4. Elliptical galaxies

- morphology ⇒ elliptical (triaxial spheroids).
- old (red) stellar populations
- v. little gas + dust

} star formation ceased a long time ago.

- classified by luminosity.

cD, gE, E, dE, dSph

⟶ L decreasing.

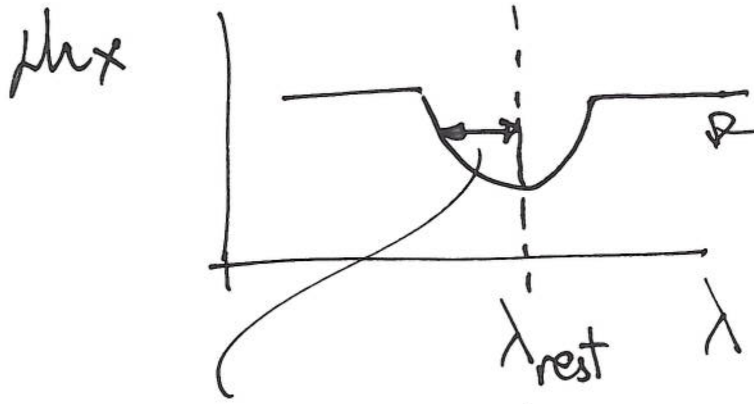
- surface brightness profiles, see 2 classes.

cD, gE, E ⟶ $I \propto \exp\left(-\left(\frac{R}{a}\right)^{1/4}\right)$

dE, dSph ⟶ $I \propto \exp\left(-\frac{R}{a}\right)$

⇒ distinct formation processes.

- kinematics, long-slit spectroscopy of ellipticals



← sum of the narrow absorption lines from billions of stars, each Doppler shifted by its own radial velocity.

$\sigma_r \equiv$ radial velocity dispersion.

Broad line at each point in galaxy, shows v. little coherent rotation. Instead the stellar orbits are randomised, the galaxy is "thermally supported" against gravity.

How measure mass from σ_r?

consider a single circular orbit of test particle.

recall, $v^2 = \frac{GM(<R)}{R}$

$$\Rightarrow K = \frac{1}{2} m v^2 = \frac{GMm}{2R}$$

↑ kinetic energy

recall, $U = -\frac{GMm}{R}$

(U → potential energy)

$\Rightarrow \; -2K = U$

Remarkably, can prove this holds for all gravitationally bound systems in equilibrium.

→ Virial theorem

Important because it links observable velocities to gravitational binding energy and hence total mass.

strictly $-2\bar{K} = \bar{U}$ – time averages.

Apply the Virial theorem to a galaxy.

$$-2\bar{K} = -2\sum_{i=1}^{N} \frac{1}{2} m_i v_i^2$$

N — total number of particles.

$\frac{1}{2} m_i v_i^2$ — K.E of individual particles

Assume m & v are uncorrelated,

total mass of galaxy.

$$= -\frac{M}{N}\sum_{i=1}^{N} v_i^2$$

$\frac{1}{N}\sum_{i=1}^{N} v_i^2$ ≡ square of standard deviation of velocities ≡ σ ≡ velocity dispersion.

$$\Rightarrow \quad -2\bar{K} = -M\sigma^2$$

In practice we measure the radial component of velocity,

$$v^2 = v_r^2 + v_\theta^2 + v_\phi^2 \approx 3v_r^2$$

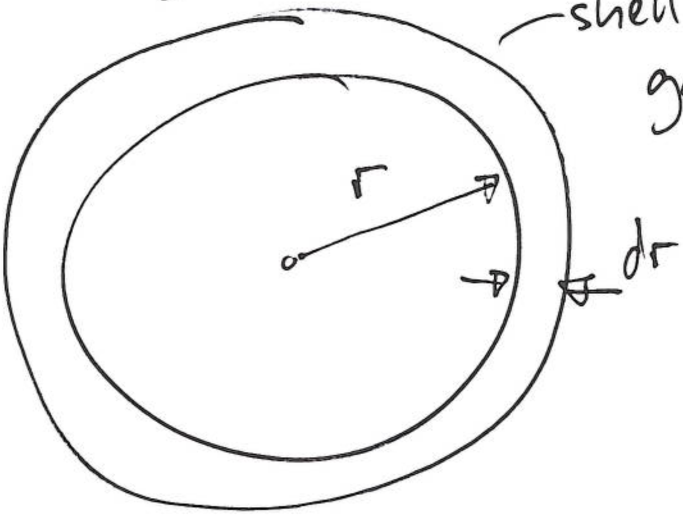
(assuming symmetry).

$$\Rightarrow \quad -2\bar{K} = -M\,3\sigma_r^2$$

σ_r — measured radial velocity dispersion.

Gravitational potential of the galaxy (V) depends on its structure.

Assume a spherically symmetric galaxy with uniform density.



Grav. potential of the shell

$$dU_r = -\frac{G M_r m}{r}$$

(M_r — mass enclosed by the shell, m — mass of the shell)

$$m = \underbrace{4\pi r^2 dr}_{\text{volume of shell}}\,\rho$$

(ρ — density of the galaxy.)

$$M_r = \underbrace{\frac{4}{3}\pi r^3}_{\text{volume enclosed.}}\rho$$

Subst

$$dU_r = -\frac{G}{r}\frac{4}{3}\pi r^3 \rho \, 4\pi r^2 \rho \, dr$$

$$= -G\frac{16}{3}\pi^2 \rho^2 r^4 dr$$

Total potential by integrating over all r 14.14.3

$$\int dU_r = -G\frac{16}{3}\pi^2\rho^2\int_0^R r^4 \cdot dr$$

R ~ size of galaxy.

$$U = -\frac{16}{15}G\pi^2\rho^2R^5$$

Eliminate density, $M = \frac{4}{3}\pi R^3\rho$

$$\Rightarrow U = -\frac{3}{5}\frac{GM^2}{R}$$

spherically symmetric

different mass distributions, just give different constants.

subst into virial theorem

$$-M\sigma^2 = -\frac{3}{5}\frac{GM^2}{R}$$

$$\Rightarrow \sigma = \left(\frac{3}{5}\frac{GM}{R}\right)^{1/2}$$

or

$$M = \frac{5\sigma_r^2 R}{G}$$

So can measure the enclosed virial mass 14.14.4
of an elliptical galaxy, by measuring the broadening of the absorption lines at a radius R.

This mass will include all the enclosed mass, (i.e. including the dark matter). The stars are being used as test particles to sample the gravitational potential.

Results

$\frac{M}{L} \sim 50$ in Es, cf $\frac{M}{L} \sim 10$ for Ss
(out to the edge of the visible disc).

So Es are slightly more dark matter dominated than Ss.

Difference is accounted for by the lower average luminosity of stars in Es (older population, young luminous stars have died).

In contrast, dE & dSph are much more dark matter dominated.

dSph : $\frac{M}{L} \sim 1000$!

⇒ the most dark matter dominated objects in the Universe.

dE/dSph have probably lost their gas early in their evolution, so cannot form new stars, probably because a handful of supernovae injected K.E. into the ISM, sufficient to overcome the shallow grav. potential.

In contrast giant galaxies seem to have held onto gas & continued to form stars (more massive galaxies have deeper gravitational potentials).

Similarly to the Tully-Fisher relation for spirals, Es show

$$L \propto \sigma^4$$ → Faber-Jackson relation.

⇒ used to estimate distances.

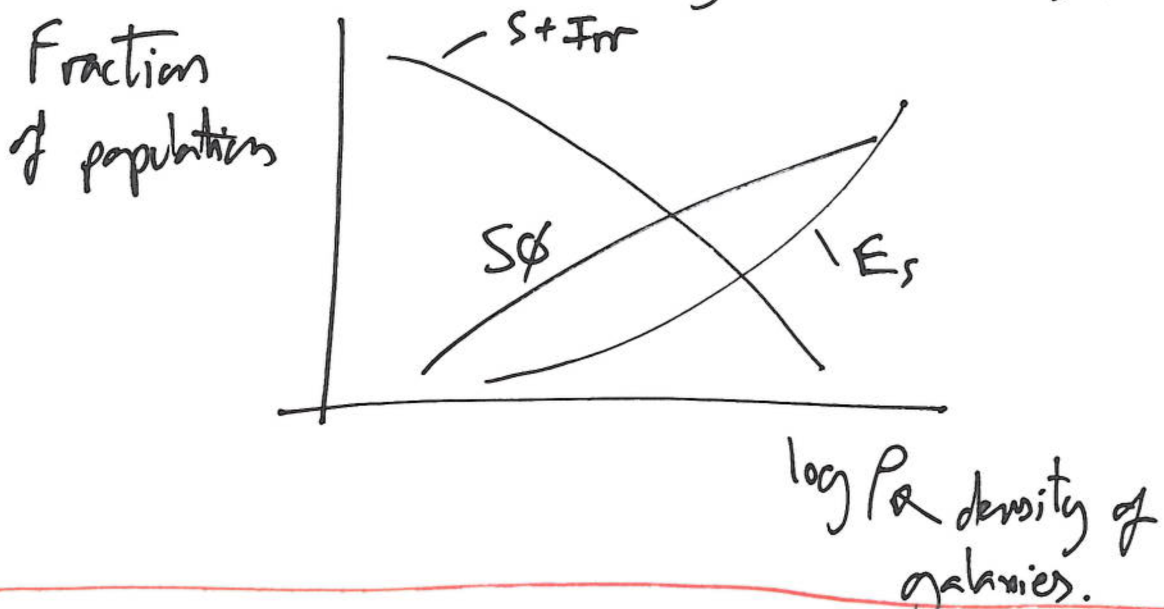
Also, indicates $\frac{M}{L}$ and surface brightness are approx constant across all giant Es.

14.14.6

Galaxy evolution: why are Es & Ss so different?

Key evidence is a correlation between galaxy type and density of environment.

In the field, only see Sp & Irr whereas in dense regions such as rich clusters are dominated by Es & dEs.



14.15.0

Why? Believed that galaxies are modified by close encounters in high density environments.

① close encounters of Irr may strip gas leaving a dE and/or may trigger star formation leading SNe, which may also strip gas.

② merger of giants disrupt the discs of spirals and randomise the orbits of the stars,

$$S + S \rightarrow E$$

→ many examples seen of colliding galaxies.
→ some material is ejected
⇒ allows some material to become bound.

→ compression of the gas disc triggers intense star formation
⇒ starburst galaxies.

→ Modeling the spectra of elliptical galaxies provides supporting evidence of distinct episodes of past star formation.

Are there enough collisions to explain the evolution of galaxies from $S_s \to E_s$?

Assume objects passing within $2R$ have collided, consider the volume swept out by a galaxy in unit time:

$$V = \pi (2R)^2 v t$$

(v: velocity, t: time.)

Number of collisions (neglecting grav. attraction).

$$N = nV = n\pi (2R)^2 v t$$

(n: number density of galaxies)

set $N = 1$, the mean time between collisions

$$t = \frac{1}{n\pi (2R)^2 v}$$

① For stars in an E,

$n \sim 1\,pc^{-3}$ $R \sim 10^9\,m$ $v \sim 200\,kms^{-1}$

$\Rightarrow$ $t = 3\times10^{17}\,yrs = 3\times10^{7}$ Hubble times!

$\Rightarrow$ collisions are not important in stellar evolution.

② For galaxies in groups, e.g. Milky Way,

$n \sim 1\,Mpc^{-3}$ $R \sim 20\,kpc$ $V \sim 150\,kms^{-1}$

$\Rightarrow$ $t \simeq 10^{12}\,yrs \simeq 100$ Hubble times.

$\Rightarrow$ consistent w. groups dominated by Ss, but containing some Es.

③ For galaxies in rich clusters, typically 10s - 100s giant galaxies,

$\Rightarrow$ $t \sim 10^{10}\,yrs \simeq$ Hubble time.

$\Rightarrow$ consistent with most galaxies in clusters having collided.

What happens to the gas in mergers?

- → some forms stars in starbursts.
- → some ejected
- → might still expect some gas to survive in Es.

Recall $\sigma = \left(\frac{3}{5}\frac{GM}{R}\right)^{1/2}$

velocity dispersion independent of mass of particles

so in a virialised system (stirred up, orbits randomised) we expect the gas to have the same σ as the stars ⇒ heated.

$$\bar{K} = \tfrac{1}{2} \mu m_p \sigma^2 \simeq \tfrac{3}{2} kT$$

μ — mean molecular weight $\simeq \tfrac{1}{2}$ for ionised hydrogen.

m_p — mass of a proton.

$$\Rightarrow T \simeq \frac{m_p \sigma^2}{3k} \simeq 10^6\,K \quad !$$

So the hot gas won't be visible at 21cm.
And is too hot to collapse to form stars.

14.15.5

Expect X-ray emission due to cooling of the plasma by bremsstrahlung emission.

Hot gas is observed filling the volume of Es.

Hot things tend to cool quickly if optically thick, $L_{BB} \propto T^4$

Bremstrahlung emissivity: ($W m^{-3}$)

$$\mathcal{L}_\nu = 1.4 \times 10^{-40}\, T^{1/2}\, n_e^2$$

↑ electron density.

14.16.0

Total energy in the gas

$$\tfrac{3}{2} NkT = \tfrac{3}{2} V \underbrace{(n_e + n_i)}_{N} kT = \underline{3 V n_e kT}$$

Equate with cooling:

$$3 V n_e kT \simeq \underbrace{1.4 \times 10^{-40}\, T^{1/2}\, n_e^2}_{\mathcal{L}_\nu} V\, t_{cool}$$

$\Rightarrow t_{cool} \simeq 5\times10^{17}\,s = 1.5\times10^{10}\,yrs$ = Hubble time!

So gas cools very slowly, all Es should have hot gas, explains why they not forming stars.

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5. Active galaxies / galactic nuclei

→ Seyfert, 1943, discovered that 1% of nearby Ss have a bright point source at the centre
→ Seyfert galaxies.

→ Optical spectra show intense broad emission lines
⇒ high velocity ionised gas.

→ Two distinct types

Type I – v. broad lines (1000_s km s^{-1})

Type II – relatively narrow lines (100_s km s^{-1})

→ Also found to be X-ray sources

Type I – unabsorbed X-ray spectra

Type II – strongly absorbed X-ray spectra.