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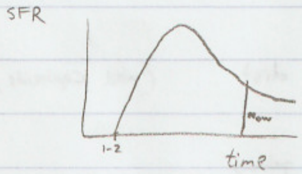
Astro 274 James Larkin
Notes: David Rodriguez

1/8/2007

Galaxies

in general ~10 billion years old

to study galaxy evolution need large look back time



can't observe galaxies forming

3 Methods to study

1. Fossil – Milky Way + Local galaxies
2. Galaxy Evolution – look further back (limited by telescope + techniques)
3. Cosmology – environment of galaxies

Brief History

Milky Way – naked eye

Galileo: MW – lots of stars

Immanuel Kant: mid 1700's MW – gravitational bound rotating disk

spiral nebulae – island universes, different orientations

Messier: late 1700's "not" comets catalog 109 (northern hemisphere)

Herschel's: William, Carolyn, John 5000 nebulae (northern + southern)

point-like objects in nebulae, planetary nebulae

Dreyer: 1888 New General Catalog (NGC), Index Catalog (IC) 1895
(7840) (5086)

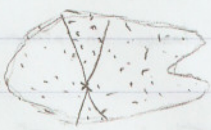
Third Earl of Rosse (William Parsons): 1845 – 72" telescope

saw star clusters in spiral galaxies

galaxies: spiral – bulge – spherical, disk; elliptical – spherical

1785 – stellar gauging – counting stars
(Herschel)

thought we were near center – obscuration by dust



galaxy is flat 5:1

Kapteyn (1920) 200 locations on sky, multiple bands, many more stars
└ looking for obscuration

stellar density fell to 10% local value by 2800pc 1% by 8500pc

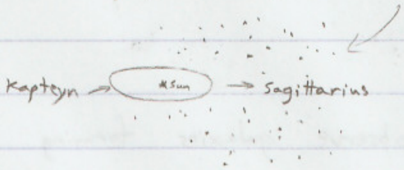
→ sun near center, 10% stars within same radius

Kapteyn Universe = $\Phi \sim 3$kpc (diameter) thickness 5 times smaller

very mild color shifts (dust, not gas) $A_V = c\,(E_{B-V})$
↑ wrong constant

1930 Trumpler – interstellar dust using open clusters
↳ faded too fast (relative to diameter)

Harlow Shapley (1919) Globular Clusters (~10^5 stars)



spherical dist of GC
15 kpc to center of dist (used Cepheids)
Diam ~100 kpc
few GCs in plane of galaxy

opposed island universe (galaxy big, so other structures would be really far away)

1920 Great Debate

Shapley – opposed island universe Hober Curtis – suported Kapteyn universe + island universe

2 30mins talks

(1912 Leavitt – 1777 Cepheids in LMC, SMC still uncertain distances)

Curtis: Against Shapley's: 1. Cepheid distances untrustworthy (true: x2 wrong)

2. Distance to GCs (brightest local stars) (brightest GC stars) x10 error

Support: 1. Vast range of sizes of spiral nebulae
↳ smallest must be very far away

2. Large # of novae seen in Andromeda + much fainter than MW novae
distance ~ 100kpc size ~ 3kpc
SN (in And) vs Novae (in MW)

3. Spectra of spirals looked like stars but broader absorption lines
↳ due to stellar motions

4. Large doppler shifts (radial motion) → should have high proper motions
→ no proper motions ∴ must be far away

5. Dark lanes in other galaxies → zone of avoidance in MW

Shapley: Against Curtis: 1. If spiral nebulae are same size as his MW then they were Mpc away

2. MW would have lower surface brightness than spiral nebulae
(obscuration + environment) other galaxies have star formation

3. Spiral disks are bluer than MW (local MS population vs. all galaxy)

4. Adriaan von Manner – "saw" spirals rotating → small distances to keep vel. small
(false observations)

Resolved with 100" telescope (Hooker)

1925 – Hubble – Cepheids in Andromeda dist ~ 300 kpc much larger than Kapteyn

proved that spiral nebulae are galaxies

1926 – distances to at least 27 Mpc (using angular sizes) — observation $\frac{1}{60}$th the radius of universe

1922 – Friedmann models

1928 – 200" Hale @ Palomar ($6 million from Carnegie)

1960's – quasistellar objects → high redshifts Schmitt

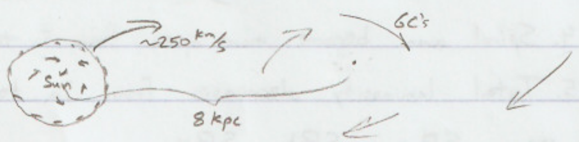
Bertil Lindblad 1920's stellar dynamics, mass of Kapteyn universe

GC's had doppler shifts of 250 km/s (escape velocity ∴ galaxy must be larger)

Equations for differentially rotating disks

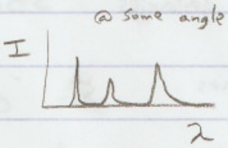
GC's were orbiting a distant location $\sim 10^9 M_\odot$

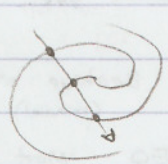
high velocity stars – 200 – 300 km/s random directions, comparable to spheroids



1951 – detection of 21 cm

1958 – 21 cm map of galaxy





Oort → differential motion equations

MW is multiarm spiral personal speed ~250 km/s

Similar to NGC 1232

OoMA

V_{earth} around Sun : 3×10^4 m/s

Diameter of Earth : 1.3×10^7 m

$\Delta t = \frac{d}{v} = 477\,s = 7.2$ min

Solar System Cross Earth $\Delta t = \frac{2.5 \times 10^5 \text{ m/s}}{(\text{Diam } E)} = 59\,s$

orbital period of solar system $R = 8$ kpc $T = \frac{2\pi R}{v} = 7 \times 10^{15}$ sec $= 2.2 \times 10^8$ yrs $= 220$ million yrs

galaxy is dynamically young

$\frac{GM}{r^2} = \frac{v^2}{r}$ $M = \frac{v^2 r}{G} = 1.8 \times 10^{41}$ kg $= 9 \times 10^{10} M_\odot$ (~100 Billion stars)

1944 – Baade : Mt. Wilson   Population I – disk Andromeda, blue, metal rich

II – red, spheroids, metal poor

no stars have primordial abundances

III no metals

1/10/2007

1936 – Realm of the Nebulae – Hubble

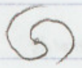
galaxy – self gravitating system of stars $M_V < -8$ $\sim 10^6 - 10^7$ stars

Spirals: Disk – flattened structure   aspect ratio (thick to diameter) < 1:5

Bulge – not always

Hubble's initial classification included bulges

Sa, Sb, Sc   Criteria: 1. Relative size of bulge to disk : Sa larges bulges



2. Prominence of spiral arms : Sc most prominent

3. Presence of dust + gas : Sc larger ratio of dust + gas to stars

4. Spiral arm become more open from Sa to Sc

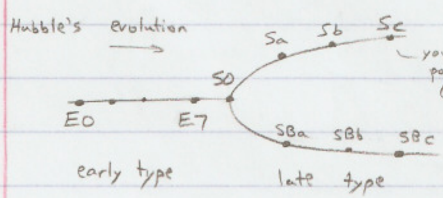
5. Total luminosity decreases from Sa to Sc

Extra feature for bar galaxies SBa, SBb, SBc

Elliptical : Beehive of stars (triaxial)  Classified by ellipticity $\frac{a-b}{a} = \epsilon$

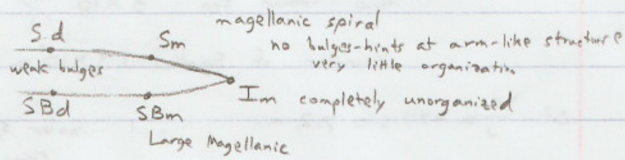
Circular E0 ($\epsilon \times 10$)   Most elongated E7 ($\epsilon \times 10$) $\frac{b}{a} \sim 0.3$ $\epsilon = 0.7$

Hubble Tunning Fork



Lenticular (S0) galaxies: Bulge dominated dustless, gassless disk 

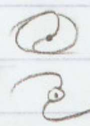
presence of dust + gas $\xleftrightarrow{\text{coupled}}$ prominence of arms



de Vaucouleurs (1959)

presence of rings   outer ring R

inner ring r



RSB(r)a Pec

MW: SAB(rs)bc

spirals go to center

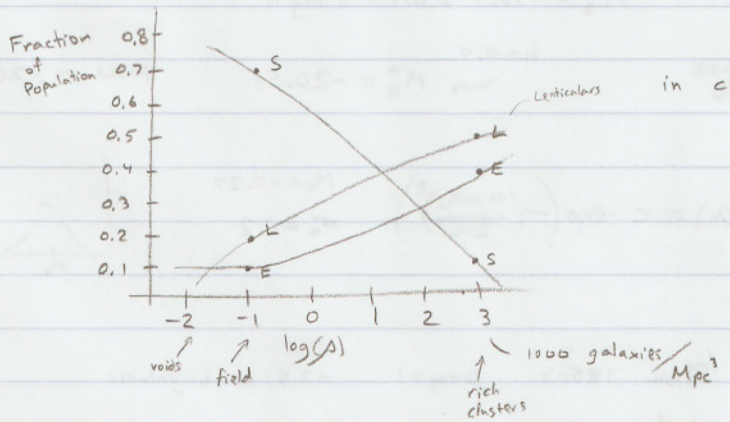
cD found in cores of clusters $\sim 10^{13}$ stars

c ← cluster, D ← extended halo

Spirals : ~70% of galaxies (brighter than −18)   by number Irr more common

Ellipticals ~10%   rest are Lenticulars ~20%

environment dependent   Dressler (1980) : Morphological Segragation



in clusters Spirals become Lenticulars

Local Group

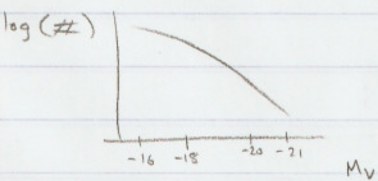
R ~ 1.5 Mpc   35 known galaxies more being found

gravitationally bound system

Bright members

	Name	Classification	Distance	M_V	
Andromeda	M31/NGC 224	Sb	725 kpc	−21.1	
	Milky Way	Sbc	8 kpc	−20.6	
	M33/NGC 598	Sc	795 kpc	−18.9	
	LMC	Irr/SBm	49 kpc	−18.1	
Draco	DDO 208	dSph/E3	76 kpc	−8.6	faintest

3 spirals   18 dwarf ellipticals spheroidals   14 irregulars

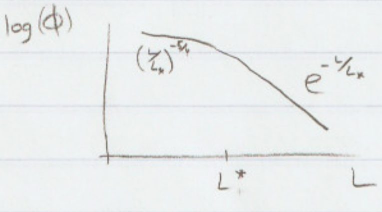


Schecter function (Luminosity of galaxies)

$$\boxed{\Phi(L) = c\left(\frac{L}{L_*}\right)^{\alpha} e^{-L/L_*}}$$

density of galaxies   dominates for faint galaxies   bright galaxies

$\alpha = -5/4$

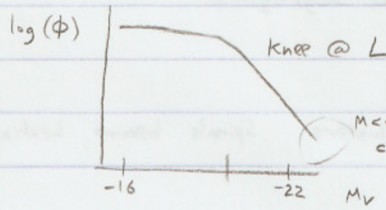


$L_* \leftrightarrow L^*$

$$\boxed{\Phi(M) = 0.4 \ln(10)\, \Phi^* \, 10^{0.4(\alpha+1)(M^*-M)} \exp\left(-10^{0.4(M^*-M)}\right)}$$

magnitude

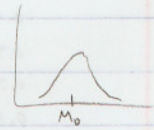
density of galaxies at L^* luminosity



knee @ L^* $\quad M^*_B = -19.7 \pm 0.1 + 5 \log h$

$h = 0.7 \rightarrow M^*_B = -20.5$ $\quad$ MW ~ −20 in B

Globular clusters: $\quad \phi(M) = c \exp\left(-\left(\frac{M - M_0}{2\sigma_m}\right)^2\right)$ $\quad M_0 = -7.27$, $\sigma_M = 1.2$



Colors of Galaxies

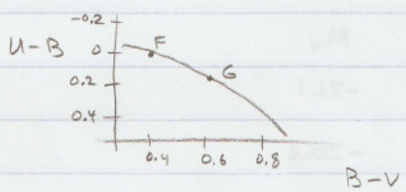
Hipparchus $1 \rightarrow 6$ $\qquad$ Posson 1850's $\quad \Delta mag = 1 \quad \times 2.511$ in brightness

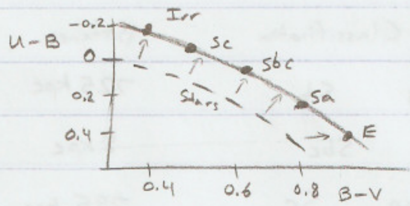
$mag = -2.5 \log f + \text{constant}$

magnitude as function of filter (wavelength) $\qquad$ Vega has same mag in all bands

positive color $B-V > 0$ redder than Vega $\qquad B-V=0$ $\qquad$ blue − red filter

Color − Color of Stars





distribution of stars

young stars contribute to U

red giants make redder

GALEX presented by: Michael Rich 1/22/2007

can see out to redshift ~1.5

made to study decline in star formation rate in recent times

sensitive to extinction and star formation rate (SFR)

Hα is starformation indicator

- drops off rapidly, extinction ∴ use UV continuum
  O stars photoionize

Hα $t \sim 1-10$ Myr UV $t \sim 10-100$ Myr Balmer lines $t \sim 0.1-2$ Gyr

Far IR $t \sim 10-100$ Myr

1960's : UV rising flux in ellipticals: hot population of stars

1970's Copernicus satellite — UV spectroscopy of ISM

1980's IUE

Galex has 1.2° FOV 5" PSF 1300 – 1800 Å FUV
1800 – 2800 Å NUV

All-Sky Imaging Survey AIS

Medium " " MIS

Deep " " DIS

Nearby Galaxy "

UV Emission – young stars forming, old stars burning He

Downsizing — SF moves to smaller galaxies

Lyman Break Galaxies

Galactic Center   presented by: Mark Morris   1/24/2007

$12 \mu m$ — see zodaical light

Evidence of bar: 1) Large, non-circular gas motions
2) Near-IR light distribution


3) Detailed gas kinematic models
4) Source count asymmetries
5) Large microlensing optical depth (~probability of microlensing) axisymmetric $\tau \sim 1 \times 10^{-6}$
bar model/observations $\tau \sim 2,3 \times 10^{-6}$

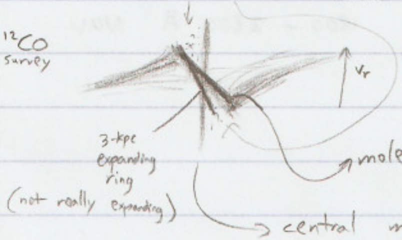
Length of bar: 3.5 kpc   Axis ratio $1:(0.3-0.4):0.3$

Bulge/Disk near-IR luminosity ratio: ~0.2

$\rho(\varphi) \propto e^{im\varphi}$ bars are m=2 modes   density wave but less affected by differential rotation

no evidence for dark matter in the inner galaxy

inside end of bar → minimum in molecular gas (gas shocks, loose angular momentum → falls in)



→ molecular ring ~4.5 kpc lots of star formation

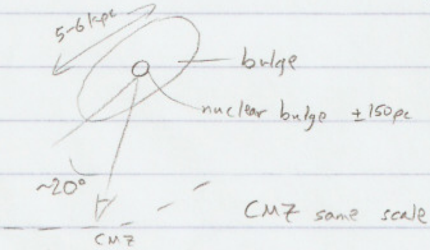
→ central molecular zone (CMZ) ~100s pc ~$10^8 M_\odot$

Mass of bulge ~$1.3 \times 10^{10} M_\odot$

Nuclear bulge (few 100 pc)   stellar density $\propto r^{-1.8}$ "central stellar cusp" "r^{-2} cluster" → center of galaxy

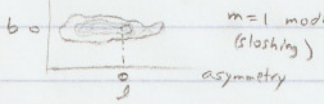
ongoing star formation (not in old bulge)   nuclear stellar disk ~230 pc – r
~45 pc – scale height

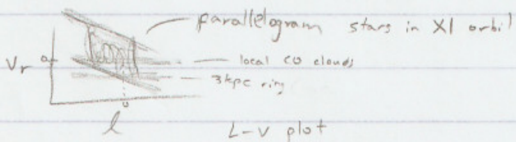
~$1.4 \times 10^9 M_\odot$ ~$2.5 \times 10^9 L_\odot$



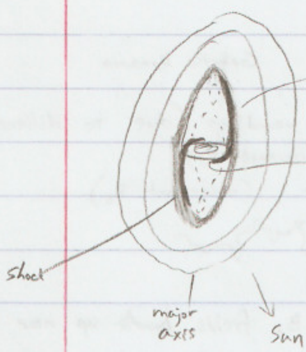
gas layer scale height — 30pc
stars in nuclear bulge — 70pc
> potential problem
→ solution: stars scattering from molecular clouds increases scale height for stars

CMZ same scale as Nuclear bulge
→ result of sustained star formation in CMZ





L–V plot
longitude   velocity



carbon monosulfide (CS) probes denser gas — dont see parallelogram

"clouds" in galactic center are streams (sheared clouds)

CMZ	Cloud in galactic disk
$10^{5-6}\ M_\odot$ $10^4\ cm^{-3}$ density $T \sim 70K$	density $10^{2.5}\ cm^{-3}$
core density $10^{5-6}\ cm^{-3}$	core density $10^4\ cm^{-3}$ $T \sim 5-15K$
line width 10-20km/s	linewidth < 5 km/s

$\langle n \rangle \geq 10^4\ cm^{-3} \left(\frac{75pc}{R_{gc}}\right)^{1.8}$ $\langle n \rangle_v \sim 10^3\ cm^{-3} \left(\frac{\Delta v}{R_{cl}}\right)^2$ (?)

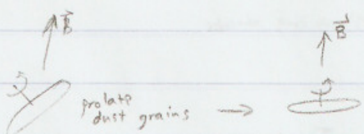
density criteria   virial criteria

else they (clouds) get strongly sheared and broken apart

CMZ is tilted to our plane (warped)

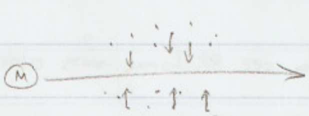
radio filaments $\perp$ to galaxy plane in bulge

nonthermal radiation → synchroton → traces out $\vec{B}$ lines   ~ milli Gauss fields else turbulence breaks it up

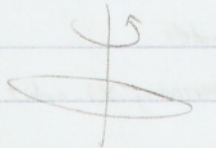


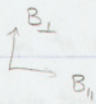
} can use polarization of dust emission to find direction of $\vec{B}$ ($\perp$ to polarization)

can allow for magnetic reconnection between HII clouds ($\vec{B}$ parallel to plane due to shear) and radio filaments ($\vec{B} \perp$ to plane) ⇒ acceleration of e^- along filaments



Dynamical Friction

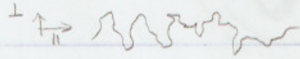




Galactic Dynamo

more wound up (due to differential rotation)
(increases $B_\parallel$)

ambipolar diffusion can reduce $B_\parallel$ fields — equilibrium ($\sim$constant $B_\parallel$)
(move up/down plane) slower than



gas is brought inward (loss of angular momentum)

observed:


$B_\perp$ fields bundle up near center
oposite directions → reconnect
∴ end result:

Stellar Populations

presented by: Michael Rich

1/29/2007

low mass $M < 1.5 M_\odot$ p-p chain radiative core He flash

$1.5 < M/M_\odot < 9$ intermediate mass CNO cycle conv. core He ignites non degenerate

$M > 9 M_\odot$ high mass CNO cycle

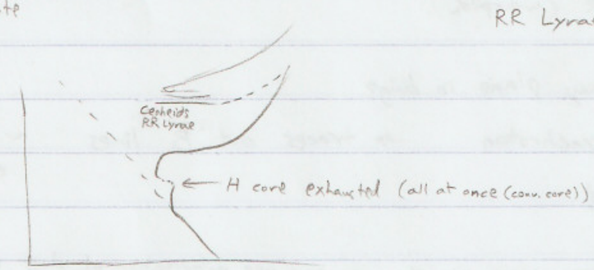
$\varepsilon_{pp} \sim T^4$ $\varepsilon_{CNO} \sim T^{16}$ $\varepsilon_{3\alpha} \sim T^{20}$ CNO cycle in H burning shell

RG ~ 5×10^8 yrs HB ~ 10^8 yrs (low mass)

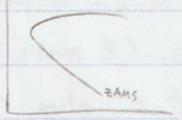
AGB – thermal pulses (He shell flashes) – water Masers, etc.

intermediate

RR Lyrae – fainter than Cepheids, still He burning

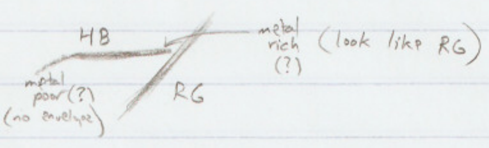


high mass



SN Ia	$0.7 M_\odot$	Irons
	$0.07 M_\odot$	Lighter
SN II	$0.07 M_\odot$	Irons
	$0.7 M_\odot$	Lighter

10^{10} yrs or older → you get RR Lyrae so if you see RR Lyrae ⟹ older than 10^{10} yrs



HB is good age indicator

Best: WD cooling

Second best: MS turn off

Fuel Consumption Theorem

Renzini, Buzzoni 1986 also Renzini 1998 AJ

$n_j = B \, L_T \, t_j$ ← life time in phase j good for older than 10^9 yrs

↳ 2×10^{-11} stars/yr (death rate) L_T in $L_\odot$ ↖ $L_{V,\,total}$ Ex: How many RG stars in M31?

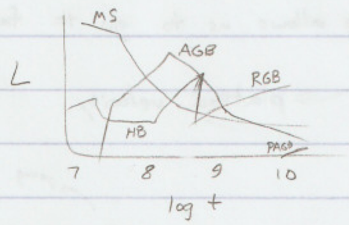
UV excess, UV rising flux → seen in elliptical galaxies

PN nebula core? no – short lived

HB stars without envelopes turning into AGBs?

Extreme HB stars in metal rich populations?

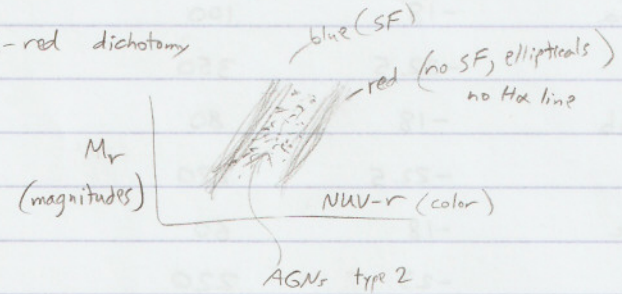
Bulges are Mg enhanced



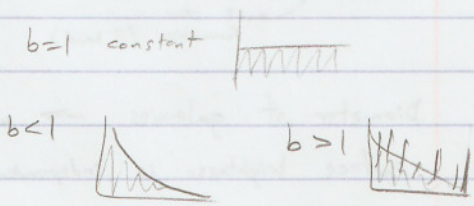
light from stars

Kennicutt(?) 1988 Kennicutt-Schmidt (?) law

blue-red dichotomy



Kennicut or b parameter $b = \frac{SFR}{\langle SFR \rangle}$



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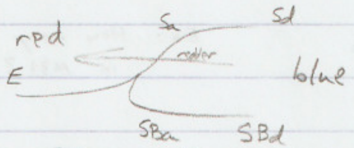
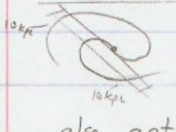
SA → no bar   SAB → weak bar   SB → bar

Hubble, de Vaucouleurs system are down to $M_B < -18$

faint galaxies don't fit into system (usually satellites)



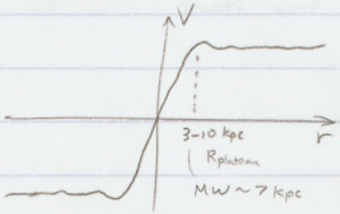
Rotation curves



Galaxy spectra dominated by stars
↳ absorption lines

also get emission lines from star formation regions

21 cm emission → cold atomic gas
↳ allows us to go to farther radii, well distributed through galaxy



→ plateau velocity

	M_B (young stars)	$V_{plateau}$ (km/s) (corresponds to mass)
Sa	-18	100
	-22.5	350
Sb	-18	80
	-22.5	280
Sc	-18	60
	-23	220

more massive ↑

brightness depends on stellar populations

Sa	-18	100 km/s
Sc	-21	100 km/s

same mass

more star formation (B band)

Diameter of galaxies → when drop out to 25 mag/arcsec² — D_{25}

surface brightness is independent of distance (not true for cosmology)

de Vaucouleurs
$$\boxed{\log(V_{plat.}) + \log\left(\frac{2 R_{plat}}{D_{25}}\right) = 2.18 \pm 0.03}$$

more massive galaxies achieve peak V faster compared to D_{25}

MW: $V_{plat} = 225$ km/s, $R_{plat} = 7$ kpc > $D_{25} = 23.4$ kpc   measured 23.1

Masses

$$\frac{GM(r)\cancel{m}}{r^2} = \frac{v^2}{r}\cancel{m}$$

Solar system $M(r) = M$ $\quad v = \sqrt{\frac{GM}{r}}$

galaxies $v = v_{plat}$ $\quad M(r) = \frac{v_{plat}^2 r}{G}$ valid in spherical systems (far away from disk)

thin disk approx: $M(r) = \frac{2 v^2 r}{\pi G}$ 35% less mass is needed for same vel.

Dynamical masses: $10^9 - 10^{13} M_\odot$

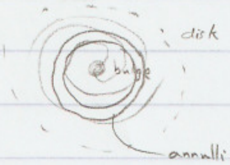
MW: 8.5 kpc $\rightarrow M = 4.1 \times 10^{11} M_\odot$ $\quad M(60\,kpc) = 5 \times 10^{12} M_\odot$ ~100 times the luminous matter

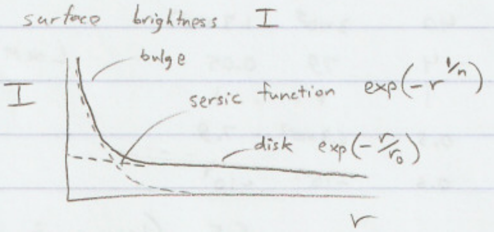
$1-2 \times 10^{12} M_\odot$ about right

in field: galaxies separated by 20 times diameter

M31 $\quad 3.4 \times 10^{11} M_\odot$ to 10 kpc $\quad \sim 10^{12} M_\odot$ @ 100 kpc

Light Distribution in Spirals



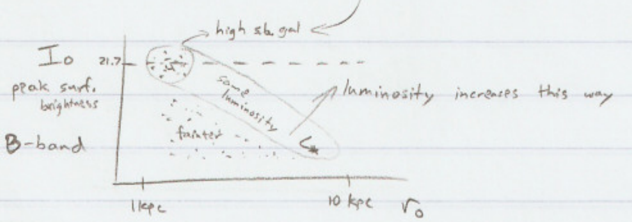


$n=4$ elliptical $r^{1/4}$ law
$n=1$ exponential – shallow

Disk: $I = I_0 e^{-r/r_0}$
peak surface brightness

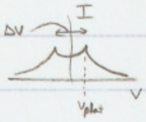
1970 Freeman law: $I_0(B) = 21.7 \pm 0.3$ mag/arcsec^2
believed to be same for all galaxies
selection effect

$L = 4\pi r_0^2 I_0$



MW: $r_0 = 5\,kpc$

Tully - Fischer 1975 21 cm line widths



double horn profile (absolute mag)

actual luminosity

$L_B \propto (\Delta V)^{\alpha}$ $\alpha = 2.5$

B – 420 nm – sensitive to SFR

H – 1.6 μm – sensitive to stellar mass

Aaronson + Mould (1983) larger sample

$\boxed{L_B \propto (\Delta V)^{3.5}}$ $L_H \propto (\Delta V)^{4.3}$ – much tighter relationship – higher SFR greatly increase L_B

Distance indicator

$\frac{GM}{r_0^2} \propto \frac{V^2}{r_0}$ $v \propto \sqrt{\frac{M}{r_0}}$ Assume: $\frac{M}{L}$ ~ constant for galaxies (not true)

$v \propto \sqrt{\frac{L}{r_0}}$

more massive systems have higher $\frac{M}{L}$ ratios in B-band

$\therefore \alpha < 4$

in H-band, more massive gal. have lower $\frac{M}{L} \Rightarrow \alpha > 4$

bright galaxies: Freeman law ~ right $L \propto r_0^2 I_0$ $r_0 \propto \sqrt{L}$

$v \propto \sqrt{\frac{L}{\sqrt{L}}} = \sqrt[4]{L}$ $L \propto v^4$

for stars $\frac{M_\odot}{L_\odot}$

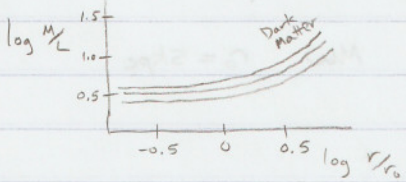
	M	L	M/L
O5	40	3×10^5	1.3×10^{-4}
A0	4	79	0.05
G2	1	1	1
M0	0.5	6.3×10^{-2}	7.9
WD	0.6	$\sim 10^{-3}$	$\sim 10^3$

$L \propto M^{3.2}$

@ r_0 — stars dominate

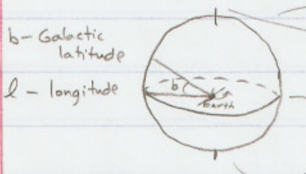
	M/L
S0	6.5
Sa	5.1
Sb	4.3
Sc	3.9
Sd	3.7

(because of initial mass function)

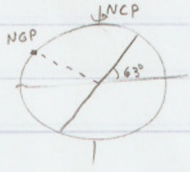


$M \propto r$ $L \propto e^{-r/r_0}$

Galactic Coordinates



Earth's axis is tipped 63° to galactic plane



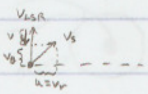
G. Center $\alpha = 17^h\ 45.7^m$, $\delta = -29°\ 0.0'$ } Sagittarius

Frames of reference

Fundamental Standard of Rest → center of mass of galaxies

Local Standard of Rest → ideal circular orbit at 8 kpc
$\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad \llcorner R_\odot$

peculiar motions – deviations from LSR



$u = V_R - \cancel{V_R(LSR)}^{0} = V_R$ radial $\quad\quad v = V_\theta - V_\theta(LSR)$ theta

$w = V_z - \cancel{V_z(LSR)}^{0} = V_z$

Measured

$U = u_{star} - u_\odot \quad\quad V = v_{star} - v_\odot \quad\quad W = w_{star} - w_\odot$

$\;\;= V_r - V_{r\odot} \quad\quad\quad = V_\theta - V_{\theta\odot} \quad\quad\quad = V_z - V_{z\odot}$

$V_\theta(LSR)$ is determined statistically: average of many stars

$u_\odot = -\bar{U} = -9$ km/s $\quad\quad v_\odot = -\bar{V} = 12$ km/s $\quad\quad w_\odot = -\bar{W} = 7$ km/s

we move towards GC

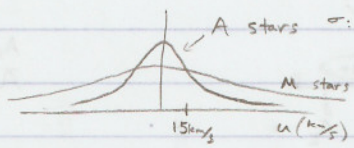
we are moving to $l = 53°$ $\quad b = 25°$

$v_{pec} = (u_\odot^2 + v_\odot^2 + w_\odot^2)^{1/2} = 16.5$ km/s

young stars have low v_{pec} (interactions with GMCs)
old stars have higher

Stellar type

pec. vel. dist. — Gaussian



A stars σ: $u = 15$ $\;v = 9$ $\;w = 6$ [km/s]

M stars σ: $u = 30$
$v = 15$
$w = 11$

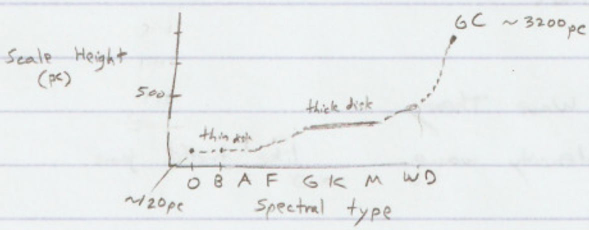
initially u & v are similar and small

High velocity stars $\sigma_v > 65$ km/s ← v_{pec} $\quad$ old stars, low net rotation, spherical distribution

typical stars:

apogalacticon < 40 kpc $\quad\quad$ typical 15 kpc
(farthest point in orbit around gal.)

perigalacticon ~ 4 kpc



$V_{LSR} = 220$ km/s

Spiral Galaxies

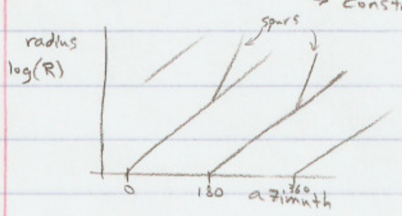
2/5/2007

(M51) Grand Design Spiral  ~10%

Multiarm spirals  Flocculent galaxies 

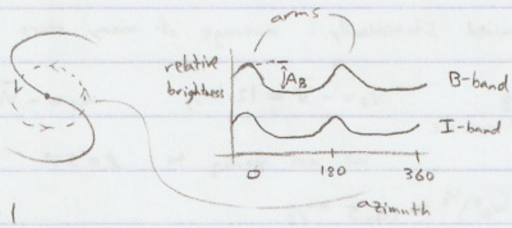
pitch angle 5°–20° — Sa → lower, Sc → higher pitch angles

↳ constant with radius



logarithmic spirals

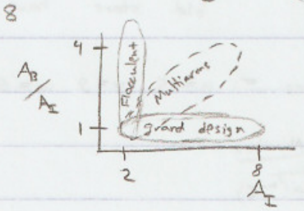
Arm–Interarm Contrast



A: ratio of peak to valley height

in grand design $\frac{A_B}{A_I} \sim 1$ — stellar density is higher in arms

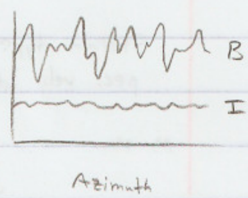
$A_I \simeq 2-8$



Flocculent

$A_B = 2-8$

$A_I \sim 2$



Winding problem – arms don't wind up multiple times

inner region $v \propto r$ Ω = constant (angular freq)

@ 5 kpc $V \simeq 200$ km/s Period $= 1.5 \times 10^8$ yrs Age $\sim 10^{10}$ yrs → 66 orbits

@ 25 kpc $V \simeq 200$ km/s Period $= 7.5 \times 10^8$ yrs → 13 orbits

⇒ pattern not rotating with stars

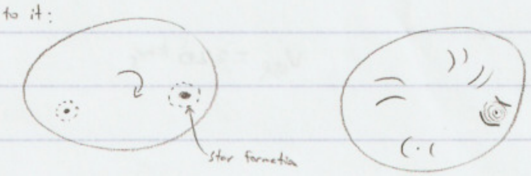
Lin + Shu 1964–1970 Density Wave Theory

spiral is a semi-stationary density wave like traffic jams

Contagious / Stochastic Star Formation Seiden + Gerola 1978

Toomre criteria – includes angular momentum and Jeans mass } how much to form stars

↳ close to it:



explanation for flocculent

explains high $\frac{A_B}{A_I}$

Motion of stars with peculiar velocities

Cylindrical coordinates

$$-\frac{\partial U}{\partial r} = \ddot{r} - \dot{\theta}^2 r \qquad -\frac{\partial U}{\partial \theta} = r\ddot{\theta} + 2\dot{r}\dot{\theta} \qquad -\frac{\partial U}{\partial z} = \ddot{z}$$

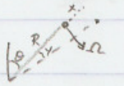
$\hat{z}$: $U = kz \quad \frac{\partial U}{\partial z} = k \quad \ddot{z} = -k$ oscillatory functions

Period of z oscillation for Sun ~65 million yrs

$r = \underset{\text{circular orbit radius (LSR)}}{R} + x \qquad x < \frac{R}{10} \qquad \theta = \underbrace{\Omega t}_{\text{pure circular rotation}} + y \qquad x, y \rightarrow$ deviations $\qquad \dot{y} < \frac{\Omega}{10}$

$$\Omega = \frac{V_{LSR}}{R}$$

$\dot{r} = \dot{x} \quad \ddot{r} = \ddot{x} \quad \dot{\theta} = \Omega + \dot{y} \quad \ddot{\theta} = \ddot{y}$



$\hat{\theta}$: $0 = (R+x)\ddot{y} + 2\dot{x}(\Omega + \dot{y}) = R\ddot{y} + \underset{\text{small}}{\cancel{x\ddot{y}}} + 2\dot{x}\Omega + \underset{\text{small}}{\cancel{2\dot{x}\dot{y}}}$

$0 = R\ddot{y} + 2\dot{x}\Omega \qquad a = R\dot{y} + 2x\Omega \qquad \boxed{R\dot{y} = a - 2x\Omega}$

$\hat{r}$: $-\frac{\partial U}{\partial r} = \ddot{x} - (\Omega + \dot{y})^2(R+x) = \ddot{x} - R\Omega^2 - \Omega^2 x - 2\dot{y}R\Omega - \cancel{2x\dot{y}\Omega} - \cancel{\dot{y}^2 R} - \cancel{x\dot{y}^2}$ smalls

$$-\frac{\partial U}{\partial r} \simeq \ddot{x} - R\Omega^2 - \Omega^2 x - 2\dot{y}R\Omega$$

$$= \ddot{x} - R\Omega^2 - \Omega^2 x - 2a\Omega + 4x\Omega^2 = \ddot{x} + 3\Omega^2 x - R\Omega^2 - 2a\Omega$$

$\frac{\partial U}{\partial r} = -\text{acc.} = \frac{V_{LSR}^2}{r} \qquad$ case 1: $\frac{\partial U}{\partial r} = \frac{V_{LSR}^2}{r}$ $\quad V_{LSR}$ — constant with radius $\quad V_{LSR} = \Omega R$

$$\frac{\partial U}{\partial r} = \frac{\Omega^2 R^2}{R+x}$$

Case 2: inner region

$V_{LSR} \sim r \qquad V_{LSR} = cr \qquad \frac{\partial U}{\partial r} = \frac{c^2 r^2}{r} = c^2 r = c^2(R+x) \quad \rightarrow HW$

Case 1: $\quad -\frac{\Omega^2 R^2}{R+x} \simeq \ddot{x} + 3\Omega^2 x - R\Omega^2 - 2a\Omega$

$-\cancel{\Omega^2 R^2} \simeq \ddot{x}R + \cancel{\ddot{x}x} + 3\Omega^2 xR + \cancel{3\Omega^2 x^2} - \cancel{R^2\Omega^2} - Rx\Omega^2 - 2aR\Omega - \cancel{2ax\Omega}$ smalls

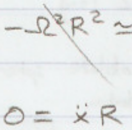
$0 = \ddot{x}R + 3\Omega^2 xR - Rx\Omega^2 - 2aR\Omega \qquad -\ddot{x}\cancel{R} = 2x\cancel{R}\Omega^2 - \cancel{2aR\Omega}$ ignore (just an offset)

$\boxed{x = x_0 \sin(\kappa t)} \quad \boxed{\kappa = \sqrt{2\Omega^2} = \sqrt{2}\,\Omega}$

$R\dot{y} = a - 2x_0 \sin(\kappa t)\Omega \qquad Ry = at + \frac{2x_0 \cos(\kappa t)\Omega}{\kappa} \qquad y = \frac{a}{R}t + \frac{2x_0\Omega}{R\kappa}\cos(\kappa t)$

a must be zero for closed loops

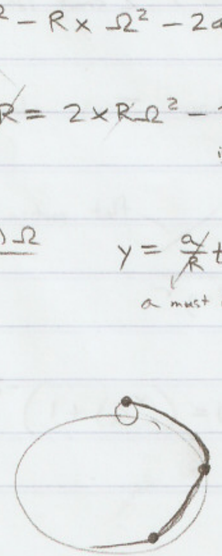
$$\boxed{y = \frac{2x_0\Omega}{R\kappa}\cos(\kappa t)} \qquad \boxed{y = \frac{\sqrt{2}\,x_0}{R}\cos(\kappa t)}$$



epicycles

$y_0 R = \sqrt{2}\,x_0$

$\kappa = \sqrt{2}\,\Omega = 1.4\,\Omega$



1.41 loops per orbit

Sun $\dot{x} = u = -9 \text{ km/s}$ (inwards) $\dot{y} = \frac{v}{R} = \frac{12 \text{ km/s}}{8 \text{ kpc}} = 1.5 \frac{\text{km}}{\text{s}\cdot\text{kpc}}$ (foward)

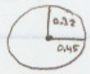
$\dot{x} = x_0 \kappa \cos(\kappa t) = x_0 \sqrt{2}\,\Omega \cos(\kappa t)$ $\dot{y} = -\frac{2 x_0 \Omega}{R} \sin(\kappa t)$

$\Omega_{Sun} = \frac{V_{LSR}}{R} = \frac{220 \text{ km/s}}{8 \text{kpc}} = 27.5 \frac{\text{km}}{\text{s}\cdot\text{kpc}}$ $T = \frac{2\pi}{\Omega} = 220$ million yrs

$\kappa = \sqrt{2}\,\Omega = 38.8 \frac{\text{km}}{\text{s}\cdot\text{kpc}}$ $T_{epi} = 156$ million yrs

$\dot{x} = 38.8 x_0 \cos(\kappa t) = -9 \text{ km/s}$ $x_0 \cos(\kappa t) = -0.232$ kpc

$\dot{y} = -6.88 \frac{\text{km}}{\text{s kpc}} x_0 \sin(\kappa t) = 1.5 \frac{\text{km}}{\text{s kpc}}$ $x_0 \sin(\kappa t) = 0.218$ kpc



$x_0^2 \cos^2 + x_0^2 \sin^2 = x_0^2 = 0.10$ $x_0 = 0.32$ kpc $y_0 = \frac{\sqrt{2} x_0}{R} = 0.056$ radians

$y_0 R = 0.45$ kpc

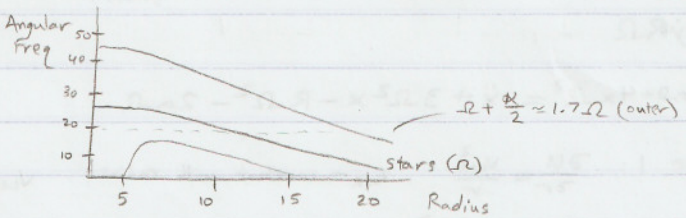
$\Omega_F = \Omega_0 + \frac{\kappa}{m}$

frame rotating

$\theta_F = \Omega_F t = \Omega_0 t + 2\pi$ if it caught up to star at same epicycle position

$(\Omega_0 + \frac{\kappa}{m})t = \Omega_0 t + 2\pi$ $\frac{\kappa}{m} t = 2\pi$ $m = \frac{\kappa t}{2\pi}$

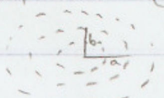
m: # orbits completed before lapping the star



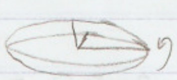
tidal forces stimulate $m=2$ mode

Ellipticals (Chpt 4) 2/12/2007

presented by: Matt Malkan



En $n = 10\left(1 - \frac{b}{a}\right)$ E0 ... E7



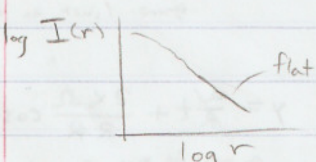
1 long axis (rotation)
2 short identical } prolate spheroid

1 short
2 long } oblate spheroid

planets are oblate spheroids due to rotation

Surface brightness $I(r)$ along major axis

pg. 11



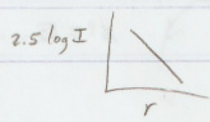
flat portion ~ r^n $n \sim -2$

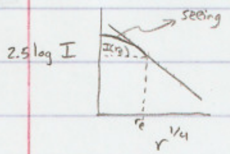
Hubble's formula $I(r) \propto r^{-2}$ (1930)

$L = \int_0^\infty I(r)\, r\, 2\pi dr \sim \ln r \Big|_0^\infty$

$I(r) = \left((r/a) + 1\right)^{-2}$ Hubble's law

Disks $I(r) \sim e^{-br}$





de Vaucouleur's $\frac{1}{4}$ law

$$I(r) = I_e 10^{-3.33\left(\left(\frac{r}{r_e}\right)^{1/4}-1\right)}$$

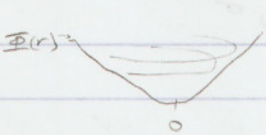
Define r_e so that integral captures half of light

$$\int_0^{r_e} I(r)\, 2\pi r\, dr = \frac{1}{2} I_{tot} \qquad I_{tot} = \int_0^{\infty} I(r)\, 2\pi r\, dr$$

$r^{1/n}$

$n=4$ great fits for ellipticals

violent relaxation – last stages of mergers, effective at distributing grav. potential energy



Φ changes $\rightarrow \Phi(t)$ rapid change

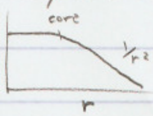
as stars move they change their potential

As potential changes with time it gives energy to objects

more E to larger mass $\rightarrow$ tries to get same E per unit mass $\rightarrow$ same velocity dispersion

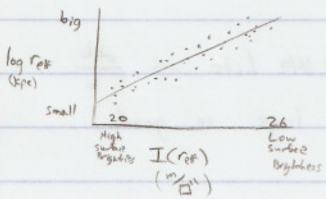
most likely velocity dist'n $\rightarrow$ Maxwellian $\propto v^2 e^{-\frac{v^2}{\sigma^2}}$ - isothermal

Isothermal Sphere: $n(r) \propto r^{-2}$ far away



2 body relaxation: 2 objects (stars) get close, massive stars give energy to lighter stars

$\therefore$ massive stars sink to center, lighter stars more extended $\rightarrow$ after many relaxation times



Kormendy relation

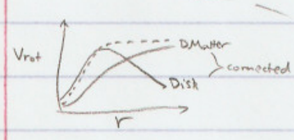
isophote twist $\Rightarrow$ not oblate or prolate but triaxial

spectral lines broadened by random motions

predict oblates have more rotational $\rightarrow$ rotationally supported

bright ellipticals $\rightarrow$ little rotation dimmer ellipticals $\rightarrow$ some rotation

Faber–Jackson relation pg. 356 $L \propto \sigma^4$ brighter galaxies $\rightarrow$ more dispersion



plot $L, \sigma, \frac{r_{eff}}{I_{eff}}$ } 3D space: all ellipticals lie together on a plane

Fundamental Plane

related to strength of $\langle Mg \rangle$ line

(negative a_4) disky isophotes

(big a_4) boxy isophotes

$r(\theta) = \underbrace{a_0 + a_1 \cos\theta + b_1 \sin\theta}_{\text{ellipse}} + \underbrace{\text{higher terms}}_{\text{boxy/peanuts disky}}$

presented by: Matt Malkan

2/14/2007

largest galaxies are cD — made by mergers

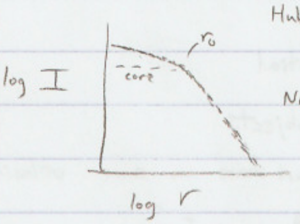
shells in ellipticals could be evidence of mergers

Possible that ellipticals experienced mergers at some time

Faber–Jackson + Kormendy relations } fundamental plane

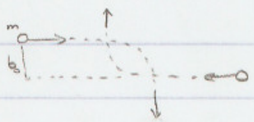
L, σ $\quad I, r_e$ $\quad I, r_e, \sigma$

Hubble images revealed core regions



Nuker Law fitted with 2 power laws

"Collisions" between stars



$$b_0 = \frac{G(m_1+m_2)}{V_{rel}^2}$$

looses memory of initial direction

relaxation time

$$\tau = \frac{1}{n\sigma v}$$ (cross section)

hard collision $\sigma = \pi b_0^2$

$$\tau = \frac{1}{n\pi \frac{G^2(m_1+m_2)^2}{V_{rel}^2} V_{rel}} = \frac{v^3}{\pi n G^2 (m_1+m_2)^2}$$

for hard collisions $\rightarrow$ not exactly for stars

stars: many little hits $\rightarrow \frac{db}{b}$ random walk

integrate: logs so good

$$\tau_{relax} = \frac{v^3}{\pi G^2 n (m_1+m_2)^2 \ln N}$$

or $$\tau_{relax} = \frac{G^{-1/2} m^{-1/2} N^{1/2} R^{3/2}}{4\pi \ln N}$$ (size of system)

for G.C. $\sim 10^8$ yrs

$\hookrightarrow \tau_r \ll \tau_H$ energy goes to equipartition: $m_1 v_1^2 = m_2 v_2^2$ higher v^2 in lower mass stars

Active Galaxies

Active – lots of energy produced that is not from stars and their processes

Broad emission lines in Seyfert 1/Quasars → obviously not stellar

tend to be more luminous + farther away but Seyfert 1 ≃ Quasars

– widths: high velocities

1000s km/s maybe caused by gravity or radiative accelerations

– large range of ionizations ex: NV – soft x-rays – not O stars $(2-4 \times 10^4 K)$

↳ UV photons

Mg II → singly ionized

continuum radiation – non stellar engine

ionization parameter $U = \frac{\left(\int_{\nu}^{\infty} \frac{L_\nu d\nu / h\nu}{4\pi r^2}\right)}{nc}$ ← # of ionizing photons for AGNs $U \sim 100$ high

narrow lines occur in different regions than broad lines

[forbidden] – lower densities

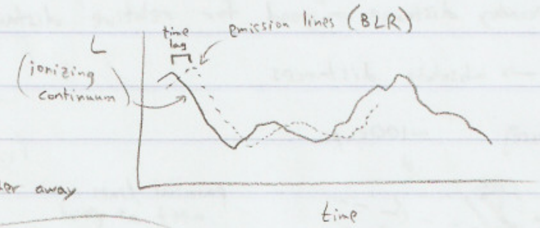
slower velocities

high v

high density

time variation → energy produced in small region

↳ years, months, even days



Cross correlation function in Fig 5.6 (hand out)

NGC 5548 – 20 day delay

narrow lines are produced farther away

2/21/2007

Extragalactic Distance Scale from George Djorgorski in Caltech

presented by: Shoko Sakai

$t_H = \frac{1}{H_0}$ $D_H = \frac{c}{H_0}$ Hubble distance $D \simeq \frac{cz}{H_0}$

in 1930s $H_0 = 560 \frac{km}{s\ Mpc}$ $t_H \sim 2$ Gyr

Bade: identified 2 types of cepheids some HII regions thought to be stars

then: 100

1970s(?) 50

Cosmological principle: universe is homogeneous + isotropic – scales larger than ~100 Mpc

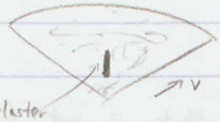
as seen in WMAP or radio sources

redshift surveys reveal large scale structures

3D distribution of galaxies

~20 galaxies in local group

Local supercluster: ~60 Mpc centered on Virgo Cluster (local group in outskirts) "finger of God" effect → cluster



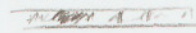
"Great Wall" ~100 Mpc structure in CfA2 redshift survey

Recent redshit surveys

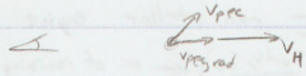
2dF (2 degree field) ~250,000 galaxies $z \sim 0.3$ 5% sky

SDSS ~565,000 galaxies

pencil beam surveys : go deep in sky in small area



$V_{total} = V_{hubble} + V_{pec, radial}$



$V_{pec} \sim 100s$ km/s so need high V_H to measure H_0 accurately

CMB Dipole : we are moving wrt CMB at ~620 km/s towards $b = 27°$ $l = 268°$

$V_H = H_0 D$ $\quad V_t = H_0 D + V_{pec}$

V_{pec} field will give mass distribution

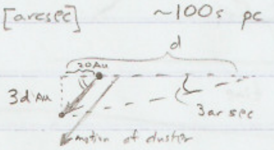
Distance ladders Absolute distances

Secondary distance → good for relative distances

- parallax + proper motions → absolute distances

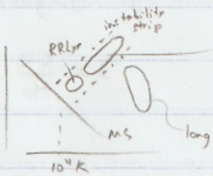
$d = \frac{1}{p}$ d: [pc] p: [arcsec] ~100s pc

- Moving cluster method



parallel lines meet at point (seen far away)

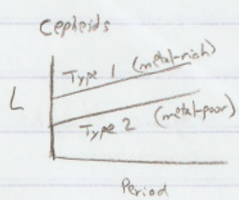
- Main Sequence Fittings
- Variable Stars



Cepheids are high mass Pop I

RR Lyrae are low mass Pop II

Cepheids



$M \sim -4$ to -7 magnitudes

need extinction corrections - since Pop I

P-L relation calibrated using distance to LMC

RR Lyrae: fainter, short periods, found in areas with less dust

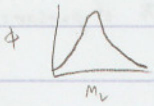
calibrated with GC distances or Magellanic clusters

- Baade-Wesselink Method - pulsating stars $f_1 = \frac{4\pi R_1^2 \sigma T_1^4}{4\pi D^2}$ $\quad f_2 = \frac{4\pi R_2^2 \sigma T_2^4}{4\pi D^2}$

from spectroscopic obs: $R_2 = R_1 + \Delta R = R_1 + \int_{t_1}^{t_2} v(t)\,dt$

3 eqs, solve for R_1, R_2, $\underline{D}$

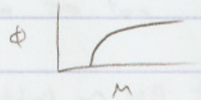
- Galaxy Cluster Luminosity Function   out to 200 Mpc



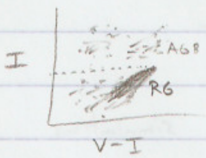
assume peak always at $M_B = -6.6 \pm 0.3$ not as precise

- Planetary Nebula Luminosity Function   strong emission in [OIII] $\lambda = 5007$ Å

  there is a sharp cutoff at bright end

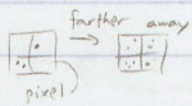


- Tip of the Red Giant Branch   good out to ~20 Mpc



$M_I = -4.1 \pm 0.1 \simeq$ constant

- Surface Brightness Fluctuations (SBF)



out to ~100 Mpc in IR

$\langle N \rangle = n (D\,\delta\theta)^2$ identical stars (same L) $f = \frac{L}{4\pi D^2}$ $F = \langle N \rangle f = nL\frac{\delta\theta^2}{4\pi}$

(n: stars/area; $\delta\theta$: ang. resolution)

average flux has dispersion $\langle N \rangle^{1/2}$ (Poisson)

$\sigma_F = \langle N \rangle^{1/2} f \propto \frac{1}{D}$ $\frac{\sigma_F^2}{F} = f$ ← can use this for relative distances

calibrated with M31

- Tully-Fisher Relation $L \sim v_{rot}^{\gamma}$ $\gamma \simeq 4$

  K-correction – at diff. redshifts you sample a diff. area of spectrum for same filter

- Fundamental Plane Relation (Faber-Jackson)

  $D_n - \sigma$ relation D_n – radius within which mean surface brightness is $20.75\mu_B$

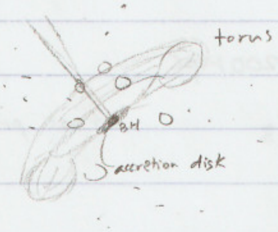
- Supernovae   Type Ia $M_V \sim -19.3$ can use multiple colors to get better light curve (MLC)

$H_0 = 72 \pm 3\,(\text{random}) \pm 7\,(\text{systematic})$ km s^{-1} Mpc^{-1} in 2001

AGNs

presented by: Sarah Gallagher

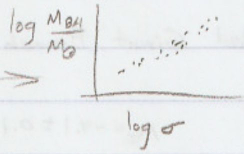
2/28/2007



jet – source of radio power (~10% of quasars)

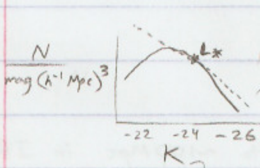
- Mass of local inactive BH are proportional velocity dispersions $M_{BH} \propto \sigma$
- Giant galaxies are not as massive as they should be

Sphere of influence of BH ~ lightyears



true also for active galaxies

M–σ relationship $M \propto \sigma$

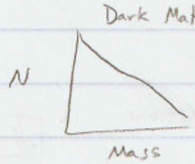


~old stars ∴ related to mass

Luminosity function

Andromed ~ L_*

Dark Matter Halo simulations



dont match

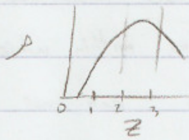
Quasar feedback: 1. Jet (injection of energy + matter as BH grows)
2. Winds

Assumptions:
1- All galaxies have BH
2- BH grows during quasar phase
3- $M_{BH} \propto M_{gal}$

} growth of BH related to host galaxy growth

Grav collapse → star forms, BH fueled → quasar feedbacks clears gas → stop S.F.

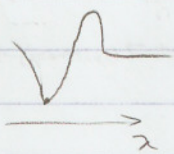
Quasar epoch: $z = 2-3$



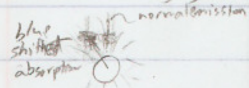
similar relationship for SFR

Outflows directly observed in ~20%

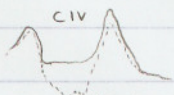
ex:



blue-shifted absorption lines (gas moving towards us + absorbing)



Lyα – strongest line in Quasar spectrum



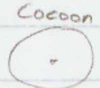
broad absorption lines (BAL) → BAL Quasars

v~25,000 km/s up to 0.1–0.2c (0.03–0.2)c

Evolution (a phase) or Orientation?

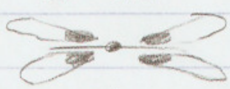
Extreme Explanations

Cocoon



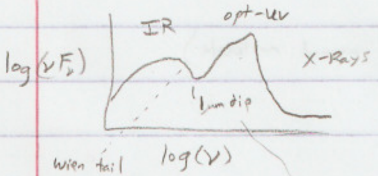
wind covers all sky 20% of time

Disk-wind



wind covers 20% of sky all the time

SED – spectral energy density

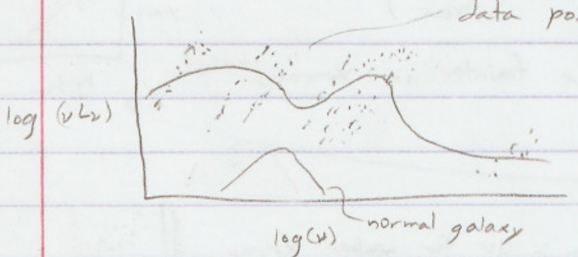


X-ray : ~AUs : close to BH
Opt-UV: (big blue bump): accretion disk <1 pc
IR: "torus" 1-10 pc

transition from accretion to reprocessed light (torus)

dust cant exist close to accretion disk

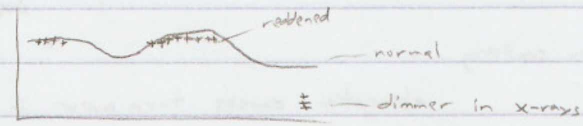
Cocoon: BAL Quasars should be mid-IR bright relative to other quasars
cocoon has dust in more sky ∴ captures more light and reproceses it
also has more absorption



data points shift diagonal: brighter quasars in past + selection effect

(not BAL Quasars)

BAL Quasars (+) — composite



no evidence that BAL Q are mid-infrared bright

Starbust – dust is cooler (heated by OB stars)
not all BAL Q have high SF

Cocoon → ruled out

Disk – wind

shielding gas → to protect wind from ionizing x-rays (wind needs to be partially ionized only)
<u>not</u> completely

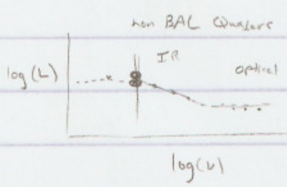
Torus must explain – ratio type 1 / type 2 1:(2-4)
– mid-to-far IR SED

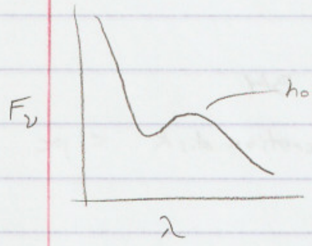
But: unstable

Maybe its a radially wind

UV photons efficient to make outflows ∴ UV + dust = outflow
→ push out on lines, not continuum or dust

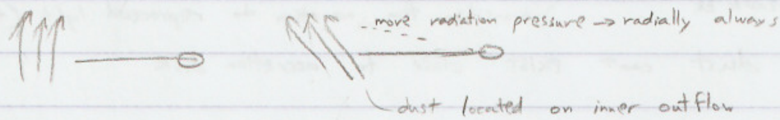
IR-Luminous Quasars typically have steeper SED
show spectral curvature



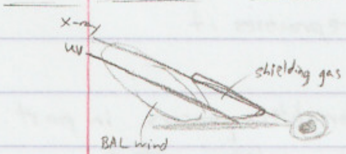


hot bump 1200K B.B. (Dust destroyed around ~1500K)

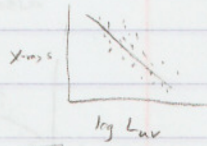
less L more L



looking ⊥ so see more dust in more L quasars



$$\alpha_{ox} = 0.384 \log\left(\frac{f_{2keV}}{f_{2500}}\right)$$



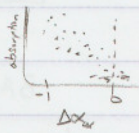
more L quasars are fainter in X-rays

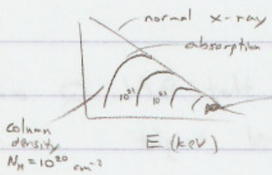
$\Delta\alpha_{ox} = \alpha_{ox} - \alpha_{ox}(L_{uv})$

↑measure ↑what we expect from

$\Delta\alpha_{ox} = 0$ x-ray normal

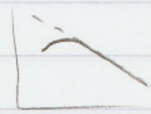
more absorption in UV for weaker X-ray





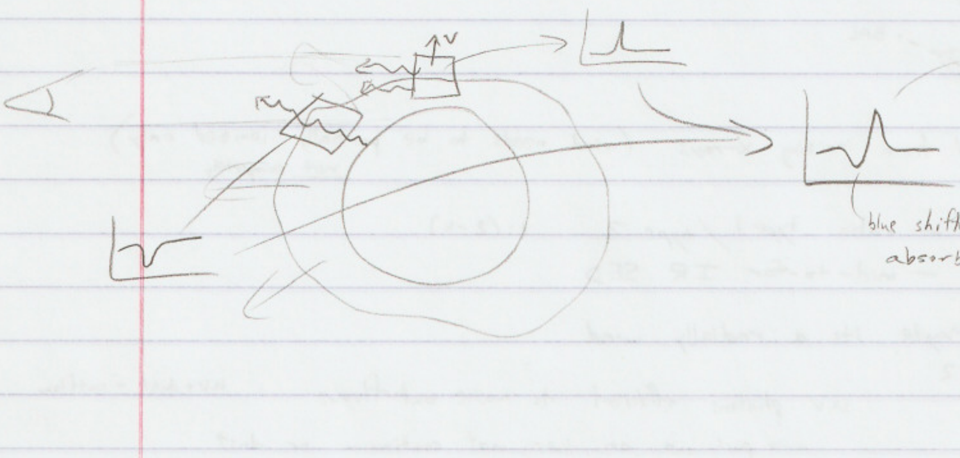
1.5×10^{24} ← Thomson scattering

absorption causes turn over in x-ray



normal underlying X-ray continua

significant absorption $N_H = (0.1 - 5.0)\times10^{23}$ cm^2 (10^{23} cm^2 → your hard)



emission from gas

P Cygni Profile

blue shifted gas outflowing absorbing light from star (continuum) presented by: Nate McCrady 3/5/2007

Starburst Galaxies

global star formation rate $\dot{M}_* \sim 4\ M_\odot\ yr^{-1}$ for MW.

low rate for most disk galaxies

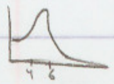
molecular gas: $2 \times 10^9\ M_\odot$ star formation can last $\sim 10^9$ yrs

local SFR $\dot{m}_*(R)$ near Sun: $\dot{m}_*(R) \sim 3 \times 10^{-9}\ M_\odot\ yr^{-1}\ pc^{-2}$

per unit area

rises as you move inward to ~4-5kpc then falls → same as H_2 distribution

fuel for SF



Schmidt Law

$\langle \dot{m}_* \rangle \propto \langle \Sigma_{gas} \rangle^N$ $N \sim 1.4$ (empirical law)

surface density of all diffuse gas

Starburst: $\dot{M}_* > 10^2\ M_\odot\ yr^{-1}$ → only in inner few hundred pc

M82 $\dot{M}_* \sim 10^2\ M_\odot yr^{-1}$ $M_{dyn} \sim 10^{10} M_\odot$ (MW: $10^{12} M_\odot$)

$L_{IR} = 3 \times 10^{10} L_\odot$ ~30% in molecular gas

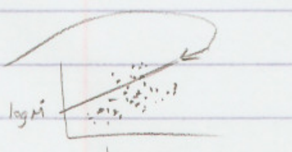
$L_{bol} > L_{bol}$ of M31

Operational Definitions: (for starburst)

— At current SFR, gas reservoir would be exhausted in less than Hubble time

— SFR per unit area is much higher than normal galaxies

— SFR approaches limit set by casuality

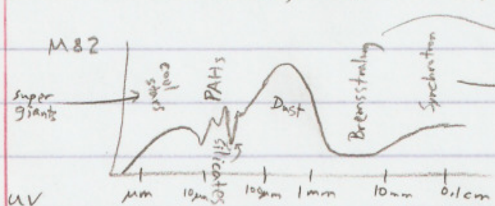


OB stars' radiation can stop star formation → Eddington limit

Starbusts are powered by high mass ($M > 8 M_\odot$) stars

Wolf-Rayet stars are associated with starburst

~ $30 M_\odot$, high winds, lots of emission, P Cygni profile



→ HII regions

→ super nova explosions B fields from ?

Dust reprocesses UV light from OB stars

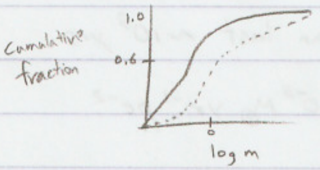
Initial Mass function

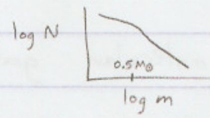
$N(m,t) = \phi(m)\,\Psi(t)\,dm\,dt$

coeval population (same age) $\Psi(t) = \delta(t)$ $dN = m^{-\alpha_i} dm$

Saltpeter $\alpha = 2.35$ for high mass stars

$\alpha = 1.3$ $0.1 \le m/M_\odot < 0.5$ — $\alpha = 2.3$ $0.5 \le m/M_\odot \le 100$ — Kroupa IMF → flatter at low masses





How to measure SFR? UV: stellar continuum 125–250 nm problem: dust

review in Kennicutt (1998) ARAA 36:189

Optical: Balmer emission, [OII] doublet

Infrared: Paschen, Brackett series Brackett γ → K band (atm window)

Far-IR dust continuum 10–300 μm

Starbursts: supernova factories 0.05 – 5 SNe yr^{-1}

morphological evidence for mergers or interacting galaxies

near M82: M81 ← massive spiral galaxies connected in HI

collisions transfer angular momentum from gas to stars allowing gas to fall to bottom of potential well

Super star clusters $\sim 10^6 M_\odot$ bright, dense, young, massive

star formation in ↗ $\sim 10^4 M_\odot\ pc^{-3}$

if they have old stars → might turn into globular clusters? (controversial)