Astro 278: Galaxies
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1/15/2008

Galaxies in the Universe by S+G ← possible book

Ellipticals
isophotes
isophotal twist  disky, boxy
$\cos(4\theta)$ term
elliptical: $2\theta$ term

prolate $A > B = C$ cigar
oblate $A = B > C$ pancake
triaxial $A > B > C$ ← suported by isophotal twists

Most are mildly triaxial (oblate) $A:B:C \sim 1:0.95:0.65$

anisotropic velocity dispersions $\xrightarrow{\text{leads to}}$ triaxiality

Lenticular galaxy disk without spiral arms S0
looks like E7

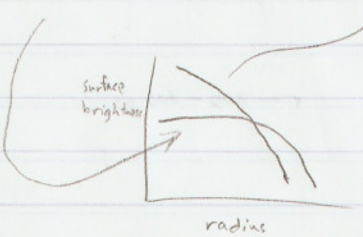
| Boxy | Disky |
|---|---|
| slightly triaxial | oblate shape |
| anisotropic velocities | rotational supported — flat due to rotation |
| slow rotators | faint disks |
| massive & luminous | like bulges of spirals |
| kinematically decoupled cores | continuation of Hubble sequence S - S0 |
| tend to be strong radio & x-ray sources | |

Mergers of star Systems ⇒ Dry (non-dissipation)

Mergers of gasseous system ⇒ Wet
dissipation → brings material to center

Core: surface brightness goes flat

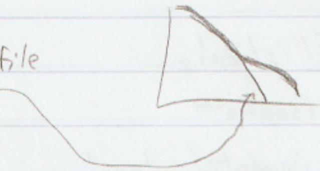
Core: surface brightness goes to cusp




fit double power law

Sersic Profile $I(r) \propto I_0 \, e^{-\left(\frac{r}{r_0}\right)^{1/n}}$

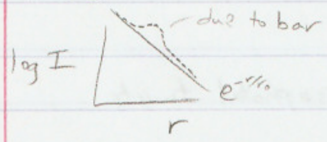
$n=1$ disk
$n=4$ de Vaucouleurs



cD galaxies don't follow de Vaucouleurs profile

also: dwarf ellipticals/spheroids
→ bigger galaxy strip out outer stars
tidal truncation

Bars




~1/3 spirals strongly barred (SB)
~1/4 weakly barred (SAB)
~1/2 – 2/3 barred (strong + weak) (55%)

more clearly seen in NIR 72%

should be confined between Lindblad resonances (also grand design spiral arms)

gas flows along bar and piles up at ends (inner or outer)

Disk can start to clump to form bars

stability condition: Toomre's Q $\quad Q \equiv \frac{\kappa \sigma_r}{3.4 \, G \, I(r)} > 1$ ← stable

($\kappa$: epicyclic freq; $\sigma_r$: v dispersion; $I(r)$: mass surface density)

Milky way: $Q \simeq 1.2$

$Q<1$ — unstable → formation of bars

hot: high $\sigma_r$ cold: low $\sigma_r$

1/17/2008

(r) — inner ring possibly at inner Lindblag resonance
R — outer ring " " outer " "

violent relaxation: pg 19 Galaxy Notes
↳ takes only several rotation (orbital) periods

Dynamical friction time is 2-body relaxation time $\times \frac{m}{M}$ → could be as short as violent relaxation time

Sandage 1975 volume IX in Stars & Stellar Systems — NED knowledgebase

gas piles up at (r) → star formation (starburst) $r \sim 200-600$ pc

Gas piled up at inner disk can become 3D
Stars form there and can look like a bulge — "pseudo-bulge"
→ bluer than bulges since younger stars

No known mechanisms to get gas piled up at 100pc to fall into BH.

Bars associated with starbursts but not AGN activity. (Hunt & Malkan 99)
BUT outer rings are associated with Sy 1+2s.

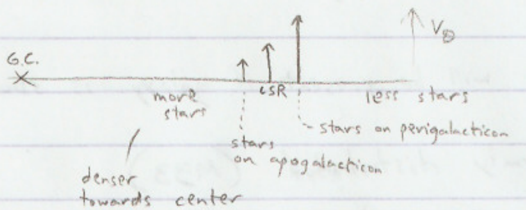
Early works: rigid DM Halos to suppress bar formation
otherwise all disks would not be here (all gas would be in bars)
BUT DM Halo does respond to gravity and influence bars
still not clear what final answer is
Are bars long-lived? unknown

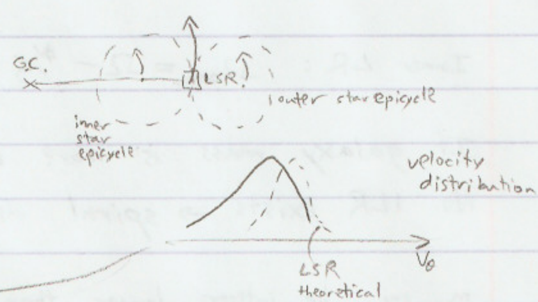
Disks also have isophotal twists M31 disk is warped in outer rings
Also MW

## Disk & Bulge Dynamics

Both self-gravitating
- Disks – rotation supported (dynamically cold)
- Bulge – dispersion supported (dynamically hot)
- Two extremes along continuum:
  rotation — asymmetric disk — dispersion

LSR — circular orbit radial oscillations (epicycle approx)




ensemble of stars is lagging LSR
⟶ asymmetric drift

$V_c^2 \sim \langle v \rangle^2 + \sigma^2$
LSR, dispersion

hotter (older stars) → $\langle v \rangle$ is less than LSR speed

Extreme: cold $\sigma = 0$ $V_c = \langle v \rangle$ pure rotation (cold Disk)
hot $\langle v \rangle = 0$ $\sigma \sim V_c$ pure dispersion (Hot Bulge)

complicated because random velocities might be different radially, tangentially, etc.
→ anisotropic random velocities

Fundamental Plane of Elliptical Galaxies

effective (half-light) radius — $r_e$

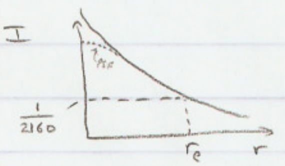
mean surface brightness — $I_e$ or $\Sigma_e$ within $r_e$

central velocity dispersion — $\sigma_0$

luminosity $L$ mass $M$

$$\Sigma_e = \frac{L/2}{\pi r_e^2} \qquad \frac{M}{r_e} = c\,\sigma_0^2 \quad \text{(Virial Equilibrium)}$$

$c$ — structure parameter
— contains unknown details about galaxy structure




from above (virial arguments)

$$r_e \propto \sigma_0^2 \Sigma_e^{-1} \qquad r_e = \left(\frac{c}{2\pi}\right)\left(\frac{M}{L}\right)^{-1} \sigma_0^2 \Sigma_e^{-1}$$

observed

$$r_e \propto \sigma_0^{1.4} \Sigma_e^{-0.85} \longrightarrow \text{Fundamental Plane}$$

consistent if $\left(\frac{2\pi}{c}\right)\left(\frac{M}{L}\right) \propto L^{0.25} \propto M^{0.2}$ ie. not a constant for all galaxies

1/22/2008

Lindblad Resonance Review

All have outer LR $\Omega_{pattern} = \Omega + \kappa/2$

pattern overtakes the more slowly moving star at same point in its epicycle

Inner LR: $\Omega_{pattern} = \Omega - \kappa/2$ will be present if galaxy is strongly centrally concentrated

If galaxy mass is more uniformly distributed (M33)
No ILR exists → spiral density can extend all the way to center

m can be integer larger than 2

uniform density : solid body rotation

$M = \rho V \propto r^3 \qquad v \propto \sqrt{\frac{M}{r}} \propto r \qquad \Omega = \frac{v}{r} = \text{constant}$

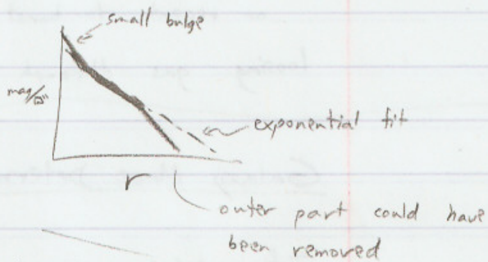
ILR can be within 1 kpc

orbits can be elongated parallel to bar → gas clouds will collide

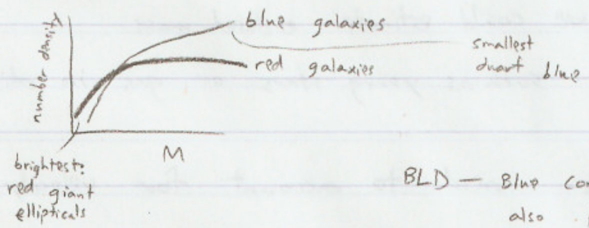
Dark sky
22 mag/arcsec²

M33 studied down to $V \sim 31$ mag/arcsec²

tidally truncated spiral near Andromeda




Galaxy Luminosity function




dE - dwarf Ellipticals
most numerous galaxies

BLD — Blue compact Dwarf
also known as Extragalactic HII regions

$$\Phi(L)\,dL = \Phi^* \left(\frac{L}{L^*}\right)^{\alpha} \exp\left(-\frac{L}{L^*}\right) \frac{dL}{L^*}$$

$L^* = 10^{10}\, L_\odot\, h^{-2} \qquad \alpha = -1.0$ to $-1.5 \qquad \Phi^* = 0.03\, h^3\, \mathrm{Mpc}^{-3}$

A double (broken) power law also generally work well (with addition of extra parameter (high-L slope))

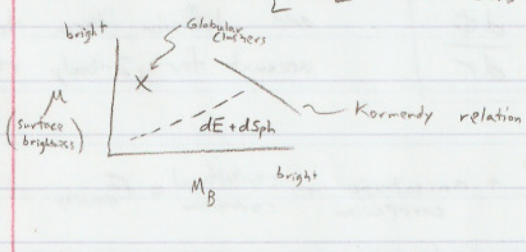
$d(\mathrm{Mag}) = -2.5\, d \log L = -2.5\, dL/L$ faint end slope becomes steeper by 1

→ converting to magnitudes

dE do not follow fundamental plane

$\frac{M}{L} \propto L^{-0.4}$ for dE → dark matter becomes dominant

if $\frac{M}{L} \propto L^{-1}$ ⟹ constant mass



dE or dSph ← same thing, different names
↑ if can resolve

No young stars similar to bright ellipticals

But: exponential profiles $I(r) = I(0) e^{-b_a (r/r_e)^{1/a}}$ $a=1 \rightarrow$ exponential

dwarf Irregulars

→ star formation
or recent star burst

extreme case: BCD — nearly all galaxy forming stars

I Zw 18 — possibly first burst of star formation

loosing gas through interactions or star formation

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1/25/2008

<u>Galaxy Mass Determinations</u>

If we knew circular velocity we could estimate enclosed mass

→ dynamically cold material such as young stars or gas in disk

for weighing bulges + ellipticals need to account for velocity dispersion

> See text on slide

we know $\kappa$ (frequency) but not amplitude
→ get that from velocity dispersion

Asymmetric Drift $= V_{circ} - \langle V_{rot} \rangle \sim \langle V_{radial} \rangle^2 / 120$ km/s (B+T pg 198-9)
↑ measured

more complicated than just adding KE + rot $\sim \frac{GM}{R}$

Collisional Boltzmann Eqn (Vlasov Eqn)

$$\boxed{\frac{\partial f}{\partial t} + v \cdot \nabla f - \nabla \phi \cdot \frac{\partial f}{\partial v} = 0}$$

continuity of distribution function in phase space

B+T Chpt 4

Jean's Eqn (spherical coords)

$$\frac{1}{n} \frac{d(n\sigma_r^2)}{dr} + 2\beta \frac{\sigma_r^2}{r} - \frac{V_{rot}^2}{r} = -\frac{d\phi}{dr}$$

over long time need to add diffusion term to account for 2-body relaxation

density

like hydrostatic support: $\frac{dP}{dr}$ + anisotropic correction + centrifugal correction $= F_{gravity}$

$n\sigma_r^2 \sim \rho v^2 \sim$ Pressure

dispersions not same in all directions (not so for gas)

→ stellar hydrodynamics

Several forms of Jean's law

$$\boxed{M(<r) = \underbrace{\frac{V_{rot}^2 r}{G}}_{\text{pure rotation}} - \frac{\sigma_r^2 r}{G}\left(\underbrace{\frac{d\ln n}{d\ln r} + \frac{d\ln \sigma_r^2}{d\ln r}}_{\substack{\text{isotropic dispersion} \\ \sim -2 \text{ or so}}} + \underbrace{2\beta}_{\text{anisotropic dispersion}}\right)}$$

to simplify: eliminate some of the terms ex $V_r \to 0$, $\sigma_r \to 0$, $\beta \to 0$

$n \propto r^{-k}$ usually $\therefore \frac{d\ln n}{d\ln r} = -k$

$\beta = 0$ isotropic velocity dispersion

$$\beta \equiv 1 - \frac{\overline{V_\theta^2}}{\overline{V_r^2}}$$

in general $V_r$ larger $V_\theta$

$\beta < 0$ tangential anisotropy

$0 < \beta < 1$ radial anisotropy $\quad V_r \to \infty$ or $V_\theta \to 0$ $\quad \beta \to 1$

$$\Rightarrow \frac{GM}{r} = V_r^2 + \sigma_r^2 \left[\text{correction term}\right]$$

can get line of sight velocity dispersion from absorption line widths in spectrum

For virialized gas (not stars) $\quad M(r) \simeq 4 \times 10^{11} M_\odot \left(\frac{T}{10^7 K}\right)\left(\frac{r}{10 kpc}\right)$

central parts of elliptical galaxies have $\frac{M}{L}$ typical for old star populations $\frac{M}{L} = 5 - 10 \frac{M_\odot}{L_\odot}$

→ dont need dark matter to explain central regions

Formulas on slides

without knowing $\beta \to$ get only lower limit for mass

cant tell about dark matter or central black hole

can estimate $\beta$ with shape of Gaussian (kurtosis) < triangular / boxy

circular velocity curves of ellipticals are flat like spirals → Dark Matter
(not actual velocity of stars)

↓ dominates around 2 effective radii

flat to $\sim 6 R_e$ → $\frac{M}{L} \sim 100 - 200$

## Stellar Populations in Galaxies

- integrated colors depend on ages and metallicities
- starformation histories give an "average" age
- age is crucial → controls MS turn off

MS 10% of mass burned

for solar metallicity $\frac{L}{L_\odot} = A\left(\frac{M}{M_\odot}\right)^b$ $\tau = 10 \frac{M}{M_\odot} \frac{L_\odot}{L}$ Gyr wrong?

| | | |
|---|---|---|
| $M > 20\ M_\odot$ | $A = 81$ | $b = 2.14$ |
| $2 < M < 20$ | $A = 1.78$ | $b = 3.5$ |
| $M < 2 M_\odot$ | $A = 0.75$ | $b = 4.8$ |

$$\boxed{\tau = 10\ A^{-1}\left(\frac{M}{M_\odot}\right)^{1-b}\ \text{Gyr}}$$

$b > 1$

As population ages, MS turnoff drops → light gets redder

$\frac{M}{L}$ ratio increases (luminosity drops as massive stars die off)

$\frac{M}{L} \sim 5$ for $\tau \sim 10\text{-}12$ Gyr

models vary because of their treatment of AGB phase

past Average star formation from massive stars seen / age (?)

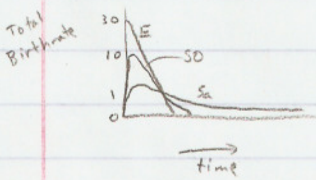
current SFR from UV light

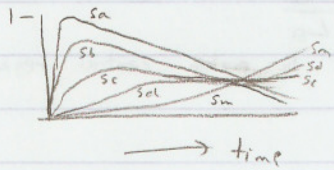
early spirals: higher SFR in the past late spirals: SFR ~ average from past

average star ages are older

Sm – Im (dwarf irregulars): higher SFR today compared to average in the past

→ starburst




← very schematic

detailed SFR history is only 2nd order effect on integrated colors

what IMF to use?

low mass stars – little light but most of stellar mass

Salpeter, Kroupa, Scalo

(simplest with −1.35 slope (power law) → only 2nd order effect on colors

→ does affect $M/L$ ratio

possibly: extreme starbursts, very young galaxies might have absence of subsolar masses, or Pop III

Metallicity also affects colors

line blanketing — lots of metals absorb UV + blue light

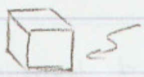
opacity changes — see deeper / less deep

red giants (metal poor) — bluer (see deeper — hotter)

→ age/metallicity degeneracy

metallicity is distribution with wide range just like age

## Closed Box Model



100% gas, initially zero mass

nothing goes in or out

star forms with a rate $\Psi(t)$

$dm$ of stars (newly formed), instantaneously return mass to box

Instanteneous Recycling

$y$ — metal yield — fraction of recycled matter that is metals

$$\frac{dM_g}{dt} = \underbrace{-\Psi}_{\text{form stars}} + \underbrace{\Psi R}_{\text{recycling}} \qquad \text{mass of gas}$$

$$Z_g \equiv \frac{M_{Z_g}}{M_g} \qquad \text{metallicity of gas}$$

star masses $= -\frac{dM_g}{dt}$

mass of metals in gas $\quad \frac{dM_{Z_g}}{dt} = \frac{d}{dt}\left(Z_g M_g\right) = y\frac{dM_*}{dt} - Z_g\frac{dM_*}{dt} = (y - Z_g)\frac{dM_*}{dt}$

$$\frac{dZ_g}{dt} = -y\,\frac{dM_g/dt}{M_g} \Rightarrow \boxed{Z_g(t) = y\ln\left(\frac{M_{tot}}{M_g}\right)}$$

Stellar metallicity distribution

→ depends on gas mass not on $\Psi(t)$

$$\boxed{\frac{dM_*}{dZ} = \frac{M_{tot}}{y}\exp\left(-\frac{Z}{y}\right)}$$

Avg. metallicity

$\langle Z\rangle \to y$ as $M_g \to 0$ $\qquad Z_\odot = 0.02 \qquad y = 0.04$ on slides

$\hookrightarrow \langle Z\rangle \to 2Z_\odot$

2/7/2008

Abundance distribution of giants in Baade's Window show $\langle Z\rangle \sim 2Z_\odot$

consistent with $y = 0.04$

But outflows are observed ex. M82  dwarf prototypical starburst

Can make leaking box model

in $\frac{dM_g}{dt} \rightarrow$ add $-\frac{dM_g}{dt}\Big|_{outflow}$  $\frac{dM_g}{dt}\Big|_{outflow} = \overbrace{\eta}^{\text{constant fraction}}(1-R)\psi$

also in $\frac{d(Z_g M_g)}{dt} \rightarrow$ add $-Z_g \frac{dM_g}{dt}\Big|_{outflow}$

$\frac{dM_*}{dZ} \rightarrow$ same but now with $y_{eff}$ (not $y$)  $y_{eff} = \frac{y}{1+\eta}$

$\therefore \langle Z \rangle \rightarrow y_{eff}$

Color-Magnitude Diagram for galaxies

using E + S0 galaxies — homogenous colors scaling with luminosity

small scatter — similar ages + metallicities at same luminosity

bluer galaxies — less metallicity  redder — more metals

(brighter, more mass, higher escape velocity)

Clusters present the red-sequence at low + intermediate redshifts

brighter ~ redder

dimmer ~ bluer

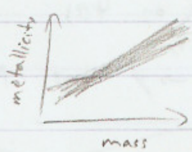
consistent with E+S0 having no strong star formation since ~7 Gyr

all that's going on is passive evolution → stars evolving normally

massive galaxies can hold on to their stars better than smaller ones

Apparently low mass galaxis have trouble holding onto all the metals they produce

Mass/Metallicity relation for spirals → same idea:



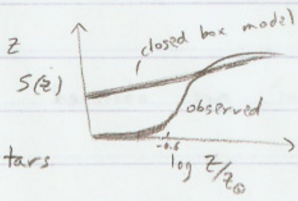

Huge amount of metals in IGM must have been expelled from cluster galaxies

looking in solar neighborhood → closed box fails

S(Z) — fraction of stars with metallicity Z

→ G-Dwarf Problem

should still see extreme metal poor stars




→ infall of metal-enriched gas
or pre-enrichment from Pop III } possible solutions

# ISM

15% of mass in stars ~ mass in ISM in MW but increases in later types

→ see slides dust ~ 1% of mass

atomic H ~90% of mass, 50% of volume disk, some in halo

molecular $H_2$ ~10% of mass dark clouds in disk 1% of volume

→ use $^{12}CO$ or $^{13}CO$ to trace

HII near hot stars, emission nebulae (radio continuum from free-free emission)

hot gas everywhere → seen with X-rays

dust mostly in disk

magnetic fields everywhere

cosmic rays everywhere

various gas phases exist in pressure equilibrium

$$nT \approx 10^3 - 10^4 \text{ K cm}^{-3}$$

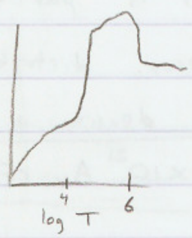
coexistence of various gas phases — result of equilibrium between heating + cooling

cooling rate $\Lambda \propto n^2$ (collisions)

$K \sim 13.6\,eV$ $\rightarrow T \sim 10^5 K$ cools very efficiently for $T \gtrsim 10^4 K$

due to collisional excitation of

few eV ($\sim 10^4 K$) ← many fine structure levels




hot gas is either found at $T \approx 10^4 K$ and $T \gtrsim 10^6 K$

Compton cooling — $e^-$ fast → gives energy to low E photons

at $10^6 K$ → nearly all elements are fully ionized — no more collisional excitation

2/8/2008

"Level 5" in NED ← lots of good/review articles

'phases' model not complicated enough

Molecular Medium
Cold Neutral Medium
Warm Neutral Medium
Warm Ionized "
Hot Ionized "

$^{12}CO$ correlating with virial mass

<u>but</u> lots of scatter

conversion factor is uncertain

Hot gas — affected by radiative loses
— can be ejected from galaxy

Interstellar Dust

PAHs are smallest dust grains

Dust is formed in the outer atmospheres of red giants.

Some are so small (large molecules), they have short wavelength emission produced by thermal pulses from absorbing single photons.

PAH features are prominent and fairly universal (except in Seyfert I nuclei)

Dust grains are very effective absorbers of optical + UV light

optical depth $\boxed{\tau_{dust} \propto \lambda^{-1}}$

Mie scattering — scattering at particles with about size of wavelength

scattered light is partially polarized

dust is approx. distributed like gas

H column density + dust extinction are correlated

$\boxed{N_H = 1.9 \times 10^{21} A_V \text{ cm}^{-2} \text{ mag}^{-1}}$ for standard dust/gas ratio

Carbon more durable than Silicon

Generally dust has mix of carbon + silicates

$A_V \gtrsim 3 \rightarrow$ see Silicon absorption ($10\mu m$, some at $18\mu m$)

low energy x-rays get absorbed not high energy

$\rightarrow$ bluening  x-ray absorption makes spectrum harder/bluer

$N_H = 10^{24}$ is Thomson-thick : absorbs everything up to gamma rays

$$\tau_{es} = \sigma_e N_H$$
$$10^{-24} \quad 10^{24} \quad \sim 1$$

Klein-Nishima correction

relativistic effects can allow some gamma rays through

## Galaxy Mergers and Interactions

- generate bulges
- gas goes to center
- intense star formation
- supernova driven super winds
- chemical pollution of environment
- cosmic star formation history

Many spirals are in small groups

Arp Atlas — lots of interaction

HI more easy to strip from galaxy

Dark Matter — facilitates mergers/interactions makes galaxies 'stickier'

Can form rings

3 problems with making ellipticals from mergers

P1 — stellar phase density is preserved during mergers
> ellipticals have higher than spirals
S > does not apply to interstellar gas, can dissipate energy and flow inwards then form stars

P2 — differing globular clusters specific frequencies of spirals + ellipticals
S > collision can make new clusters

P3 — high relative velocity of galaxies in cluster
> not enough time for interaction
S > structure forms hierarchical, small groups moving slower

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2/14/2008

Evidences for Mergers in ellipticals → see slide
kinematically distint cores, residual gas and dust, large scale tidal features

Dust lanes in E galaxies
— suprisingly common

Shells around ellipticals

spiral-spiral merger remnants have approx $r^{1/4}$ stellar density profile

violent relaxation — grav. potential changes faster than stellar orbit periods
└ tends to make isothermal sphere

in simulations + real life you get incomplete violent relaxation
— seen in phase space structure (historical info about initial conditions)

Dark Matter plays a crucial role in mergers.

During merger, gas + stars form bars. The gas bar leads ahead of star bar.
Stars drag bar of gas → gas looses angular momentum and spirals in

Nuclear starburst can occur when gas spirals in.
A lot more angular momentum must be lost to reach black hole.

Ultra Luminous IR Galaxies (ULIRG)
— show final stages of spiral-spiral mergers with heavy star formation

Most galaxy pairs do not have starburst
Though there is statistical correlation between starburst + collisions

Minor mergers ($\frac{M_1}{M_2}$ more than ~5) — more gradual
small galaxy can be tidally disrupted
can puff up disk or make warps of larger galaxy

More close pairs as you go back in redshift

2/15/2008

Selection Criteria for Clusters and Groups

Abell's Catalog of Rich Clusters (1958)
Criteria (on slide)
— >50 members within $R_{abell} = \frac{1.7}{1+z} \approx 3\, h_{50}$ Mpc
— Redshift $0.02 < z < 0.2$
— sorted into richness classes
— Usually no redshifts measured, but determined from brightness of brightest galaxy
— used Palomar Sky Survey

Biased in favor of elongated objects projected along our line of sight

| Richness class | R | N |
|---|---|---|
| Virgo | 0 | 30–49 |
| Coma | 2 | 80–129 |

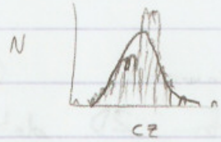
Coma Cluster

70 Mpc ($z=0.02$) Best-studied of all clusters

$\sim$ up to 10,000 members brightest are ellipticals

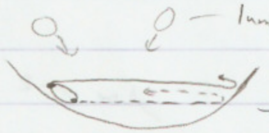
Cluster Kinematics $\sigma_r \sim 10^3$ km/s substructure in Gaussian

it appears "relaxed" but not complete yet




Many clusters how substructure.

Phase Mixing




lumps get smeared out in phase

Dynamical evolution will rapidly erase substructure.

1 km/s for $10^6$ yrs $\rightarrow$ 1 pc

Substructure has only a minor effect on virial masses.

$$M_{cl} \sim 10^{15} M_\odot \left(\frac{\sigma_r}{10^3 \frac{km}{s}}\right)^2 \left(\frac{R}{1 Mpc}\right)$$ Virial mass

typical for $\rho \propto r^{-2}$

luminous matter $\sim 5-10\%$ of $M_{cl}$

Coma is one of brightest X-ray sources in sky.

all approx for isothermal sphere

$r^{1/4}$, power law, Hubble profile $\sigma(r) = \sigma_0 \left(1+\left(\frac{r}{r_c}\right)\right)^{-2}$, King profile $\sigma(r) = \sigma_0 \left(1+\left(\frac{r}{r_c}\right)^2\right)^{-1}$

2/19/2008

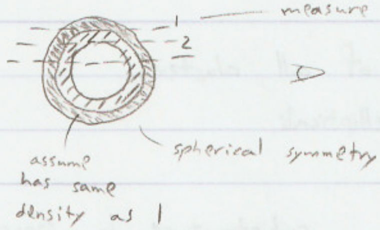
$$\frac{M_{virial}}{M_{galaxies}} \sim 25$$

| | |
|---|---|
| Globular clusters | $1-2$ $M_\odot/L_\odot$ |
| Elliptical | $5-10h$ " |
| Groups of Galaxies | $100-300h$ " |
| Rich Clusters | $300-500h$ " |

Even including anisotropy ($\beta$) can get lower limits to mass (and still too large)

not really measured for galaxies

## X-rays in Clusters




— measure surface density of outer shell

2 is super position but 1 gave me what the shell was so I'll subract both
→ density

I can work inwards (→ taking spatial derivative)
to get 3D from 2D data

but noise keeps increasing → need very good data

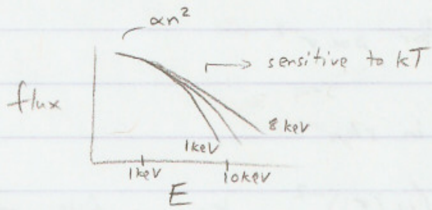
Usually a smoothly varying function is assumed

X-ray emission $\propto \rho^2$ (Brehmsstrahlung)

if $\rho \propto r^{-2}$ expect $\propto r^{-4}$
but actually $\propto r^{-3}$
because of this 3D projection

Can get $\rho$ and M of x-ray emitting gas
→ has more mass than all the galaxies (generally)

Emissivity from free-free emission $\quad j_{ff} = \dfrac{n_e n_i \, e^{-h\nu/kT_e}}{\sqrt{T_e}} g_{ff}$




line emission
Fe K complex at 6.7 keV
hot iron – only 1, 2 $e^-$ left — most iron is cold

x-ray knocks out inner $e^-$ in iron
upper $e^-$ fall down emitting x-ray line

### Intra Cluster Medium (ICM)

- most baryonic mass in cluster (~80%)
- density ~$10^{-4}$ cm$^{-3}$ – $10^{-2}$ cm$^{-3}$
- hot, low density, optically thin plasma
- Temperature: $kT \sim 0.5 - 15$ keV ($\sim 10^6 - 10^8$ K)
  - x-ray range, not isothermal, dependent on depth of grav. potential
- ~1/3 solar metallicity, ionized H & He

If hot gas is in thermodynamic equilibrium, you can get total mass

$$M(<R) = -\frac{k T_{gas}}{\mu m_H G}\left(\underbrace{\frac{\partial \ln \rho_{gas}}{\partial \ln r}}_{-2} + \underbrace{\frac{\partial \ln T_{gas}}{\partial \ln r}}_{\text{assume } 0 \text{ for isothermal}}\right)$$

so $M \propto T$, self-similar but at low T doesnt hold

→ "Entropy Floor"

→ implies non-gravitational effects extra cooling of larger clusers

and/or heat input in smaller clusters

Searches for "cooling flows" have in generally failed

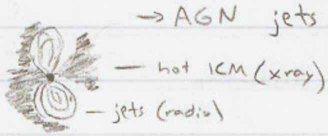
central part (higher density) cools fastest so without high T it falls in to central galaxy → cooling flows

Potential additional sources of heat

- SN winds, some fraction escapes galaxy and heats ICM
- AGN

Perseus Cluster central galaxy is AGN 3C 84, Perseus A, NGC ...

→ AGN jets have blown holes / bubbles in ICM




Virial + X-ray + Gravitational Lensing

hot gas has more mass than galaxies but still not enough

10 – 20 % of cluster mass

2/21/2008

where did the hot intracluster gas come from?

Two possibilities:

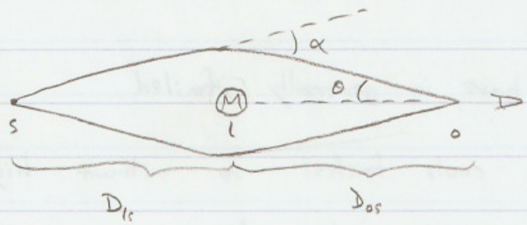
1) Gas expelled from galaxies (but not cluster) by winds
   - explains metallicity ($\frac{1}{3}$ of solar)
   - galaxies in cores of clusters are deficient in HI gas

   BUT $M_{gas} >> M_{gal}$

2) Gas is primordial

## Gravitational Lensing

light deflected through angle $\alpha$ satisfying $\theta D_{os} = \alpha D_{ls}$




$$\alpha = -\frac{4GM}{bc^2}$$

impact parameter

$\alpha \sim 2\theta$

$\theta \sim \frac{2GM}{bc^2}$

$\left(\frac{GMm}{b} / mc^2\right)$

$$\theta \sim 30 \text{ arcsec} \left(\frac{M}{10^{15} M_\odot}\right)^{1/2} \left(\frac{D}{\text{Gpc}}\right)^{-1/2} \qquad D = \frac{D_{ol} D_{os}}{D_{ls}}$$

For sun $\sim 1''$

surface density

$$M = \Sigma_{crit} \pi b^2 \qquad \Sigma_{crit} = \frac{c^2}{4\pi G} \frac{D_{os}}{D_{ol} D_{ls}}$$

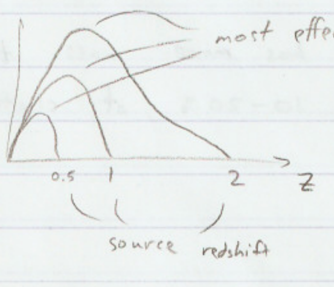
makes image larger while preserving surface brightness $\therefore$ appears brighter

strong lensing: $\frac{\Sigma}{\Sigma_{crit}} > 1$ multiple images, long arcs

weak lensing: $\frac{\Sigma}{\Sigma_{crit}} < 1$ small arcs and distortion

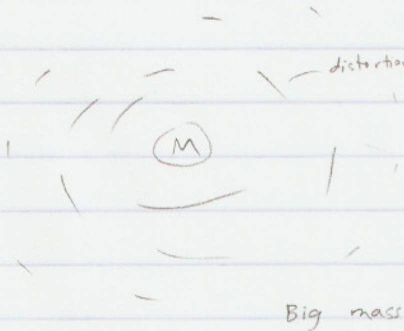
magnefied in tangential direction

larger distance: more effective



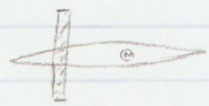
- Can get mass + distribution of dark matter
- Can be used to see distant galaxies

Richard Ellis's
$z \sim 7$ by looking
where magnification is best




Map distribution of matter
→ maximum entropy mode: smoothest possible distributio

Big mass sheets — degeneracy, can't usually tell if they are there



might be broken by counting lensed galaxy (?)

Lensing Mass & x-ray Mass usually agree

---

Some new clusters found using weak lensing 2/28/2008

3/4 of cases have mass distributed where light is distributed

Brightest cluster galaxy tends to be elongated in same direction as cluster.

Clusters with $T_x > 8$ keV show signs of dynamical activity (infall not equilibrium)
Most, though, are relaxed

Best method?

Weak Lensing
- ✓ independent of dynamical state
- ✓ reconstructs 2-D potential
- ☹ need superb seeing
- ☹ cannot separate components along line of sight

X-rays
- ☹ depends on thermal/dynamical state of ICM
- ☹ cannot separate components along LoS
- ✓ all sky surveys → large, homogeneous sample

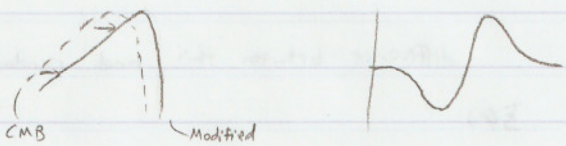
Dynamis of Galaxies
- ☹ depends on dynamical state
- ☹ need large # of velocities
- ✓ can separate structures along LoS

"Bullet cluster" — dark matter is dissipationless

→ keeps moving on when clusters collide

but x-rays dissipate energy and clump between

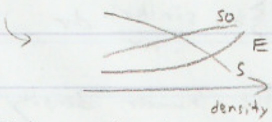
Sunyaev - Zeldovich Effect




$\frac{M}{L}$ of clusters: $100 - 500 \ \frac{M_\odot}{L_\odot}$ if this were it, $\Omega < 1$ (assuming same everywhere)

since critical density needs $\sim 1500 \ \frac{M_\odot}{L_\odot}$

Morphological / Density Relationship seen locally + at higher redshift




Why? Nature vs. Nurture

Nurture — interactions

galaxy - cluster (combined gravity of cluster stretches out galaxies that pass near center)

galaxy - galaxy (harrassment, or merger)

ram pressure ISM — ICM (ram pressure stripping)


Uniformly red color in E/S0 galaxies in cluster (red sequence)

→ means all stars formed a long time ago

Butcher - Olmer effect: A star absorption lines in E/S0
(?) (young stars)

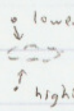
High redshift sample not comparable to low redshift

↳ Progenitor bias E/S0 old E/S0 or merger product (?)

Clusters of Clusters — Super clusters

Finger of God (virialization of clusters)

Palm of God infall to large structures



lower redshift due to infall

higher redshift due to infall

Supercluster — Cluster possible fractal structure

Need quantitative measure of clustering

Ex: percolation length circle of friendship increase length so all galaxies in same group

multiplicity function how many companions

void probability function

difference between this and random galaxies from simulatio

Two Point Correlation Function $\xi(r)$

- excess probability of having a companion in certain distance

Luminous galaxies more strongly clustered (redder)

Natural if more luminous galaxies populate more massive halos

Can convert to power law $P(k) = \int 4\pi r^2 \xi(r) \frac{\sin(kr)}{kr} dr$

$\xi(r) = 1$ this is where you find twice the number density of random Poisson

$\xi(r) = \left(\frac{r}{r_0}\right)^{-\gamma}$ $r_0 \sim 6$ Mpc, $\gamma \sim 1.76$

Projected Correlation Function
(or Angular) based on angular separation

$W(\theta) \propto \theta^{-0.7}$
(?)

## The Local Group

Majority of nearby galaxies (~85%) are not in clusters but in groups

Group ~30 galaxies within a radius of 1-2 Mpc

within group: earlier types of galaxies more strongly clustered, tend to lie closer to center

fossil group - dominated by large central elliptical, final stages of group evolution

Local Group

- can study star ages, history, chemistry, kinematics in detail

42 members (including tidal streams of Sagittarius)

2 dominant members: MW + M31

gas-rich, later-type irregulars distributed throughout the group, less concentrated

Missing Satellite Problem

CDM predicts 100-1000's of satellites for a MW-like galaxy

Dwarf galaxies most numerous in Universe

dSph - old stars    dwarf irregulars - old + recent starformation    always old stars present

Starformation histories varies dramatically from galaxy to galaxy

dIrr - presence of enhanced SF activity in last few hundred Myrs

dSph / dE - no current SF, presence of non-negligible intermediate-age to young star formation activity is common

GC - all old stars, no recent SF (at least in MW, not true in LMC) spherical, centrally concentrated

For all dwarf galaxies the younger populations tend to be more centrally concentrated (and possibly more chemically enriched)

SF regions extend out to 6 optical scale lengths → SF is truncated at <u>lower</u> gas density thresholds <u>than</u> in spirals

Evidence for harassment of galaxies in Local Group

- Sagittarius dSph galaxy

- $\omega$ Centauri
  - GC with range of different ages + large metallicty spread ← odd
  - May be core of accreted dwarf galaxy

- Tidal features

etc. see slide

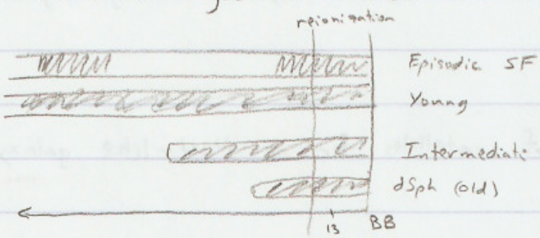
Hierarchical scenario: SF as early as $z \sim 30$

Cosmic re-ionization squelches SF in low-mass substructures

Galaxies $< 10^8 - 10^9\ M_\odot$ lose SF material via photoevaporation during re-ionization

$\therefore$ low mass galaxies must form stars before reionization

but




$\therefore$ this model seems to fail

More luminous (massive) galaxies are more metal-rich

At same luminosity, the old populations of dSphs are more metal-rich than those of dIrrs

# Active Galactic Nuclei

3/4/2008

Comparable power emitted across ~7 orders of magnitude in photon energy

Dust absorbs short wavelength and reemits long-wavelength photons thermally

Every AGN emits at least 15% of its total energy in thermal IR wavelength

Interstellar HI in galaxy absorbs EUV / Soft X-ray

$\tau_{HI} = N_{HI}\,\sigma_{912Å}$ (Ly limit) $\qquad \sigma_{Ly\,limit} = 6\times10^{-18}\ cm^2$

900 – 100 Å or so is absorbed

$N_{HI} \sim 10^{19}\ cm^{-2}$ or higher

this is Big Blue Bump peak (source of ionizing photons)

Is all IR emission thermal or nonthermal?

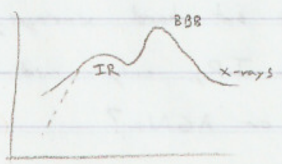
Blazar jets: violently variable, strongly variable polarization → synchrotron

If thermal: $L = A\sigma T^4$ lower limit on $A$ ⇒ distribution of dust

if size > light crossing time (variability) → can't be thermal

synchrotron emission is compact, bright, polarized (can be)

farthest IR goes down: 60μm turnover could be produced by synchrotron self-absorption




Most AGN lack blazar properties (variability, polarization)

Non-variable mid-IR continuum, very little polarization

→ range of $T_{dust}$

Problems: $T_{evap}$ should produce 1μm cutoff (not seen) — emissivity is higher at lower wavelength → appears hotter but not enough

Energy budget → very large covering fraction required (~1/3) to get 15% in IR but cannot block out UV light (which we see)

Clean lines of sight ($N_x < 10^{20}\ cm^{-2}$) → but early studies were biased against absorbed Seyferts

where are the silicate features in Sy 1's?

Wien cutoff is indeed seen around $1 \mu m$ (hot dust evaporates if it gets too hot)

Sy 2's always looked dusty as expected → see Silicon absorption

Some Sy 1's show Silicon in emission

$L_{IR} \sim \frac{1}{2} L_{UV}$


warped/puffed up disk + lumpy to get enough IR from UV

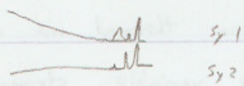
Archetype Sy 1 (?) NGC 4151

Higher frequency light → more rapid variability

Hotter dust ($2 \mu m$) should have variability with delay of months to years

→ this is confirmed by several people including Brant Nelson (UCLA thesis)

Sy 2's do have less UV light




How can we identify obscured AGN?

1 – soft x-ray absorption

2 – Reddened broad lines, reddened UV/optical continuum

3 – Central engine (BLR/ Big Blue Bump) completely blocked as in Sy 2's

4 – Compton thick absorption ($N_H \sim 10^{25}$ cm$^{-2}$) even blocks out hard x-rays, gamma rays

5 – Totally buried: even NLR is quenched, even in IR, only mid-IR to far-IR

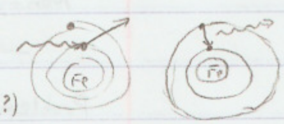
→ warm dust in ULIRG heated by young stars or AGNs?

why hard x-rays not absorbed but soft x-rays are?

Surveys in hard x-rays do show that $N_H \sim 10^{23-24}$ cm$^{-2}$ exist + are common

Hard x-rays can be absorbed by inner $e^-$ → Fe K$\alpha$ line

6 keV(?)




Archetype Sy 2 NGC 1068

NGC 1068 – no hard xrays but see lots of Fe K$\alpha$

Unified Model

Antonucci & Miller 1985, ApJ, 297, 621

Antonucci 1993, ARAA, Vol 31, p. 473

NGC 1068 — polarized flux shows broad lines

— huge Fe K$\alpha$ EW confirms buried Sy 1

Geometric orientation inspired by radio core-dominant / lobe-dominant unification

seen along jet

But nothing is holding up torus against gravity

No direct evidence of torus

Galaxtic Dust Model

3/10/2008

Downsizing

→ star formation has been moving to smaller galaxies

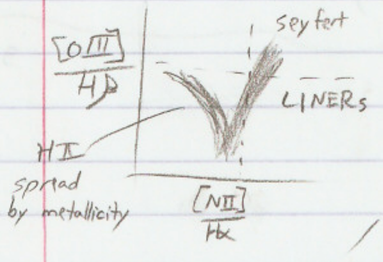
Also for active galaxies

Today: low power AGN Past: high power AGN

Low Ionization Nuclear Emission-line Regions (LINERs)

→ found in most nuclei bulge-dominated galaxies

have strong OIII 4363, OI 6300




Might be starving BH $L \ll L_{Edd}$

or could be shocks

In high-vel. shocks: many temperatures present

just behind it — gas is collisionally excited


$\frac{OIII\ 4363}{OIII\ 5007}$ ⟹ gives temperature

Sometimes compact radio source

or nuclear X-ray source

has been modeled with ADAF or other weak accretion modes

Accretion disk spectral energy distribution

$$T^4(R) = \frac{3GM\dot{M}}{8\pi R^3}\left(1-\left(\frac{R_*}{R}\right)^{0.5}\right) \rightarrow \text{multicolor blackbody}$$

matches big blue bump

Evidence: wanted Ly limit absorption → not always seen
(like O star)

electron scattering can give low polarization

Broad Fe K$\alpha$ line (6.4 eV) shows ~double peak

BUT relativistic beaming increases blue not red

ALSO gravitational redshift drags it to the red

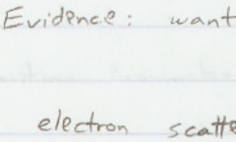
BLR

are motions orbital? (gravity)

$$U = \frac{L}{4\pi r^2 n c} \sim 0.01 \quad \text{Ionization parameter}$$

Size from reverberation mapping 10–20 light-days

shortest lags – highest ionization, broadest lines




$$M = f c \tau \sigma^2 / G$$

fudge factor (~5.5)

3/11/2008

| dSph | vs. G.C. |
| --- | --- |
| Multiple ages, metallicity | 1 old, metal poor population |
| $\frac{M}{L} \sim 30-50$ mostly D.M. | $\frac{M}{L} \sim 3$ no D.M. |

Holy Grail in AGN: Black Hole Masses

2 methods (rev / u)
~ factor of 2.5–3 difference

from reverberation mapping
or
from ionization parameter
} get distance of BLR

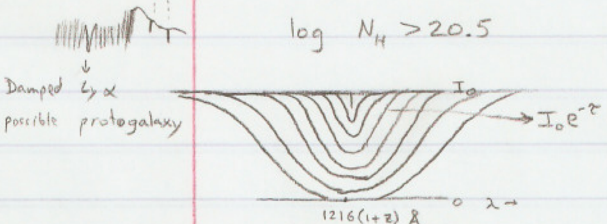
+ velocity dispersion = mass

other lines (metals) of gas (usually of damped Lyα system)

Resonance absorption line : ground to first excited state (usually UV) (?)

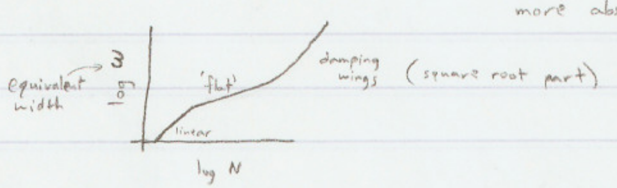
Damped Ly α absorbers easily found in quite a few quasars (Ly α forest)

$\log N_H > 20.5$



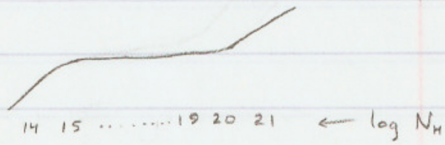

$\tau = N_{HI} \underbrace{fg}_{\text{quantum/atomic stuff}}$ linear part of curve of growth

more absorbers → less light




in 'flat' region
W changes very little with column density

For Ly α :

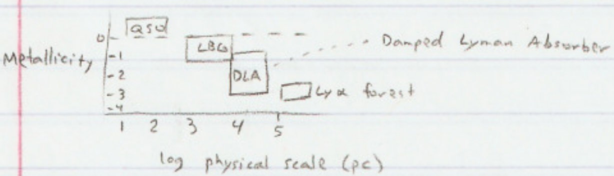



O stars have intrinsic Ly break

At $\sim 10^{17}$ cm$^{-2}$ , $\tau_{Ly\ limit} > 1$
(912 Å)

Some metal absorption lines are seen redward of Ly α

In Ly α forest, metals are highly ionized (low n ⇒ high u $u \sim \frac{1}{n}$)




Some IGM (former Ly α forest) becomes gravitationally heated (shocked to $T = 10^{5-7}$ K)

very hard to detect except maybe by absorption in FUV, soft x-rays (OVI absorption)

→ missing most baryons if ignore hot IGM absorptions

($slides$ on $\Omega_{baryons}$) missing ~50% of baryons ($z < 2$)

→ hard to detect $10^6$K gas (very hot gas O VII, O VIII (hard))

with Chandra some OVII was detected in absorption for 1 case ?