier-component with wave number k of the density contrast

$$\delta_k = 1/V_u \int \delta(\boldsymbol{x}) \exp(i\boldsymbol{k}\cdot\boldsymbol{x})\,\mathrm{d}^3 x.$$

Because of rotational and translational invariance $P(\boldsymbol{k}) \equiv P(k)$. The brackets $\langle\ldots\rangle$ denote an ensemble average. The background is homogeneous and isotropic, and therefore the ensemble average can be replaced by an average over a fair sample, or the spatial average within it.

$P(k)$ and the 2-point correlation function $\xi(x)$ are a Fourier transform pair

$$P(k) = \frac{4\pi}{V_u} \int \xi(x) \frac{\sin kx}{kx} x^2 \mathrm{d}x\ ;$$

$$\xi(x) = \frac{V_u}{\pi^2} \int P(k) \frac{\sin kx}{kx} k^2 \mathrm{d}k\ ;$$

$P(k)$ and $\xi(x)$ give equivalent information.

The initial power spectrum must be derived from physical processes in the early universe. The model of the inflationary universe [90L1] predicts a form $P(k) \propto k$.

For a power law

$$P_i(k) = A_i k^n$$

the index n is constrained, because for $n \gg 1$ there would be an overproduction of small-mass objects, while for $n \ll 1$ the large masses would be produced in too large a number.

Changes of the power spectrum in the linear regime

The initial power spectrum $P_i(k)$ will be changed already in the linear regime by the time evolution of the DM components around $t_{\rm eq}$ [86B1].

$$P(k,t) \equiv C(t) P_i(k) T_{\rm lin}^2(k).$$

The linear transfer function $T_{\rm lin}(k)$ is approximately for CDM

$$T_{\rm lin} \approx \begin{cases} 1 & \text{for } k < \frac{2\pi}{\lambda_{\rm eq}} \approx 0.64\,(\Omega h^2)\,\mathrm{Mpc}^{-1} \\ k^{-2} & \text{for } k > \frac{2\pi}{\lambda_{\rm eq}} \end{cases} ;$$

for HDM

$$T_{\rm lin} = \begin{cases} 1 & \text{for } k < \frac{2\pi}{d_\nu} \\ e^{-d_\nu k} & \text{for } k > \frac{2\pi}{d_\nu} \end{cases} .$$

For baryon the typical horizon size is ct_R, the horizon at recombination ($k_R = 0.05(\Omega\, h^2)\mathrm{Mpc}^{-1}$)

$$T_{\rm lin} = \begin{cases} 1 & \text{for } k < k_R \\ k^{-2} & \text{for } k_R < k < k_s \\ e^{-(k/k_s)^2} & \text{for } k > k_s \end{cases} ;$$

k_s is a damping scale which is produced by photon diffusion at epochs before recombination, when baryonic perturbations oscillate like accoustic waves. The mass-scale corresponding to this "Silk damping" [83S1] is

$$M_s = 3 \cdot 10^{12}\,(\Omega h^2)^{5/4}\, M_\odot .$$

A useful fitting formula to the linear transfer function for CDM is [86B1]

$$T_{\rm lin}(k) = \frac{\ln(1+2.34q)}{2.34q}\left\{1 + 3.89q + (16.1q)^2 + (5.46q)^3 + (6.71q)^4\right\}^{-1/4},$$

where $q \equiv \dfrac{k}{\Gamma h \mathrm{Mpc}^{-1}}$. A shape parameter for the power spectrum has been introduced as $\Gamma \equiv \Omega_0 h$ [92E1].

9.7.10.3 Normalization

The amplitude $C(t)A_{\rm i}$ must be fixed, and this is usually done by a comparison with astronomical data. Under the assumption that the linear theory is valid until the present epoch, we write

$$C(t) = \left[\frac{D_1(t)}{D_1(t_0)}\right]^2,$$

where $D_1(t)$ is the linear growth function. COBE results for the microwave anisotropies apply to scales where even at the present epoch $T_{\text{lin}} = 1$, and they lead, for $\Omega_0 + \Omega_1 = 1$ models, to

$$A_{\text{COBE}} = \left(\frac{96\pi^2}{5}\right)\Omega_0^{-1.54} H_0^{-4} \left(\frac{Q_{\text{rms}}}{T_{\gamma 0}}\right)^2,$$

where Q_{rms} is the COBE rms-quadrupole fluctuation. Then at large scales, where $T_{\text{lin}} = 1$, all models have the same $P(k)$.

Another popular way to normalize makes use of the amplitude of the mass fluctuation in randomly placed spheres of radius S:

$$\left\langle \left(\frac{\delta M^2}{M}(S)\right)\right\rangle = \int_0^\infty W^2(kR)P(k)\frac{k^2 \mathrm{d}k}{2\pi^2} \;;$$

W is a filter function. For a so-called top-hat window

$$W(x) = \frac{2}{x^3}(\sin x - \cos x).$$

If the two-point correlation function of galaxies ξ_{g} is taken as a measure of the clustering of mass, then at a scale of $8h^{-1}$ Mpc one finds [80P1]

$$\sigma_{8,\text{g}} \equiv \left(\frac{3}{4\pi S^3}\right)\left(\int_V \mathrm{d}V_1 \mathrm{d}V_2 \xi_{\text{g}}(r_{12})\right)^{1/2} \approx 0.96.$$

Fits to the observations can be achieved in DM models, if the rms overdensity in mass $\sigma_{8,\text{m}}$ is set equal to $b^{-1}\sigma_{8,\text{g}}$. b is a so-called "bias" parameter [85D1]. In a CDM model with $P_i(k) \propto k$, $\Omega = 1$, a value of $b^2 \approx 10$ is required to achieve a reasonable fit to ξ_g. The physical basis for the bias is the idea that the galaxies do not trace the DM distribution, but rather that peaks in the DM density field correspond to galaxies.

9.7.10.4 The Status Quo

Several quantities are needed for a model of structure formation: the amplitude and spectrum of the initial density perturbations, the type and fraction of dark matter, and the bias factor (or function) have to be specified to define a model, whose linear evolution can be computed unambiguously. In addition, of course, the parameters of the cosmological model (H_0, Ω_0, Ω_Λ, $T_{\gamma 0}$) are needed. There seems to be a wide range of possible models, but this freedom in model building is due to our lack of knowledge of the basic physical processes, as well as the large uncertainties in the measurement of the cosmic parameters. Looking at the situation from first principles there is only one correct model of structure formation, since the cosmic parameters, as well as the type and fraction of dark matter can be determined from observations, while the initial density perturbations as well as the bias factor should be derived from physical mechanisms operative in the very early universe, and in galaxy formation, respectively.

9.7.10.5 Nonlinear gravitational clustering

The study of the formation of nonlinear structures uses N-body numerical simulations, and analytic considerations. The largest N-body simulations so far have 17 million particles and they have almost enough resolution to cover the dynamic range from galaxies (0.1 Mpc) to large-scale structures (100 Mpc).

Analytic approximations are the Zel'dovich pancake model, the Press-Schechter model (P-S), and higher order perturbation theory [91S2].

a) The Zel'dovich approximation [70Z1, 95B1] is used to set up the initial particle distribution for numerical computation as accurately as possible. The linear power spectrum is evolved to some redshift z_i, when the N-body codes take over. $P(k, z_i)$ is the input, and it is derived from the linear initial conditions via the Zel'dovich method [85E1, 91H1].

b) The Press-Schechter approximation [74P1] is an application of the exact solution for isolated spherical collapse [83N1] to a statistical collection of collapsed objects of DM starting from an initial Gaussian distribution. For instance, the number density of objects of mass M which have turned around and collapsed at redshift z can be calculated under the assumption that initially spherical random Gaussian fluctuations collapse and form bound objects

$$n(M,z)\mathrm{d}M = -\left(\frac{2}{\pi}\right)^{1/2} \frac{\rho_0}{M} \frac{\delta_c}{\Delta^2(M,z)} \frac{\mathrm{d}\Delta(M,z)}{\mathrm{d}M} x \exp(-\delta_c^2 / 2\Delta^2(M,z))\mathrm{d}M\,.$$

$n(M, z)$ is the comoving number density at redshift z of objects with mass between M and $M + \mathrm{d}M$, ρ_0 is the present mass density, and $\Delta(M, z)$ is the density fluctuation at a scale M and redshift z computed from linear theory; δ_c is a critical density contrast which is chosen close to $\delta_c = 1.69$ [94L2].

Studies with N-body simulations show that the P-S estimate is quite a good approximation to a hierarchical model of galaxy formation, where smaller objects aggregate to form successively larger structures as time progresses [93K1, 94K1].

c) Numerical simulations
N-body simulations are nothing but the numerical solutions of the Newtonian equations of motion for N particles interactig only by gravitation. This has become a standard tool in the field of structure formation [92E1, 93P1, 93S2, 93W2]. At present 10^7 particles can be followed in their development into the highly clustered regime. This is easily sufficient to address most problems. This, however, concerns only the DM distribution. Real galaxies, i.e. simulations of the clustering of the baryons, have not been incorporated into large scale structure calculations.

9.7.10.6 Observational tests

Statistical measures of the topology of the galaxy distribution have not been applied to such an extent that useful tests of models can be done. The 2-point correlation function of galaxies is still the most widely used tool. For a range of scales $5h^{-1}$ Mpc $\le r \le 10h^{-1}$ Mpc this function $\xi(r)$ is approximately a power-law

$$\xi(r) = (r_0/r)^\gamma$$

where r_0 and γ are typically $\gamma = 1.8$, $r_0 = 5h^{-1}$ Mpc [80P1, 90M2, 96L1, 96M1, 98J1].

There are deviations from the power law on larger and smaller scales, and for different galaxy catalogues there are also differences in $\xi(r)$. Comparing model predictions for the mass correlation with the galaxy correlation function obtained from the APM survey [90M2], and from the Las Campanas survey, one may conclude [98J1, 97P1] that the current CDM models are inconsistent with the observational results, unless there is a scale-dependent bias in the distribution of galaxies relative to the mass distribution. A similar conclusion is reached for the pairwise peculiar velocity dispersion [98J1, 97L1].

Constraints on models can also be derived from the cluster-cluster correlation function [88B2], from the abundance of damped Lyman-α systems [94M3, 95W1], and from cluster abundance [93B1, 94J1]. Very few models can be excluded. A good fit can be obtained for all observational data from a CDM model with $n = 1$; $\Omega_{\mathrm{CDM}} = 0.3$, $\Omega_\Lambda = 0.7$.

9.7.11 Particle physics and cosmology

9.7.11.1 Baryogenesis

Models to explain the small ratio of baryons to photons $n_B/n_\gamma \approx 10^{-10}$ from an initially symmetric state (equal number of particles and antiparticles, $n_B = 0$) make use of an asymmetric particle decay in a GUT theory [83K1] or of an electro-weak phase transition in the early universe [96R1].

9.7.11.2 Inflation

The idea of an early exponentially fast expansion of the universe, driven by the energy density of the ground state of a scalar field, has led to a flood of speculative models [81G1, 81S1, 90L1]. An interesting prediction of these models is a flat model $\Omega_m + \Omega_\Lambda = 1$, and a power spectrum of density perturbations

$$P_i(k) \propto k.$$

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