Astron. Astrophys. 142, 1–8 (1985)

ASTRONOMY
AND
ASTROPHYSICS

Distribution and motions of atomic hydrogen in lenticular galaxies

III. NGC 3998

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Received May 9, accepted July 13, 1984

Summary. Synthesis observations of H I in the active SO galaxy NGC 3998 show that the gas is in a polar ring, inclined about 80° to the optical major axis. The position angle of the ionized gas in the inner galaxy is intermediate between those of H I and the light, suggesting differential precession of the gas structure. Weak extensions on the radio continuum emission from the nucleus are roughly perpendicular to the inner gas distribution. The circular velocity derived from the H I is normal for a galaxy of this luminosity; however, the ratio of central bulge velocity dispersion to circular velocity is anomalously high. This, and the extreme central light concentration, suggest that the galaxy contains a central massive object.

Key words: galaxies: general – galaxies: evolutions of – galaxies: NGC 3998 – kinematics and dynamics of galaxies

1. Introduction

This is Paper III in a series of studies of the H I distribution in nearby early-type disc galaxies carried out at the University of Groningen using the Westerbork Synthesis Radio Telescope (WSRT). Single-dish surveys of SOs and ellipticals have shown that the H I emission is undetectable from most of these galaxies. In an attempt to understand the relationship between the presence of gas in early-type galaxies and the evolution of their stellar populations, and to understand the origin of gas in early-type galaxies, we have undertaken a study of the distribution and kinematics of the gas in a sample of the detected galaxies. The problems to be approached in this programme have been outlined by van Woerden et al., 1983 (Paper I). In the present paper, we describe observations of the active galaxy NGC 3998. H I observations of the galaxy with the NRAO 91 m telescope (Gallagher et al., 1984) showed the possible presence of weak (peak flux ~20 mJy), broad H I line emission from NGC 3998. The distribution of H I was therefore investigated by synthesis mapping using the WSRT.

Some known properties of the galaxy, including the kinematics of the stellar component, the kinematics of the ionized gas and the radio continuum properties are summarized in the next section. In Sect. 3, the H I synthesis observations with the WRST are described and the results presented. In Sect. 4, the results are discussed, particularly as they relate to the dynamics of the gas in NGC 3998 and other galaxies with polar rings. In Sect. 5 we present the conclusions of this paper.

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2. The properties of NGC 3998

The observational properties of the galaxy described in this section are summarized in Table 1.

2.1. Morphology, colour, distance, and luminosity

NGC 3998 is listed in the major catalogues (de Vaucouleurs et al., 1976: RC2; Sandage and Tammann, 1981: RSA; Nilson, 1973: UGC) as an early-type SO galaxy. The disc contains no structure, nor is there any evidence for the presence of dust anywhere in the galaxy. The Palomar Observatory Sky Survey prints show that NGC 3998 is probably a member of a group of galaxies of various morphological types. While it is the brightest galaxy in the group, it is not near the centre of the group but rather at its eastern edge. NGC 3998's neighbour, NGC 3990, type SO^-(RC2), is at an angular distance of 3.2 arcmin (a projected linear distance of 14 h^{-1} kpc), and has a radial velocity of 720 km s^{-1}. The colours of NGC 3998, corrected for redshift, inclination and galactic extinction are $(B\text{–}V)_T^0 = 0.87$, $(U\text{–}B)_T^0 = 0.46$, typical of an old stellar population.

The galaxy's radial velocity is 1009 km s^{-1} (Tonry and Davis, 1981; hereafter TD). This velocity, corrected for the motion of the Galaxy with respect to the Local Group (RC2) and the motion of the Local Group with respect to the Virgo Cluster (Aaronson et al., 1982), gives a distance of 15.2 h^{-1} Mpc, where $H_0 = 100\,h$ km/s Mpc^{-1}. This corrected blue magnitude in the RC2 then gives $L_B^0 = 1.1\ 10^{10} h^{-2} L_{\odot}$. NGC 3998 thus has the properties of a normal bright early-type SO galaxy. In at least two respects, however, it is very unusual. The kinematics of the galaxy near the nucleus are peculiar, and the object has an active nucleus which is a source of emission in optical lines, radio continuum and X-rays.

2.2. Kinematics

The galaxy is kinematically remarkable in several respects. The stellar velocity dispersion observed at the centre is very large;

Table 1. Kinematics and luminosity of NGC 3998

Central position: (1950)	$\alpha = 11^h55^m21\overset{s}{.}4$	Dressel and Condon (1976)
	$\delta = +55°43'57''$	
Type:	SA(r)O?; SO	RSA, RC2
Radial velocity:	$1009 \pm 23\,\mathrm{km\,s^{-1}}$	TD
Distance:	$15.2\,h^{-1}$ Mpc	Aaronson et al. (1982)
Face-on diameter D_0	3.2 arcmin	RC2
Total corrected magnitude B_T^0:	$11\overset{m}{.}27$	RC2
Corrected Colours $(B\text{–}V)_T^0$:	$0\overset{m}{.}87$	RC2
$(U\text{–}B)_T^0$:	$0\overset{m}{.}46$	RC2
Total blue luminosity L_B^0:	$1.1\ 10^{10}\,h^{-2}\,L_\odot$	
Major axis position angle:	$140° \pm 5°$	UGC
Kinematic major axis of ionized gas:	$95° \pm 5°$	Blackman et al. (1983)
Peak rotation velocity of ionized gas:	$270 \pm 30\,\mathrm{km\,s^{-1}}$	Blackman et al. (1983)
Stellar velocity dispersion:	$314 \pm 20\,\mathrm{km\,s^{-1}}$	TD; Huchra (1983)
Velocity dispersion of ionized gas:	$250 \pm 20\,\mathrm{km\,s^{-1}}$	Blackman et al. (1983)
Radio flux (1416 MHz):	100 ± 8 mJy	Present paper
Radio power (1416 MHz):	$2.8\ 10^{21}\,h^{-2}$ Watt/Hz	

Table 2. WSRT observations of NGC 3998

Observing date:	April 19, 1982
Total observing time:	12 h
Baselines:	72, 144 ... 1440 metres
HA coverage:	$-90°$ to $90°$
Field Centre coordinates (α, δ, 1950):	$11^h55^m20^s$, $+55°47'$
Primary beam (FWHM):	37.0 arcmin
Synthesized beam:	$24\overset{''}{.}5 \times 29\overset{''}{.}7$
Heliocentric radial velocity:	$1058\,\mathrm{km\,s^{-1}}$
Total bandwidth:	5 MHz
Velocity resolution:	$40\,\mathrm{km\,s^{-1}}$
Channel spacing:	$33\,\mathrm{km\,s^{-1}}$
RMS noise in unsmoothed channel maps:	0.7 mJy/beam $\equiv$ 0.7 K

values of 280–315 $\mathrm{km\,s^{-1}}$ have been found (TD; Capaccioli, 1979; Blackman et al., 1983; Huchra, 1983). Such high values of the velocity dispersion are found or exceeded only for the most luminous galaxies in the TD sample. Spectra taken along the optical major axis (Bertola and Capaccioli, 1978) show that the stellar component is rapidly rotating, with a projected rotation velocity rising to $\sim 110\,\mathrm{km\,s^{-1}}$ at $\pm 4''$ radius and then flattening off. The major axis of NGC 3998 has a position angle of 140° (UGC) with the SE side of the galaxy receding. Using the observed axial ratio of 1.2 (RC2) and assuming an intrinsic ratio of 0.2, Bertola and Capaccioli (1978) calculate an inclination of 36° and thus a circular velocity in the disc of 240 $\mathrm{km\,s^{-1}}$ (after correction for integration along the line of sight).

A region of ionized gas extended over radius $\gtrsim 25''$ is found in the inner regions of the galaxy. Along the major axis, the gas and stars rotate together (Capaccioli, 1979). This *may* be a coincidence; spectra taken at several position angles (Blackman et al., 1983) give a kinematic major axis for the ionized gas at a position angle of 95° with a peak rotation velocity of 270 $\mathrm{km\,s^{-1}}$.

2.3. The galactic nucleus

The final remarkable thing about NGC 3998 is that it has an acitve nucleus, resembling that of Seyfert galaxies (cf. Heckman, 1980). The emission lines at the position of the nucleus are very broad, with $\sigma = 250\,\mathrm{km\,s^{-1}}$ (Blackman et al., 1983). The light distribution is strongly peaked towards the nucleus (Disney and Cromwell, 1971).

The nuclear region of NGC 3998 is also a bright X-ray (Dressel, 1984) and radio source (Hummel, 1980). The 1415 MHz luminosity is the highest for any SO galaxy and places it among the top 10% of ellipticals.

The continuum emission from NGC 3998 has been measured between 1 and 10 GHz and is flat at ~ 100 mJy (see e.g. the references in Hummel, 1980). Much of the flux of the nucleus arises from a very small region; the galaxy is detected at VLBI resolution (Hummel, 1982). The source also has weak extensions at P.A. $\sim 15°$ and 195° (Hummel, 1980; Wrobel, 1982).

3. The H I synthesis observations and results

3.1. The WSRT observations

NGC 3998 was observed with the WSRT in April 1982 for one twelve-hour period. The instrumental and observational parameters are listed in Table 2. A digital spectrometer (Bos et al., 1981) was used to observe two polarizations in 31 channels over a bandwidth of 5 MHz, giving a channel spacing of 33 $\mathrm{km\,s^{-1}}$ and a velocity resolution of 40 $\mathrm{km\,s^{-1}}$. The velocities in this paper are

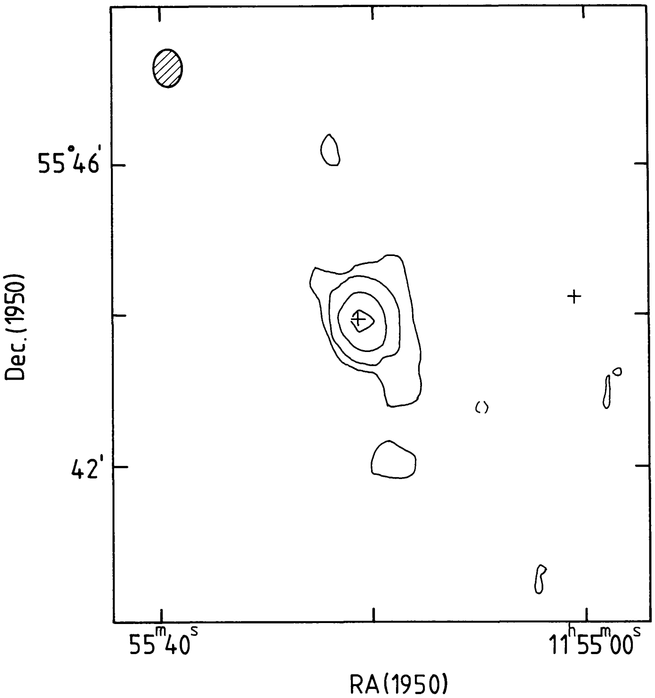

Fig. 1. Cleaned continuum map (1416 MHz) of NGC 3998. The central positions of NGC 3990 and NGC 3998 (the eastern galaxy) are marked by crosses. The spatial resolution is 25″ × 30″; the HPBW is shown in the upper left hand corner of the figure. The contours are drawn at −1.5 mJy, 1.5 mJy, 5, 15, and 75 mJy/beam; negative contours are dashed. The weak extension of the source in NGC 3998 at position angles 15° and 195° are also seen on VLA maps by Hummel (1980) and Wrobel (1982)

Table 3. H I parameters of NGC 3998

Integrated H I flux:	6.4 Jy km s^{-1}
H I mass M(H I):	3.5 $10^8 h^{-2} M_\odot$
H I diameter:	2.5 arcmin
Systemic velocity:	1040 ± 50 km s^{-1}
H I profile widths $W_{0.2}$:	655 ± 60 km s^{-1}
$W_{0.5}$:	580 ± 60 km s^{-1}
M(H I)/L_B:	0.031 $M_\odot/L_\odot$
Kinematic major axis:	60° ± 5°

heliocentric and calculated according to the conventional optical definition ($V = c\Delta\lambda/\lambda_0$).

The data were calibrated, and Fourier transformed to produce maps of the intensity distribution in each channel. The subsequent data reduction was carried out in Groningen using the Groningen Image Processing System GIPSY (Shostak and Allen, 1980; Allen et al., 1984).

The maps were first examined for hydrogen-line emission to find the velocity ranges free of such emission which could be used for continuum subtraction. The first two and last two channels were not used in the data reduction since, being at the edges of the band, they are of poor sensitivity. Channels 3, 4, 26, 27 and 28 were found to be free of line emission; from them velocity-weighted average continuum maps were made which were then subtracted from the corresponding line channel maps. The central part of the continuum map, after cleaning, is shown in Fig. 1. The bright central continuum source and the weak southwest extension described by Wrobel (1982) are seen. The flux density of the source is S(1416 MHz) = 100 ± 8 mJy (April, 1982), in agreement with previous determinations.

The resulting continuum-subtracted line channel maps were found to be essentially free of the sidelobe and grating-ring effects of the bright central source. The maps were then Hanning smoothed to a resolution of ~66 km s^{-1} to improve the signal-to-noise ratio, and most subsequent processing was done with these smoothed maps.

3.2. *Results: The H I distribution in NGC 3998*

The H I parameters for NGC 3998 derived from our observations are summarized in Table 3. The continuum-substracted channel maps are shown in Fig. 2. The flux in the individual channel maps is detected at a level of only a few times the rms. noise.

In the channel maps (Fig. 2) we show the distribution of the H I, smoothed to a resolution of 40″ × 40″, as a function of velocity. The positions of NGC 3998 and its neighbour NGC 3990 are indicated. The velocity of NGC 3990 is 720 km s^{-1}, partly inside the velocity range of the maps in Fig. 2. No H I associated with NGC 3990 is seen. The maps clearly show the presence of a rotating H I structure centered on NGC 3998. While the structure is slightly resolved (size ~1′) in each channel map, it moves across NGC 3998 with increasing velocity in a roughly south-west → north-east direction. There is no sign of any interaction of the gas in NGC 3998 with NGC 3990, although this conclusion is limited by the low H I signal level.

The global H I profile was constructed using the original channel maps with 40 km s^{-1} resolution by adding the flux at each velocity over an area a little larger than that of the galaxy and correcting for the attenuation of the primary beam. The resulting H I global profile is shown in Fig. 3 and agrees reasonably well with those observed with the NRAO 91-meter telescope (Gallagher et al., 1984; Lewis and Crane, 1984), although no profile is observed with enough sensitivity to determine well the true profile shape. The integrated H I flux of 6.4 Jy km s^{-1} agrees with the values of 6.7 Jy km s^{-1} found by Gallagher et al. (1984) and 7.0 Jy km s^{-1} found by Lewis and Crane (1984). For the distance assumed (Table 1) the H I mass is 3.5 $10^8 M_\odot$ and the value of $M_{\rm H\,I}/L_B$ is 0.03. These values are low for detected S0s, but typical of those found for detected elliptical galaxies, and are listed, along with the H I profile width and mean velocity, in Table 3.

A map of the integrated H I distribution was constructed from the full resolution channel maps as follows. The intensities in the 25″ × 30″ maps were summed in velocity only in those areas where the intensity in the 80″ × 80″ maps exceeded 2.2 mJy per beam (2σ: ≡ 0.25 K). In Fig. 4 this map of the H I column density is shown superimposed on a broad-band image-tube photograph of the field (Blackman et al., 1983) kindly made available by Wilson. The H I distribution is remarkable in having its major axis almost perpendicular to that of the optical galaxy. The major axis of the H I feature has a position angle of 60° ± 5°, and its elongated appearance suggests that it may be almost edge-on to the line of sight. Since the inclination of the H I feature is not well enough known we cannot define a "face-on" isophotal diameter. The observed diameter, corrected for instrumental smoothing, is 150″ at a column density of 2.2 10^{20} cm^{-2}.

No 21-cm line absorption was seen towards the central continuum source, with a 3σ upper limit on the column density of any absorbing cloud of ~4 10^{20} cm^{-2} if $T_s = 100$ K. The apparent features seen in the upper right and lower left corners of Fig. 4 are due to single-channel noise spikes, and do not correspond to dwarf

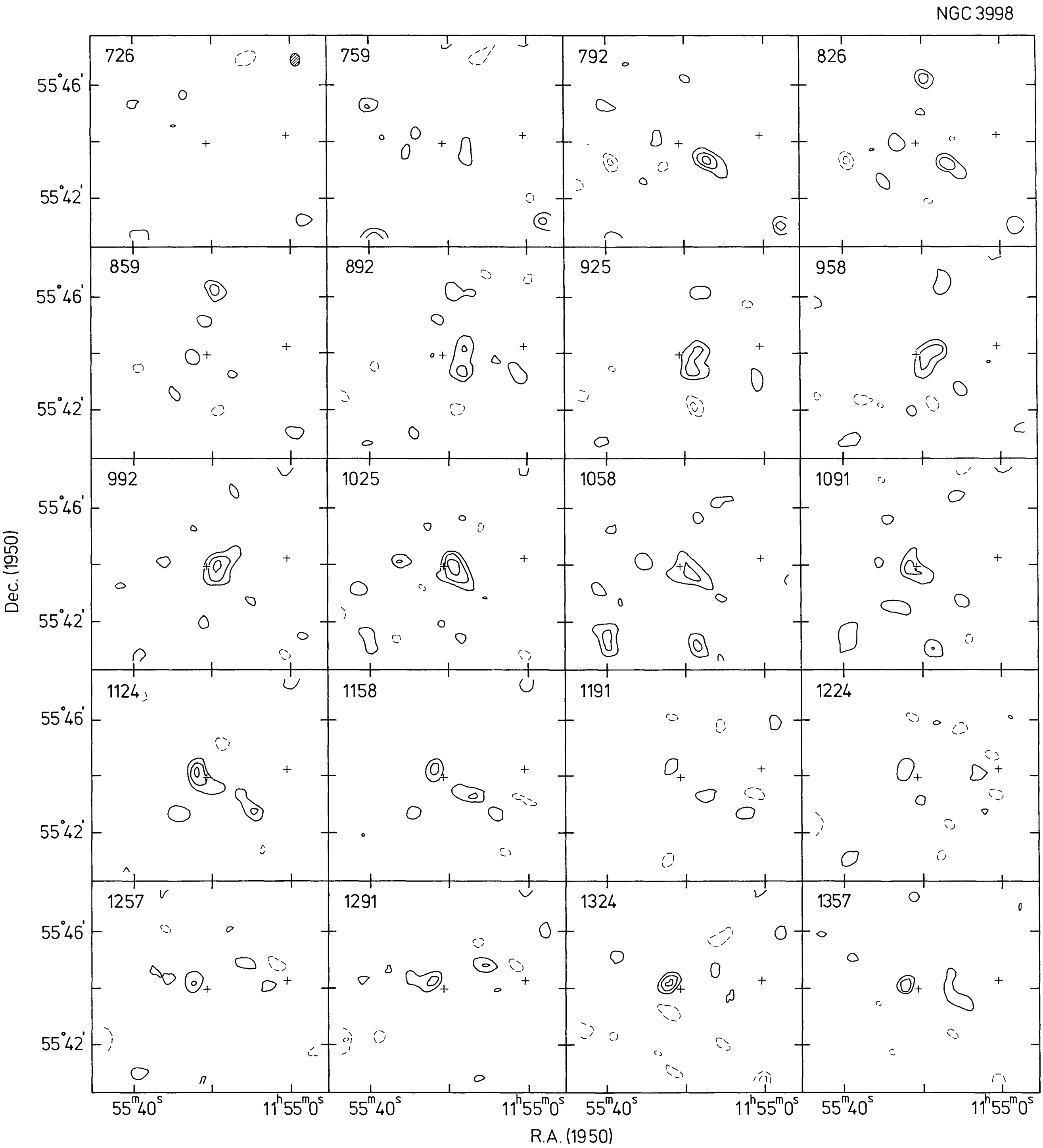

Fig. 2. H I line channel maps for NGC 3998, observed with a resolution of 40″ × 40″. The HPBW is shown in the lower right. The crosses give the positions of NGC 3998 (the eastern galaxy) and NGC 3990; the systemic velocities of these galaxies are respectively 1009 km s^{-1} and 720 km s^{-1}. Negative contours are dashed. The first positive and negative contours are at ± 0.60 K (2 σ); the contour interval is ΔT_b = 0.30 K (1 σ). The central velocity of each map is given in the top left hand corner

galaxies, for example. No H I other than that associated with NGC 3998 (and the spiral NGC 3982) is found in the field.

3.3. *The H I kinematics in NGC 3998*

The velocity field in the galaxy was constructed from the channel maps by fitting a gaussian to the profile in each pixel, and is shown in Fig. 5. While the map is fairly ill-defined owing to the poor signal-to-noise ratio and beam-smearing effects, it clearly shows rotation along the H I feature, with the velocity increasing from the south-west to the north-east. Thus although the H I feature is highly inclined to the optical galaxy (by 75° ± 8°), its projected motion is prograde with respect to that of the optical galaxy (major axis P.A. = 140°).

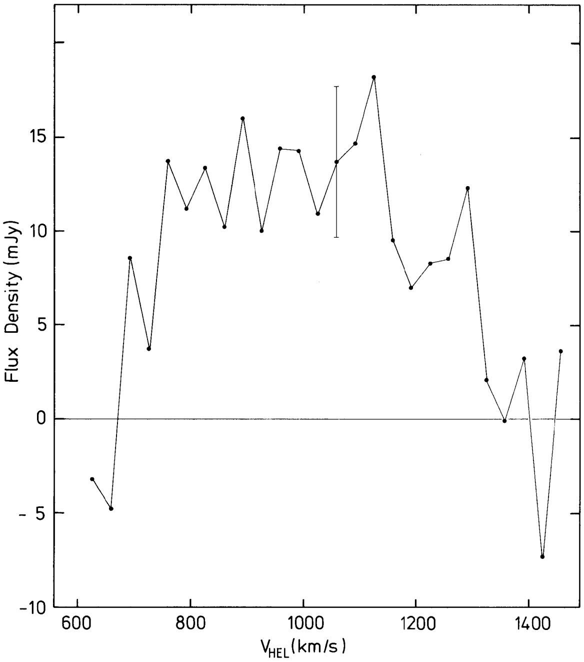

Fig. 3. Global H I profile for NGC 3998 from the WSRT observations. The velocity resolution is 40 km s^{-1}, and the rms noise ± 4 mJy

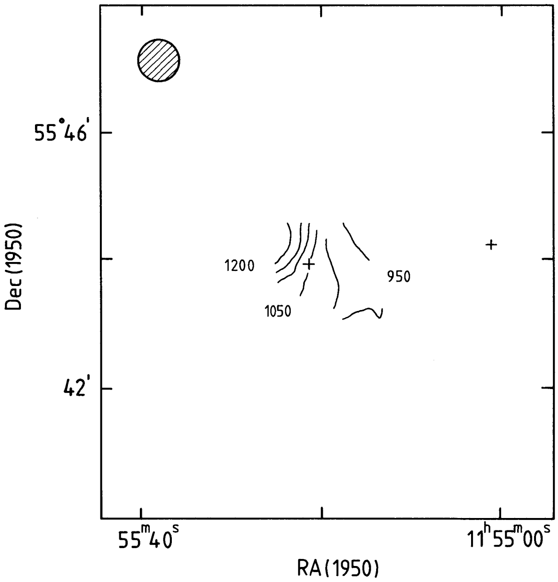

Fig. 5. Velocity field of NGC 3998 found by gaussian fitting to the profile at each pixel. The spatial resolution is 50″ × 50″ and the HPBW is indicated in the upper left

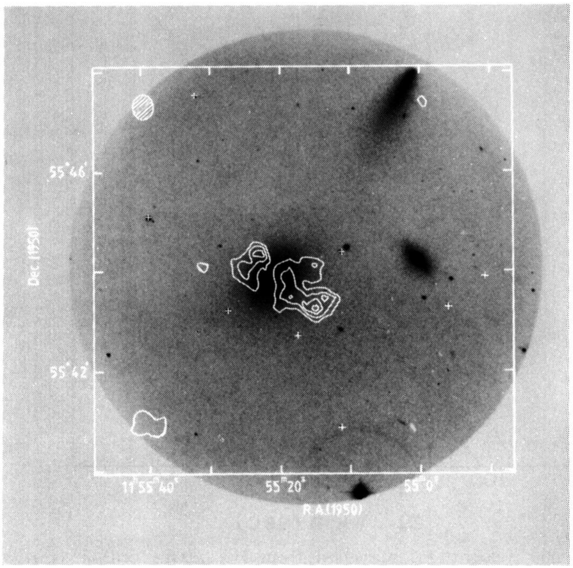

Fig. 4. Integrated H I column density map for NGC 3998, observed with a resolution of 25″ × 30″ overlaid on a broad-band image-tube photograph of NGC 3998 (from Blackman et al., 1983, plate 1). The HPBW is shown in the upper left. The crosses give the position of NGC 3998 and NGC 3990. The lowest contour is 3.9 10^{20} cm^{-2} and the contour interval is 2.4 10^{20} cm^{-2}

In Fig. 6 we show a plot of the H I intensity as a function of velocity and position along the H I major axis. The linear appearance of this velocity-position map, and the fact that the H I column density map (Fig. 4) shows maxima to either side of the centre rather than at the central position, both suggest that the H I is distributed in an annulus rather than a disc. The H I distribution is quite asymmetric, however (Figs. 4 and 6).

From Fig. 3 (the H I global profile) and Fig. 6 (the velocity-major axis contour map) the H I systemic velocity is 1040 $\pm$ 50 km s^{-1}, in good agreement with that of the stars (TD: See Table 1). Figure 6 suggests that the projected rotation velocity of the gas at radius 70″ is 260 ± 30 km s^{-1}, consistent with the estimate $(W_{0.5})/2 = 290 \pm 30$ km s^{-1} derived from the global profile (Fig. 3). The velocity field, Fig. 5, suggests a lower rotation speed, but an estimate of the rotation speed from this figure is less reliable, owing to the effects of noise on the gaussian fits. We then take the average value, 275 ± 30 km s^{-1}, as the observed projected rotation velocity.

3.4. Summary of the data

The data presented above show that the H I in NGC 3998 lies in a ring at an angle of ~80° to the optical major axis of the galaxy. The ring diameter, 2.5 arcmin, is very similar to the optical minor axis diameter. (The data in RC2 give for the observed isophotal diameters of the galaxy $D_{25} \times d_{25} = 3.1 \times 2.5$ arcmin.) The observed mean column density of the H I feature is ~1.3 10^{21} cm^{-2}. If half of this gas is on the near side of the galaxy, the expected extinction for the standard gas-to-dust ratio is $> 0^{m}.33$, depending on the inclination and thickness of the ring. This value is probably too small to have been noticed in the data existing to date but could possibly be found in images taken with linear devices. The detection of a dust ring in this galaxy would be very important; among other things it would give the orientation and inclination of the H I feature.

From Fig. 4, the extent of the H I along its minor axis is < 40″, which is similar to the extent of the ionized gas feature (Capaccioli, 1979). Thus, if the H I feature is in a rotating ring or disk, its inclination to the plane of the sky is > 70° and the true rotation velocity of the H I is no greater than 293 ± 32 km s^{-1}. The present data thus suggest $275 \lesssim V_r \lesssim 293$ km s^{-1}, and we take the circular velocity to be $V_c = 285 \pm 40$ km s^{-1}.

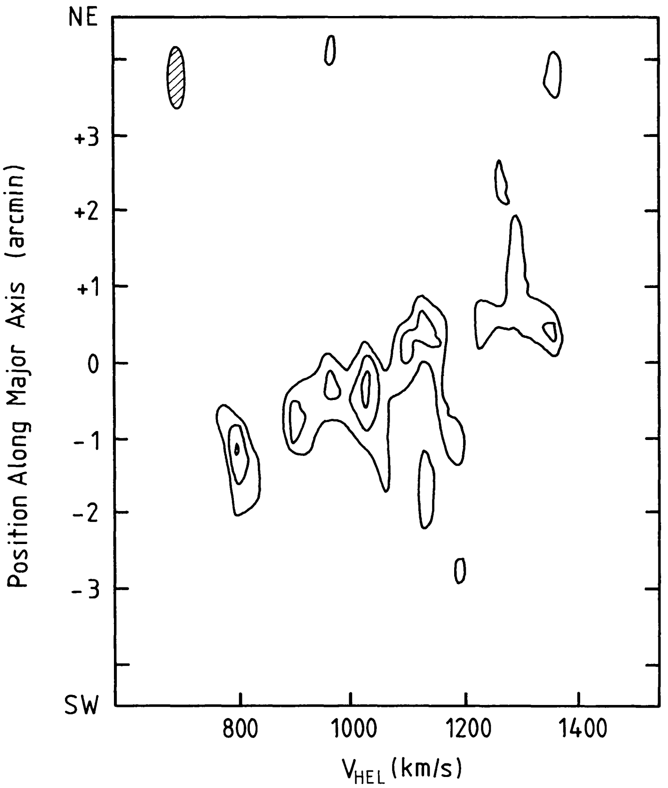

Fig. 6. Map of the intensity distribution of H I in NGC 3998 along the H I major axis (position angle = 60°) as a function of velocity. The spatial resolution is 48″ and the velocity resolution 40 km s^{-1}, these are indicated in the upper left. The first contour is at $T_b = 0.42$ K (2σ) and the contour interval is 0.21 K (1σ)

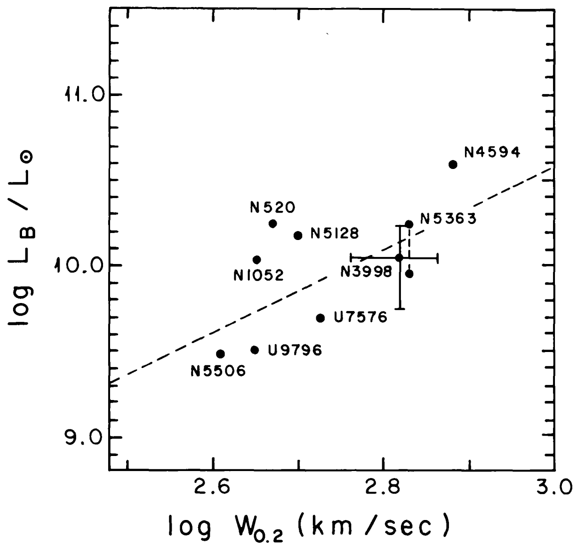

Fig. 7. Blue luminosity L_B versus $W_{0.2}$, the H I line width at the 20% power points, for polar ring galaxies and NGC 4594. The two points for NGC 5363 correspond to the two distances found from the model of Aaronson et al. (1982). The line shows the relation for spirals found by Tully and Fisher (1977), corrected for the population difference between ellipticals and spirals

This value agrees well with the peak rotation velocity of the ionized gas of 270 ± 30 km s^{-1} (Blackman et al., 1983). Since the ionized gas reaches this velocity at 4″ from the nucleus, these data show that, at least between 4″ and 75″ the rotation velocity for the galaxy is roughly constant. The kinematic major axis of the H I (position angle = 60°) is reasonably close to that of the ionized gas (95°).

In its morphology, the H I ring in NGC 3998 strongly resembles the almost polar dust and gas rings associated with many *E* and spindle galaxies (e.g. Kotanyi and Ekers, 1979; Shane, 1980; Hawarden et al., 1981; Schechter et al., 1983), though we believe it to be the first such to be discovered in H I. In the next section, we discuss the dynamics of NGC 3998 and compare this galaxy with other anomalous-ring galaxies.

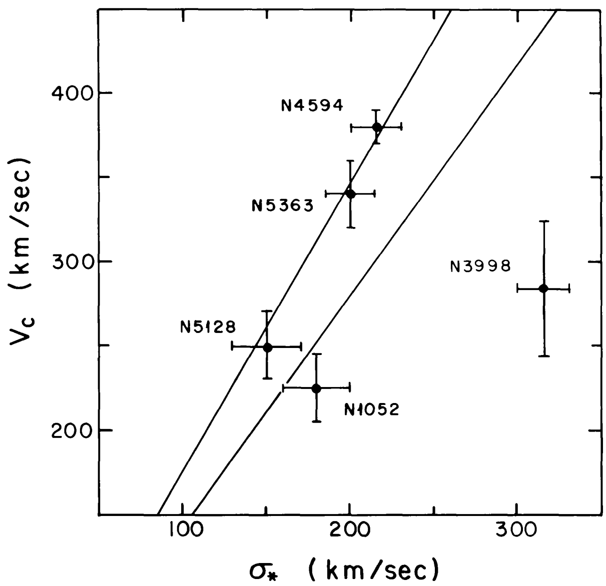

Fig. 8. Circular velocity V_c, measured from H I, versus central velocity dispersion, σ_*, for polar-ring galaxies and NGC 4594. The upper line corresponds to $V_c = \sqrt{3}\,\sigma_*$ and the lower line to $V_c = \sqrt{2}\,\sigma_*$ (see text)

4. Discussion

NGC 3998 joins the growing list of bulge-dominated galaxies whose gas distribution is at some large angle to the optical major axis of the galaxy. Indeed, the difference between the major axes of the H I and of the optical galaxy is $80° \pm 8°$, and since the inclination of the H I ring is high ($\gtrsim 70°$), the ring is essentially polar relative to the optical body of the galaxy. The kinematic major axis of the ionized gas, 95° (Blackman et al., 1983), is intermediate between the major axes of the stars and of the H I, suggesting that with decreasing radius the gas is settling to the principal plane of the galaxy. It seems probable that this is due to differential precession, and since the time scale of that process is of order 10^9 yr (Schechter et al., 1984), the gas is likely to have been captured on the same short time scale. The uneven distribution of gas in the ring is consistent with such recent capture.

The derived circular velocity of the gas, 285 ± 40 km s^{-1}, gives a mass $M = (10 \pm 3)\,10^{10}\,h^{-1} M_\odot$ within $r = 5$ kpc (70″) for a spherical mass distribution; the resulting mass-to-light ratio is $M/L_B = (9 \pm 3)\,h\,M_\odot/L_\odot$. This value is much smaller than the global ratio of $M/L_B = 26\,M_\odot/L_\odot$ found by TD. The reason is easily seen; the high value found by TD is calculated from their large value of the central stellar velocity dispersion, $\sigma_{*c} = 314$ km s^{-1}.

Is NGC 3998 unusual in this respect? In Figs. 7 and 8, we compare its global kinematics with those of other anomalous-ring galaxies. Included for comparison also in Figs. 7 and 8 are data for the bulge-dominated spiral NGC 4594. In Fig. 7, we plot the Tully-Fisher (1977) diagram for the currently available data for galaxies with polar rings. This diagram shows the blue luminosities, L_B, versus $W_{0.2}$, the full-width of the H I line at the 20% power points. Also given for comparison in Fig. 7 is the relation found for nearby spirals by Tully and Fisher (1977) with the values of L_B reduced by a factor of three to account for the stellar population differences between spiral and elliptical galaxies. The values of L_B are calculated using the relationships given in RC2; the two values for NGC 5363 correspond to the two possible distances given by the Virgocentric flow model of Aaronson et al. (1982). The values of $W_{0.2}$ are from Bajaja et al. (1984) NGC 4594; Thuan and Wadiak (1982) for NGC 520, NGC 5363 and NGC 5506; from Haynes and Giovanelli (1981) for NGC 5363; from Knapp et al. (1978) for NGC 1052 and from Gardner and Whiteoak (1976) for NGC 5128. The circular velocity for NGC 5128 found from the observations of Gardner and Whiteoak (1976) is $\sim 250\ \mathrm{km\,s^{-1}}$, in agreement with the value suggested by the observations of Taylor and Atherton (1983) (however, Marcelin (1983) finds a much larger value, $315\ \mathrm{km\,s^{-1}}$). In the case of all of these galaxies, it is known from the presence of dust and/or H I absorption that the H I structures are almost edge-on, so that inclination corrections are likely to be small. The data (both $W_{0.2}$ and L_B) for UGC 07576 and UGC 09796, which both have edge-on polar H I rings, are from Schechter et al. (1984). The error bars shown for the point corresponding to NGC 3998 include both inclination and line width uncertainties for $\Delta V_{0.2}$. These errors are likely to be larger for NGC 3998 than for other galaxies because of the weakness of the H I signal and uncertainty about whether the H I ring is edge-on. The errors shown for L_B are a factor of two, because of uncertainties in the distances of galaxies at velocities near that of the Virgo cluster. The scatter in Fig. 7 is considerable, due in part to distance uncertainties, but on the whole the galaxies, including NGC 3998, lie acceptably close to the normal $L_B \sim W$-line.

A completely different picture emerges when we plot V_c versus σ_{*c}, the one-dimensional stellar velocity dispersion observed at the center of the galaxy, which is done in Fig. 8. This plot is independent of distance. The values of V_c are half of the line width at the 50% power points, with errors as quoted by the above authors. Since most of these rings seem to be almost edge-on, the inclination uncertainties are assumed to be negligible. The values of σ_{*c} and its uncertainty are taken from Davies et al. (1984) for NGC 5128; from Kormendy and Illingworth (1982) for NGC 4594; from Sharples et al. (1983) for NGC 5363; from TD for NGC 3998; and from Davies and Illingworth (1984) for NGC 1052. For simple mass distributions in the galaxies, a simple numerical relationship between V_c and σ_{*c} is expected. Assuming spherical symmetry in the distribution of density $\varrho(r)$, and isotropic motions with a one-dimensional velocity dispersion $\sigma(r)$, then

$$\frac{d}{dr}\left(\varrho(r)\,\sigma^2(r)\right) = \frac{-GM(r)\,\varrho(r)}{r^2} \tag{1}$$

where $M(r)$ is the mass. For $\varrho = \varrho_0 (r/r_0)^{-2}$, Eq. (1) gives $\sigma^2 = 2\pi G \varrho_0 r_0^2$, ie σ is constant with radius. If the distribution of luminous matter (stars) is $\varrho_* \sim r^{-3}$, and σ_* is the one-dimensional stellar velocity dispersion, then

$$\frac{d}{dr}\left(\varrho_*(r)\,\sigma_*^2(r)\right) = \frac{-Gm(r)\,\varrho_*(r)}{r^2} \tag{2}$$

giving $\sigma_*^2 = 2/3\sigma^2$, again constant with radius. Thus since $V_c^2(r) = GM(r)/r$, $V_c = \sqrt{3}\,\sigma_* = \sqrt{3}\,\sigma_{*c}$. In Fig. 8 we have plotted the lines corresponding to $V_c = \sqrt{3}\,\sigma_{*c}$ (stellar density $\sim r^{-3}$) and $V_c = \sqrt{2}\,\sigma_{*c}$ (stellar density $\sim r^{-2}$. The points for NGC 4594, NGC 5363 and NGC 5128 lie close to the line corresponding to $V_c = \sqrt{3}\,\sigma_{*c}$, as do observations of the bulges of spiral galaxies (e.g. Whitmore, Kirschner and Schechter, 1979). For NGC 3998, however, Figs. 7 and 8 show that the value of σ_{*c} is anomalously large. The value of σ_{*c} for NGC 3998 has been measured by several groups with consistent results lying between 280 and $315\ \mathrm{km\,s^{-1}}$, values larger than those found for most giant ellipticals, e.g. NGC 4472. This large value of σ_{*c}, coupled with very bright, central peak in the light distribution (e.g. Disney and Cromwell, 1971), suggests that, like M 87 (Sargent et al., 1978) NGC 3998 is the site of a massive central object. Detailed observations of the distributions of the light and the stellar velocity dispersion in NGC 3998 are urgently needed.

In the absence of quantitative mapping of the velocity field and the light distribution, we cannot calculate an accurate value for the central mass of NGC 3998, as was done for M 87 by Young et al. (1978) and Sargent et al. (1978). However, an estimate can be made using the available data. The central light peak is observed to be barely resolved (cf. Disney and Cromwell, 1971), so we take the radius of the peak to be $\sim 1''$ ($r_a = 75$ pc at a distance of 15.2 Mpc). The one-dimensional stellar velocity dispersion σ_{*c} observed in the direction of the centre will be a brightness-weighted mean of the velocity dispersion in the core and that further out; the later may be estimated at $\sigma_* \sim V_c/\sqrt{3}$ or $\sim 165\ \mathrm{km\,s^{-1}}$. However, the contribution of the exceptionally bright nucleus is likely to dominate. Hence in the core the three-dimensional velocity dispersion is $\sigma_a \sim 600\ \mathrm{km\,s^{-1}}$, and the mass within $1''$ is $\sim 3\ 10^9\,M_\odot$.

The major axis of the galaxy is at position angle 140°; the H I axis is at 60° and the ionized gas at 95°. Thus the position angle difference between the radio continuum extensions (Fig. 1) and the inner gas structure is $\sim 80° \pm 10°$, in agreement with the finding by Kotanyi and Ekers (1979) of perpendicularity between radio jets and gas distributions. This supports accretion disk models for fuelling the central activity in galaxies.

5. Conclusions

We have mapped the distribution of the weak H I emission in the SO galaxy NGC 3998 using the WSRT. These observations show:

1) The relative H I content of the galaxy is $M(\mathrm{H\,I})/L_B = 0.03$, similar to values found for H I in the detected ellipticals, but low for detected SOs.

2) The H I is distributed in a ring whose appearance suggests that it is almost edge-on. The major axis of the ring is almost perpendicular to that of the optical galaxy. No visual extinction associated with the ring has yet been seen.

3) The H I ring diameter is 11 kpc, and the circular velocity agrees with that of the ionized gas seen at much smaller radii. Thus M/L increases with radius in this galaxy as it does in spirals. The total M/L at $r = 5.5$ kpc is $> 9\,h\,M_\odot/L_\odot$.

4) Comparison of the major axes of the H I, the ionized gas and the stellar distribution suggests that the gas distribution is bending towards the major axis of the galaxy with decreasing radius. This may be the result of differential precession.

5) A small extension is seen in the radio continuum distribution at position angle 15°, suggesting a pair of oppositely directed jets.

These are at a position angle roughly perpendicular to that of the inner gas distribution.

6) The galaxy is remarkable in showing an anomalously large ratio of stellar velocity dispersion to gas circular velocity. NGC 3998 also has an extremely bright and concentrated nucleus and is therefore an excellent candidate for containing a central massive condensed object.

Acknowledgements. We thank the staff of the WSRT for their help with the observations, J.E. Gunn, R.H. Sanders, R. Sancisi and P.J. Teuben for valuable discussions and J. Wrobel, F. Bertola, M. Davis, C.P. Blackman and A.S. Wilson for supplying data before publication. G. Knapp is grateful to Z.W.O. for a visiting fellowship to the University of Groningen during the summer of 1981. Partial support for this work was provided by the National Science Foundation via grant AST-8213292 to Princeton University and by NATO grant R.D. No. 098.82. The Westerbork Radio Observatory is operated by the Netherlands Foundation for Radio Astronomy with the financial support of the Netherlands Organization for the Advancement of Pure Research (Z.W.O.). W.V.D. is supported by Z.W.O. through the ASTRON Foundation.

References

Aaronson, M., Huchra, J., Mould, J., Schechter, P.L., Tully, R.B.: 1982, *Astrophys. J.* **258,** 64
Allen, R.J., Ekers, R.D., Terlouw, J.P.: 1984, in preparation
Bajaja, E., van der Burg, G., Faber, S.M., Gallagher, J.S., Knapp, G.R., and Shane, W.W.: 1984, *Astron. Astrophys.* **141,** 309
Bertola, F., Capaccioli, M.: 1978, *Astrophys. J. Letters* **219,** L95
Blackman, C.P., Wilson, A.S., Ward, M.J.: 1983, *Monthly Notices Roy. Astron. Soc.* **202,** 1001
Bos, A., Raimond, E., van Someren Greve, H.W.: 1981, *Astron. Astrophys.* **98,** 251
Capaccioli, M.: 1979, in *Photometry, Kinematics and Dynamics of Galaxies*, ed. D.S. Evans, *University of Texas Press*, p. 165
Davies, R.L., Danzinger, I.J., Fabian, A., Hanes, Hanes, R., Jones, B.T.J., Jones, J., Morton, D.C., Pennington, R.: 1984, *Bull. Amer. Astron. Soc.* (in press)
Davies, R., Illingworth, G.: 1984, in preparation
Disney, M.J., Cromwell, R.H.: 1971, *Astrophys. J. Letters* **164,** L35
Dressel, L.L.: 1984, in preparation
Dressel, L.L., Condon, J.J.: 1976, *Astrophys. J. Suppl.* **31,** 187
Gallagher, J.S., Knapp, G.R., Bushouse, H., Faber, S.M.: 1984, in preparation
Gardner, F.F., Whiteoak, J.B.: 1976, *Proc. Astron. Soc. Australia* **3,** 63
Hawarden, T.G., Elson, R.A.W., Longmore, A.J., Tritton, S.B., Corwin, H.C.: 1981, *Monthly Notices Roy. Astron. Soc.* **196,** 747
Haynes, M.P., Giovanelli, R.: 1981, *Astrophys. J.* **246,** L105
Heckman, T.M.,: 1980, *Astron. Astrophys.* **87,** 152
Huchra, J.: 1983, private communication
Hummel, E.: 1980, *Astron. Astrophys. Suppl.* **41,** 151
Hummel, E.: 1982, *Astron. Astrophys.* **114,** 400
Knapp, G.R., Gallagher, J.S., Faber, S.M.: 1978, *Astrophys. J.* **83,** 139
Kormendy, J., Illingworth, G.: 1982, *Astrophys. J.* **256,** 460
Kotanyi, C.G., Ekers, R.D.: 1979, *Astron. Astrophys.* **73,** L1
Lewis, B.M., Crane, P.C.: 1984, private communication
Marcelin, M.: 1983, in I.A.U. *Symp.* 100, ed. E. Athanassoula (D. Reidel), p. 335
Nilson, P.: 1973, Uppsala General Catalogue of Galaxies, *Uppsala Astron. Obs. Ann.* **6.** (UGC)
Sandage, A.R., Tammann, G.A.: 1981, Revised Shapley-Ames Catalogue, Carnegie Institution Publication No. 635. (RSA)
Sargent, W.L.W., Young, P.J., Boksenberg, A., Shortridge, K., Lynds, C.R., Hartwick, F.D.A.: 1978, *Astrophys. J.* **221,** 731
Schechter, P.L., Sancisi, R., van Woerden, H., Lynds, C.R.: 1984, *Monthly Notices Roy. Astron. Soc.* **208,** 111
Shane, W.W.: 1980, *Astron. Astrophys.* **82,** 314
Sharples, R.M., Carter, D., Hawarden, T.G., Longmore, A.J.: 1983, *Monthly Notices Roy. Astron. Soc.* **202,** 37
Shostak, G.S., Allen, R.J.: 1980, in Proceedings of ESO Workshop on Two Dimensional Photometry, ed. P. Crane and K. Kjär, p. 169
Taylor, K., Atherton, P.: 1983, in I.A.U. *Symp.* 100, ed. E. Athanassoula (D. Reidel), p. 331
Thuan, T.X., Wadiak, E.J.: 1982, *Astrophys. J.* **252,** 125
Tully, R.B., Fisher, J.R.: 1977, *Astron. Astrophys.* **54,** 661
Tonry, J.L., Davis, M.M.: 1981, *Astrophys. J.* **246,** 666 (TD)
de Vaucouleurs, G., de Vaucouleurs, A., Corwin, H.C.: 1976, "Second Reference Catalogue of Bright Galaxies", University of Texas Press (RC2)
Whitmore, B.C., Kirschner, R.P., Schechter, P.L.: 1979, *Astrophys. J.* **234,** 68
van Woerden, H., van Driel, W., Schwarz, U.J.: 1983, in I.A.U. *Symp.* 100, ed. E. Athanassoula, p. 99, (Paper I)
Wrobel, J.: 1982, private communication
Young, P.J., Westphal, J.A., Kristian, J., Wilson, C.P., Landauer, F.P.: 1978, *Astrophys. J.* **221,** 721