PX 269: Galaxies

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Disclaimer:
This revision guide has been set up to help you prepare for your Galaxies exam. This is not a set of lecture notes. It is designed to provide you with the key concepts you need to grasp in this module. As such, there may well be examinable material that, for the sake of brevity, is not covered in this revision guide. Furthermore, while the utmost care has been taken to ensure the reliability of this revision guide, the Mathematics and Physics Society cannot guarantee that this guide is completely accurate. We therefore recommend you use this guide as a support and not the entirety of your revision. Good luck!

Part 1: Historical Overview

The course started with a short history lesson and introduced Hubble.

In 1924, Hubble discovered Cepheid Variables in M31, they are **standard candles** (an astronomical object with a known luminosity) and can determine distance.

$$m - M = 5\,log_{10}\,d(pc) - 5$$

Where m is the apparent magnitude and M is the absolute magnitude

In 1929, Hubble discovered the expansion of the Universe. He did by plotting radial velocity against Cepheid Distance of different galaxies. Hubble showed:

$$v_r = H_0 d$$ where H_0 is the Hubble Constant.

This also implies a characteristic age and size of the observable Universe (assuming constant expansion):

$$Hubble\ time = \frac{1}{H_0} = 14Gyr \qquad Hubble\ Radius = \frac{c}{H_0} = 4300Mpc$$

Red shift (z) is now a common proxy for distance:

$$1 + z = \frac{\lambda_{obs}}{\lambda_{emit}} \qquad z = \frac{\Delta\lambda}{\lambda_{emit}} \simeq \frac{v}{c} \qquad cz = H_0 d$$

Part 2: Classifications of galaxies

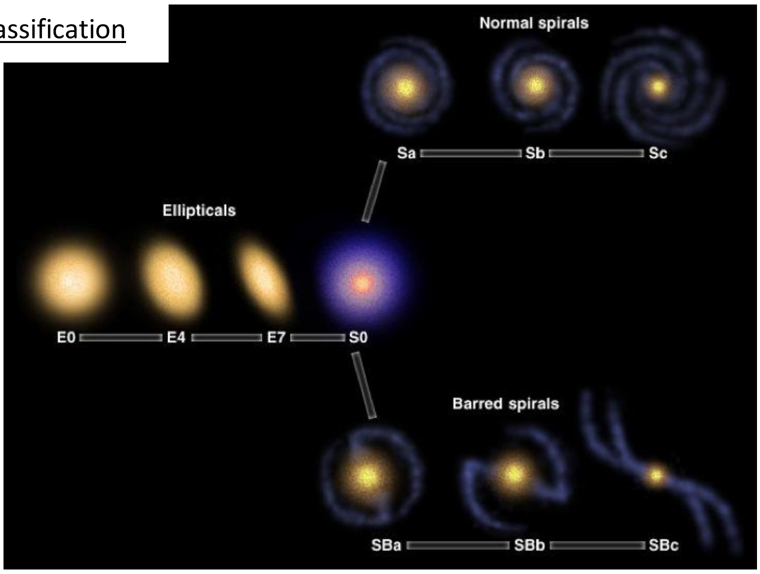
There are 3 main types of galaxies and I found the best way to learn and remember them was to annotate the Hubble Classification Diagram.

3 main types:

- Spiral (**S**): disc morphology, spiral structure. Red bulge in centre with a blue disc.
- Elliptical (**E**): elliptical morphology, often red
- Irregular (**Ir**): irregular morphology, but flat/disc like. Blue usually without bulge.

All types of stars tend to form together: $L \propto M^3$ but $\tau_{ms} \propto \frac{M}{L} \propto M^{-2}$ this implies massive stars die young (they use their fuel up more quickly).

Part 2.1: Hubble Classification



The proportion of different galaxies is 60% Ellipticals, 30% Spirals and 15% Irregulars (*I know it doesn't add up to 100... shows how good Physicists are at maths*).

Elliptical Classifications: The Hubble Classification depends on viewing angle.

Faintest	**dSph**: Dwarf Spheroidals	$L{\sim}10^{-4}L_*$
	dE: Dwarf Ellipticals	$L{\sim}10^{-2}L_*$
	E/gE: Ellipticals	$L{\sim}L_*$
Brightest	**cD**: Central galaxies in Galaxy Cluster	$L{\sim}25L_*$

Spiral Classification: $L \sim L_*$ Spirals have a more narrow range than Ellipticals. However the spiral pattern does correlate with luminosity.
High Luminosity Spirals: Prominent Spiral often called "Grand Design Spiral"
Low Luminosity Spirals: Weaker, fractured spiral structure, often called "flocculent"
The lowest luminosities run into Irregular galaxies.
NB; $L_*$is characteristic luminosity, i.e. $L_{MilkyWay}$

Part 2.2: Describing Galaxies
Sizes of galaxies:
Difficult to define due to lack of obvious edge, usually use half-light radius or effective radius R_e.
S/E: $R_e \sim 10Kpc$, **cD:** $R_e \sim 100Kpc$, **dE/dSph:** $R_e \sim 200Kpc$

Surface Brightness Profiles $\mu(R)$
Spirals Disk Profiles: $I(R) = I_0 e^{-R/a}$ I is Intensity, I_0 is Intensity at centre and a is a scale length
In magnitude; $\mu(R) = \mu_0 + 1.086\left(\frac{R}{a}\right)$
dE & **dSph** also show exponentially profiles

Elliptical Profiles: $I(R) = I_0 e^{-\left(\frac{R}{a}\right)^{\frac{1}{4}}}$ This is attributed to **E/gE/cD**, peaked towards the centre
In magnitude; $\mu(R) = \mu_0 + 1.086\left(\frac{R}{a}\right)^{\frac{1}{4}}$
This profile is also found in the bulges of Spirals
Total Luminosity is determined by integrating: $L(R_{MAX}) = \int_0^{R_{MAX}} 2\pi R I(R) dR$

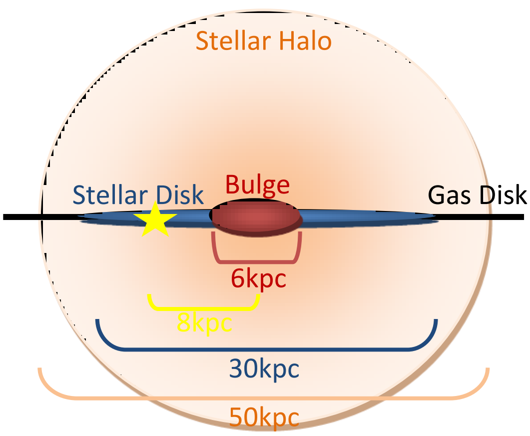
Luminosity Function: Number of Galaxies Vs Luminosity
The Schechter Function: $\phi(L) = \frac{\phi_*}{L_*} e^{-\frac{L}{L_*}} \left(\frac{L}{L_*}\right)^{\alpha}$ α= Power Law Index ≈-1.2
Total Luminosity Density can be estimated by integrating : $\mathcal{L} = \int_0^{\infty} L\phi(L)dL$
Total Number Density shows it diverges: $n = \int_0^{\infty} \phi(L)dL$

Part 3: Spiral Galaxies and the Milky Way

Total Surface Brightness Profile (Disk + Bulge): $I(R) = I_{0,D} e^{-R/a_D} + I_{0,B} e^{-\left(\frac{R}{a_B}\right)^{\frac{1}{4}}}$
Disk is dominated by blue, young stars ≡ Population I
Bulge is dominated by red, old stars ≡ Population II
NB; Population III stars are postulated to have formed early in Universe, massive but short-lived.

Mapping the Galaxy;
- The first map of the Milky Way was made by from counting stars, then knowledge of HR Diagram was introduced but still put the Sun near the centre of the galaxy.
- Discrepancies resolved by understanding dust extinction in the Interstellar Medium (ISM)
- Use the Distance Modulus: $m - M = 5\,log_{10}\,d(pc) - 5 - A_{\lambda}$ with A_{λ}= Extinction (1mag kpc^{-1})

Part 3.1: Galactic Structure
Stellar Disk is 1kpc in height



Part 3.2: Galactic Components

Stellar Components

- Population I: young stars found in disk, where there is ongoing star formation
- Population II: old stars found in Galactic Halo,

Non-Stellar Components

- Gas
- Interstellar Dust
- Dark matter
- Hydrogen: Hydrogen gas exists in 3 states:
  - Molecular (H_2): this form has no 21cm transition & very hard to detect.
  - Atomic (HI): most common form of hydrogen and only excited at high temperatures. All HI in Universe radiates at 21cm.
  - Ionised Gas (HII): Most visible emitting strong recombination emission lines. The size of the HII region is found by setting he balance between ionisation & recombination

Part 3.3: Star Formation Indicators

1. UV light from massive (short lived) stars
2. H_α emission from HII regions. Particularly useful for low z galaxies
3. Strong IR emission from dust heated by obscured massive stars

Galaxies with very strong 1 & 2 indicators are **Starburst** Galaxies

Galaxies with very strong 3 indicator are **ULIRGs** (Ultra Luminous IR Galaxies)

Part 4: Kinematics of Spiral Galaxies

Use Doppler Effect to map radial velocity across galaxy from $\frac{\Delta\lambda}{\lambda_{emit}} = \frac{v}{c}$ and $v = v_r \sin i$, where i is inclination.

This is assuming the galaxy is circular and comparing the projected semi-major & minor-axis.

Discs are supported against gravity by rotation but the bulge is supported by pressure.

In galaxies the mass is not concentrated at the centre.

$$M(< R) = \frac{v^2 R}{G}$$

is the enclosed mass of an orbit. E.g. for a typical spiral $M(< 20kpc) = 3 \times 10^{11} M_\odot$

$$\frac{dM}{dr} = \frac{v^2}{G} = constant$$

This shows that rotations curves are flat out to the edge of the observable galaxy, which means it is a constant mass per radius.

Now compare

$\frac{dM}{dr} = \frac{v^2}{G} = 2\pi rt\rho \Rightarrow \rho(R) = \frac{v^2}{2\pi tRG} \propto \frac{1}{R}$ and Surface Brightness Profile $\propto e^{-R/a}$

This difference can only be explained by **DARK MATTER!**

We assume dark matter is spherically symmetrically distributed $\rho(R) = \frac{v^2}{4\pi G R^2} \propto \frac{1}{R^2}$

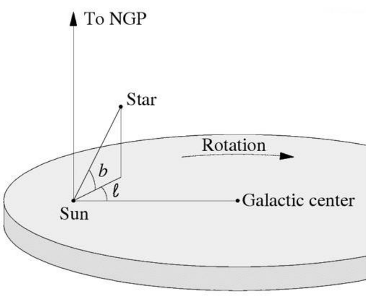
Part 4.1: Kinematics of the Milky Way

1) **Proper Motion**: motion of a star wrt distant stars v_t (transverse velocity)measure angular velocity $\mu = \frac{d\theta}{dt} = \frac{v_t}{d}$ so need distance to the star
2) **Radial Velocity**: from Doppler shift

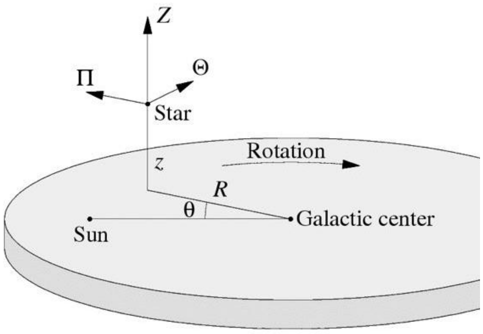
Combining both creates a 3D velocity for nearby stars .

Part 4.2: Galaxy Coordinates

Sun-Centred Coordinates:



Galaxy Centre Coordinates:



To calculate the rotation of Milky way, we are required to be able to see large distances and measure velocities. The single spectrum along the line of site contains many clouds. To calculate the distance and hence velocity of the stars, we need to know the distance to the cloud which is blocking the view.

Part 5: Dark Matter

What is Dark Matter? (not normal stars, dust or gas)

2 Main Candidates:

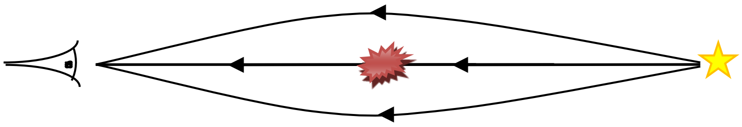
MACHOS; Massive Compact Halo Objects

Normal Inorganic matter e.g. planets, white dwarfs, Black Holes

WIMPS; Weakly Interacting Massive Particles

Exotic elementary particles, with mass which interacts weakly with other matter, apart from gravity.

Searching for MACHOS using Microlensing



When the MACHO and the stars are perfectly aligned, gravitational lensing occurs, amplifying the light of the background star.

WIMPS are most likely candidate for DM, survey of Milky Way Halo found MACHO's in the galactic halo but nowhere near enough to account for the amount of dark matter around the Milky Way.

Part 6: Active Galaxies

In 1943, Seyfert noted that approximately 1% of nearby galaxies have a bright point source at the centre.

Seyfert Galaxies are an example of a Radio-Loud Active Galaxy, usually these are spirals.

The optical spectra dominated by intense emission lines;

Type I: have very broad lines & Type II: relatively narrow lines

They are also X-Ray Sources;

Type I: unabsorbed X-Ray Spectra & Type II: strong photoelectric absorption

Part 6.1: Nature of Active Galaxies

AGN (**Active Galactic Nuclei**)

1st Constraint: variability places a limit of the size of an object. $\Delta t = \frac{R}{c}$

2nd Constraint: luminosity places a limit on the mass

The luminosity of the object is usually less than the **Eddington Luminosity,** the luminosity limit at which radiation pressure force balances gravitational force.

$$\frac{\sigma_T L}{4\pi r^2 c} = \frac{GMm_p}{r^2} \Rightarrow L_{Edd} = \frac{4\pi GMm_p c}{\sigma_T} = 1.5 \times 10^{31} \frac{M}{M_\odot} W$$

where σ_T = Thompson Scattering Cross section

Schwarzchild Radius of a Black Hole Horizon can be estimated by equating c with escape velocity:
$\boldsymbol{R_s = \frac{2GM}{c^2}}$
Energy source for AGN must be accretion (the release of GPE from falling material): $\boldsymbol{E_{acc} = \frac{1}{2}mc^2}$

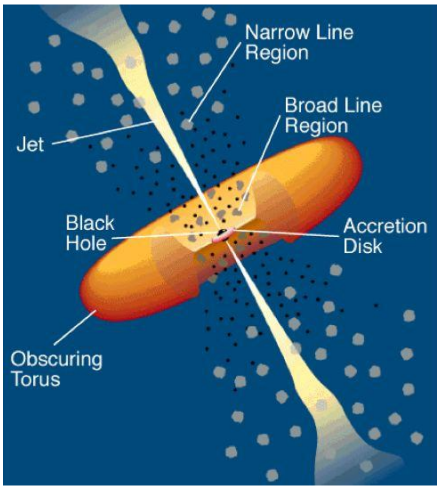
Part 6.2: Two Other Types of AGN's

1) **Radio galaxies**: Brightest sources in the sky, powered by jets from central galaxy. Most are elliptical galaxy whereas

Broad Line Radio Galaxies (BLRGs): Type I
Narrow Line Radio Galaxies (NLRGs): Type II

2) **Quasi-Stellar Radio Sources- QUASARS**: bright, point like objects with strong radio emissions. Optical spectra, emission lines, with strong red shift.

Part 6.3: The Unified Model of AGN



High Velocity Clouds in the Broad Line Regions.
Low Velocity Clouds in the Narrow Line Regions.

Part 7: Super Massive Black Holes in Normal Galaxies

All giant galaxies were once active galaxies and all with SMBHs
Observations in IR with adaptive optics of the Milky Way suggest that there are high velocity stars very close to the Galactic Centre. We can calculate the enclosed mass of each orbit and using Kepler's 3rd Law we know that there must be a black hole at the centre of the Milky Way.

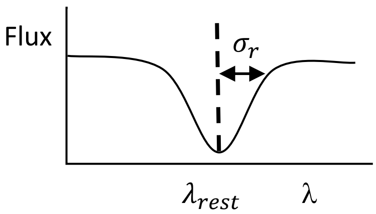
Part 7.1: Correlation between M_{BH} – σ Relation

$$\boldsymbol{M_{BH} \propto \sigma^4}$$

Elliptical & spirals bulges are not dominated by rotation, unlike spiral discs where we see Doppler Broadening.
Width of the gap tells us about the range of velocities.

$\boldsymbol{\sigma = \sqrt{\frac{1}{N}\sum_{i=1}^{N} v_i^2}}$ $\qquad$ $\boldsymbol{\sigma^2 = 3\sigma_r^2}$

Standard deviation of Velocities = Velocity Dispersion σ
Where σ_r is the radial velocity dispersion.



You can use σ to measure the mass of elliptical galaxy:

$$\boldsymbol{K = \tfrac{1}{2}mv^2 = \frac{GMm}{2R} \;\&\; U = -\frac{GMm}{R} \Rightarrow -2K = U}$$ **The Viral Theorem**

This remark holds for all gravitationally bound systems in equilibrium.
It links observable velocities of stars to gravitational potential and hence mass.
Assume all stars have the same mass $\quad \boldsymbol{M = Nm \;\Rightarrow\; -2K = -M\sigma^2}$
We get potential energy by summing shells assuming spherical symmetry;

$$dV_r = \frac{-GM(<r)m}{r}, \qquad m = 4\pi r^2 \rho dr, \qquad M_r = \tfrac{4}{3}\pi r^3 \rho \;\Rightarrow dV_r = \tfrac{16}{3}G\pi^2\rho^2 r^4$$

$$U = \int dV_r \quad \Rightarrow \quad U = \frac{3}{5}\frac{GM^2}{R} \quad \Rightarrow \quad \sigma = \left(\frac{3}{5}\frac{GM}{R}\right)^{\frac{1}{2}}$$

So Velocity Dispersion doesn't depend on the mass of the particles.

M_{BH} is negligible (10^6-10^9 $M_\odot$) compared to mass of whole galaxy (10^{11} $M_\odot$), there is a fundamental link between formation of a galaxy and formation of a super massive black hole.

Part 7.2: Gas in Elliptical Galaxies

Gas in Ellipticals was discovered using X-Ray telescopes. The gas is too hot to form new stars, the high temperatures come from randomisation/virialisation of orbits of gas.

$\frac{1}{2}m_p v^2 = \frac{3}{2}kT$

Spirals galaxies have large bulk velocity but low velocity dispersion ⇒Cool Gas

Ellipticals galaxies have low bulk velocity but high velocity dispersion ⇒ Hot Gas

The difference is from the Ellipticals have been stirred up but Spirals are ordered.

Part 8: Distances to Galaxies

Concept of the **Cosmic Distance Ladder**, 2 types of methods: geometric & standard candles

1) Parallax (Geometric Method); $tanp = \frac{1AU}{d}$
2) Cepheid Variables; standard candles method using knowledge of luminosity of an object
3) Spectroscopic Parallax/Main Sequence Fitting; standard candle method again but using main sequence stars
4) Supernovae Shell Expansion; only works for nearby supernova $d = \frac{age \times v_r}{\theta}$
5) Supernovae as Standard Candles; very luminous so can reach large distance.
   - Core collapse of SN are poor standard candles however type Ia SN are good standard candles.
6) Tully-Fisher Relation; using spiral galaxies as standard candles
7) Red shift die to expansion of Universe; as a proxy for distance, calibrated by other methods.
   - Discovery that expansion of Universe: its accelerating

Part 9: Spatial Distribution of Galaxies

Not evenly distributed in space, most are either in groups or clusters

Groups: <50 Galaxies, only a few giant clusters. Dark Matter Dominated!

R= 1.5Mpc σ = 150ms^{-1} $M(<R) = \frac{5}{3}\frac{R\sigma^2}{G} \Rightarrow M_{Groups} = 10^{13}M_\odot \Rightarrow \frac{M}{L} = 250\frac{M_\odot}{L_\odot}$

Clusters: number of galaxies; poor = 50- 1000 = rich. Very Dark Matter Dominated!

R= 6Mpc σ = 800ms^{-1} $M_{Cluster} = 10^{15}M_\odot \Rightarrow \frac{M}{L} = 400\frac{M_\odot}{L_\odot}$

Collisions between spirals are thought to randomise orbits of stars and gases, implying is it virialised. We often see evidence of collisions; often see 2 spiral bulges extended tidal tails of gas & stars. Looking at Luminosity Functions vs Density, it shows that a small fraction of spirals collide in Groups, but most galaxies have collided at least once in regular clusters.

Part 9.1: Time between Collisions

We neglect gravitational attraction and assumer a collisions occur if galaxies pass within 2R

In time t, a galaxy sweeps out a volume $V = \pi(2R)^2vt$, then the number of collisions is $N = nV$, where n is the density of galaxy.

Set N=1 and calculate the time required for 1 collision to occur; $t = \frac{1}{n\pi(2R)^2}$

- Stars in a galaxy: t=3x10^{17}years Stars never collide, even in galaxy mergers

- Galaxies in Groups: $t=10^{12}$years Most galaxies have no collided
- Galaxies in Clusters: $t=10^{10}$years Most galaxies in clusters have suffered a collision