ASTR368
Galaxies! Chapter 25.

What is a galaxy? A collection of stars, gas, dust (and dark matter) that are gravitationally bound together.

First observations found lots of these (some in Messier catalog; Herschel found a bunch; New General Catalog has thousands). As telescopes improved, more found.

Debate over where they were located - in our Galaxy our outside of it. Shapley/Curtis Great debate 1922. Shapley thought inside our own Galaxy, Curtis thought outside. Reasonable arguments for both (given the data at the time), but obviously outside is correct. Hubble confirmed this by observing Cepheids in Andromeda in 1923. The distance to Andromeda must be very large, not possibly within our own Galaxy.

Types of Galaxies

Three main types: spirals, ellipticals, and irregulars.

Other types: cD, dwarf spheroidals, dwarf ellipticals, lenticulars (in between spirals and ellipticals)

This diversity in galaxy types indicates differences in their formation and evolution.

Spirals

Like the MW. Can have bar. Well-defined spiral arms where star formation is present. Bulge. Ordered rotation.

Ranked from Sa to Sc. (if bar, has B added to create SBa to SBd, intermediate classes Sba, etc.). Milky Way SBbc.

This ordering takes into account - bulge to disk (total light) ratio (higher in Sa than Sd)
- how tightly wound the arms are (higher in Sa than Sd).
- Bulge to disk ratio and arm winding are correlated (not necessary the case).
- The "Pitch Angle" tells you how tightly the spiral arms are wound. Defined as angle between spiral arm direction and line tangent to spiral arm. A higher pitch angle means more tightly wound.

All these are correlated - otherwise the classification scheme would be worthless!

Ellipticals

Triaxial shape, not spherical, more like a football. Few young stars. Best analogy is a spiral bulge. No well-defined rotation. Extremely large range of masses

Categorized based on ellipticity, $\epsilon = 1 - \beta/\alpha \times 10$; where β is projected semiminor axis and α is projected semimajor axis: E0 to E7. $\epsilon = 0$ for perfectly circular, $\epsilon = 0.7$ is maximum ever found. Obviously, depends on observed direction.

Lenticulars

Are in between spirals and ellipticals. Look like ellipticals but have characteristics of spirals. Ranked S0. Dust but no gas. Not much star formation. Possibly due to mergers that erased spiral arms.

Irregulars

No well-defined structure. Ranked Im ("magellanic-like") or Irr (truly irregular). Tend to have lots of star formation given their masses.

Others

cD: enormous ellipticals at the center of clusters of galaxies

dwarf ellipticals (dE): smaller than other ellipticals. Little to no gas or dust.

dwarf spheroidal (dSph): just like dE, but spherical.

Blue compact dwarf (BCD): very luminous blue elliptical galaxies with lots of gas and dust (strange for ellipticals)

And many more! We keep defining galasies based on their observational characteristics, and in the distant Universe Galaxies had different morphologies.

Hubble's tuning fork

Thought by Hubble to be evolutionary sequence, but it's not. "Early-type" is relic of this thinking, and refers to ellipticals; "late type" to spirals (esp. Sc).

de Vancouleur sub-divided so - SA (capital A) have no bar
- SB have bar
- SAB have weak bar
- (r) for ring
- (s) for "s"-shaped
- So-called "transition" galaxies are given the symbol (rs)
- added Sd that have "flocculant" arms, little to no bulge, Sm (irregular, "Magellanic"), Ir (highly irregular)
- Lenticular galaxies classified as unbarred (SA0) or barred (SB0), with the notation S0 reserved for those galaxies for which it is impossible to tell if a bar is present or not (usually because they are edge-on to the line-of-sight).

Visually, the de Vaucouleurs system can be represented as a three-dimensional version of Hubble's tuning fork, with stage (spiralness) on the x-axis, family (barredness) on the y-axis, and variety (ringedness) on the z-axis.

List of common galaxies with their classifications: https://en.wikipedia.org/wiki/List_of_spiral_galaxies

Galaxy characteristics Look at tables 25.1, 25.2, 25.3

B-band magnitude. Dominated by young stars. Ellipticals have large range. How to convert from magnitude to number of stars? $M_{V,\odot} \approx 5$.

Mass. Note that mass range of 100 is magnitude range of 5

M/L ratio. What is this telling us? Massive stars emit lots more light per unit mass. Therefore they will have low M/L ratio. Since massive stars also evolve much faster than low-mass stars, this is a proxy for age of stellar population.

VMax. What is this telling us? Larger galaxies rotate faster (see homework). Ellipticals have no ordered rotation.

B-V Color. This is the difference between the integrated blue and visual magnitudes. High values mean what? If B is higher, less blue.

$M_{\rm gas}/M_{\rm total}$ is measure of star formation potential

Schechter Luminosity Function

This tells us the relative number of galaxies of various luminosities, with all galaxy types summed into one distribution.

$$\Phi(L)dL = \left(\frac{\Phi^*}{L^*}\right)\left(\frac{L}{L^*}\right)^{\alpha} \mathrm{e}^{-(L/L^*)}dL \tag{1}$$

Where the asterisks indicate typical values and the alpha is a power law index at low luminosities. The units of ϕ are usually given in Mpc^{-3}, and this is the volume density of galaxies that have luminosities between L and $L + dL$.

Nothing fundamental about this. The real power here is that we can look at this relation for various environments.

From figure: dEs and dwarf irregulars are the most common. This is like for stars - least massive are the most common

S and Es are the most conspicuous. Virgo has more ellipticals - mergers? Larger clusters have even more Es!

Nearly three quarters of local galaxies are spirals. "Local" key here because the percentage of spirals changes with time. How can we explain their spiral structure?

Light Distributions

Let's say that I is the measured intensity. I_0 is I in the center of the galaxy.

For Ellipticals,

$$I \simeq I_0 \left(\frac{r}{r_0}\right)^{-1/4} \tag{2}$$

This is known as the deVaucouleurs $r^{-1/4}$ profile. The book defines these in terms of surface brightness, or magnitude per square arcsecond, which is the same thing. Note that this follows a straight line in a log-linear plot.

More general Sersic profile:

$$I \simeq I_0 \left(\frac{r}{r_0}\right)^{-1/n} \tag{3}$$

Massive ellipticals have index of $n = 4$, while discs of spirals have Sersic index near $n = 1$.

Bulges of spiral galaxies follow $n \simeq 4$, just like ellipticals Smaller ellipticals more like spirals - points to different formation scenarios.

Galaxy Rotation

Just like the Milky Way, galaxies rotate! What kind of galaxies rotate? Spirals! (some irregulars) Stars in ellipticals do not have ordered rotation.

What can we learn from this rotation? Mass!

How can we trace the rotation? Measure V_r from the Doppler shift? We need an emission line. H I probably the best, maybe $H\alpha$ or CO.

OK, so now we know how to measure V_r. Unfortunately, galaxies are inclined (draw inclination geometry, show slide)
Face-on ($i = 0\,^\circ$)
Edge-on ($i = 90\,^\circ$)
This leads to

$$\frac{\Delta\lambda}{\lambda_{\rm rest}} \simeq \frac{V_r}{c} = \frac{V \sin i}{c} \tag{4}$$

Or in terms of components of the velocity, we measure

$$V_r = V_0 + \Pi(R,\theta)\sin\theta\sin i + \Theta(R,\theta)\cos\theta\sin i + Z(R,\theta)\cos i\,, \tag{5}$$

where V_0 is the systematic velocity, caused by Universe expansion (more on this later!), Π, Θ, and Z have their usual definitions. If $i = 0\,^\circ$ (faceon), only get Z. If $i = 90\,^\circ$ (edgeon), do not get Z. We can usually assume axisymmetric, so no θ-dependence.

For pure rotation with no out of plane or motion toward or away from galactic center

$$V_r(\rho,\phi) = V_0 + \Theta(R)\cos\theta\sin i \tag{6}$$

If $i = 0\,^\circ$ (faceon) we just get systematic velocity.

Many galaxies are not resolved, and in such cases we get a double horned profile. What does this tell us? There is a lot of matter moving at particular velocities (the horns). The rotation curve must be flat. The distance between the horns is basically twice the rotation speed.

"Velocity dispersion" is the rms of velocity distribution,

$$\sigma = \langle v^2 \rangle^{1/2} \tag{7}$$

Show examples

How are these observations used?

1) Get velocity field
2) Cut across major axis
3) Fold, account for i. $V_{\rm rot} = V_r/\sin i$.

This gives you a rotation curve. Who cares? You can get $V_{\rm max}$, which is related to the mass (and luminosity) of the galaxy.

If we set circular centripital acceleration equal to gravitational acceleration:

$$\frac{V^2}{R} = \frac{GM_r}{R^2} \tag{8}$$

Solve for V:

$$V = \left(\frac{GM_r}{R}\right)^{1/2} \tag{9}$$

Solve for M_r:

$$M_r = \frac{V^2 R}{G} \tag{10}$$

So velocity and mass are related. If we make the additional assumption that all spirals have the same mass to light ratio, $M/L =$ constant, and since we are only concerned with the total mass, we want the maximum velocity V_{max}

$$L \simeq \frac{V_{\text{max}}^2 R}{G} \tag{11}$$

and if we finally make the assumption that all spirals have the same surface brightness, $L/R^2 =$ constant so

$$R \propto L^{1/2} \tag{12}$$

and

$$L \propto V_{\text{max}}^4 \tag{13}$$

This is known as "Tully-Fischer relationship." Real power is that it turns all Galaxies into standard candles! We saw how powerful standard candles are for SN Type Ia and Cepheids. All we need do is measure V_{max} and we can approximate the luminosity (and therefore mass).

Faber-Jackson is elliptical version of TF. We can derive it! Start with Virial theorem: $2K + U = 0$.

For kinetic:

$$K = 1/2Nm\Sigma v^2 \tag{14}$$

(This is defined per particle, thus the little m). For ellipticals, we can't measure Σv^2 because of the lack of ordered rotation, but we can measure the velocity dispersion, $\langle\sigma\rangle$. This is simply the standard deviation of the velocities, $\sigma = \langle v^2\rangle^{1/2}$. We can measure this from the width of a spectral line, for example. So

$$K = 1/2m\langle\sigma^2\rangle \tag{15}$$

What is U?

$$U = -4\pi G \int M_r \rho r dr \tag{16}$$

and if we assume $M_r = 4/3\pi r^3 \rho$, we get

$$U = -\frac{3}{5}\frac{GM^2}{R} \tag{17}$$

Therefore, solving Virial, we find

$$M\langle\sigma^2\rangle = \frac{3}{5}\frac{GM^2}{R} \tag{18}$$

One complication is that we only measure one component of the velocity dispersion:

$$\langle\sigma^\rangle = \langle\sigma_r^2\rangle + \langle\sigma_\theta^2\rangle + \langle\sigma_\phi^2\rangle = 3\langle\sigma_r^2\rangle \tag{19}$$

(if we assume isotropic velocity distribution). We only measure the radial component of course. Putting it all together:

$$M = \frac{5R\langle\sigma_r^2\rangle}{G} \tag{20}$$

This is a classic result!!

If we again assume that $M/L \propto$ constant, and $L/R^2 \propto$ constant,

$$L \propto L^{0.5}\sigma_r^2 \tag{21}$$

or

$$L \propto \sigma_r^4 \tag{22}$$

We get essentially the same relation as we had for spirals. The dispersion however is much greater. The exponent does depend on the sample of galaxies (types of ellipticals). The basics are true though. Larger galaxies have a larger velocity dispersion.

Spiral Structure

Spiral arms can be “grand design” or “flocculant”.
Grand design: two well-defined symmetric arms (M51)
“flocculant”: lots of small arm segments (NGC2841)

They can also have multiple-arms (> 2; M101; 4 is most common) or just 2.

Spiral galaxies rotate. In what direction? Are spiral arms leading or trailing? How can we check? They are basically all trailing, although there are some instances where one arm appears to be leading, but this is due to tidal interactions.

How do spiral galaxies rotate? What is Θ? Constant-ish. What is Ω? $\Omega = \Theta/R$. If Θ = constant, then $\Omega \propto 1/R$. What does this mean? Interior parts of galaxies rotate more frequently. Outer parts rotate less frequently, even though they are all moving at the same velocity.

This is a problem? If spiral arms are “real” structures, the interior parts of spiral arms will rotate faster than the outer parts. Very quickly everything will be all wound up. This is known as the “winding problem” for spiral arms.

How can we solve this? If spiral arms are not real structures. This is known as the “Lin-Shu hypothesis.” Spiral arms are “quasistatic density waves.” This is really the same as a traffic jam.

These density waves are over densities of just a few percent in stars, but 20% in terms of gas and dust.

These arms have a constant angular velocity, $\Omega_{\rm gp}$, the “global pattern speed.”

If the stars are going as $\Omega \propto 1/R$ and the arms are as $\Omega \propto$ constant, what happens?

Stars near the center of the Galaxy have $\Omega > \Omega_{\rm gp}$ and pass through the arms! There is a single radius where $\Omega = \Omega_{\rm gp}$, known as the “corotation radius.” Stars exterior to the corotation radius lag behind the spiral arm.

What do we know about spiral arms? What if the Lin-Shu hypothesis is correct? What do we expect?
Spiral arms have OB stars. Where are these stars born? In spiral arms! Then why are they not found outside of the arms? Lifetime too short!
What about red stars? Why are they outside of arms? Lifetime long!
What about gas clouds? They are found on the leading edge of spiral arms (show M51).

How do the arms form stars?
Spiral arms are small overdensities of gas and dust. As such they are gravitational potential minima. As gas clouds near the arms on their orbits, they are gravitationally attracted in to the arm and pulled in. They are then compressed and interact with other clouds within the arm to form stars before passing out of the arm.

What are the orbits of stars like?
The book does a nice derivation, but we'll skip to the results.
Stars follow simple harmonic oscillator motion in the $\hat{R}$ and $\hat{z}$ directions:

$$\rho(t) = A_R \sin(\kappa t)\,, \tag{23}$$

where A_R is the amplitude and κ is the epicycle frequency. Similarly:

$$z(t) = A_z \sin(\nu t + z_i)\,, \tag{24}$$

where A_z is the amplidude, ν is the vertical oscillation frequency, and z_i is the phase offset between $\rho(t)$ and $z(t)$. Finally:

$$x_i(t) = (2\Omega/\kappa) A_R \cos(\kappa t) \tag{25}$$

in the azimuthal direction.

Closed orbits

Stellar orbits are of course not usually closed, but we can always choose a pattern speed where the orbit is closed. In these orbits, the star completes n orbits while executing m epicycle orbits, after which time the star is back at its starting point. Thus,

$$\Omega_{\rm lp}(R) = \Omega(R) - \frac{n}{m}\kappa(R)\,, \tag{26}$$

where $\Omega_{\rm lp}$ is the local pattern speed, the pattern speed that causes a star's orbital motion to be that just of the epicycle.

Now assume a spiral galaxy with global angular pattern speed $\Omega_{\rm gp}$. If for example $(n, m) = (1, 2)$ and if $\Omega_{\rm lp}$ is not a function of R, $\Omega_{\rm gp} = \Omega_{\rm lp}$ and the orbital patterns are nested, creating a bar-like structure. Twisting these orbits then gives rise to a two-armed spiral pattern.

But is there a value of Ω that is valid over the entire disk? Not really, but

$$\Omega_{\rm lp} = \Omega - n\kappa/2\,, \tag{27}$$

or $(n, m) = (1, 2)$ is flat over most of the disk. For these parameters, the pattern can be long-lived.

Resonances develop in the pattern at specific angular pattern speeds. These resonances arise when stars always encounter the spiral wave at the same point in their orbits, so they are push into/pulled out of the density wave in the same manner each orbit.

Inner Lindbladt Resonance

When the local angular pattern speed of the star equals the global angular pattern speed for the case when $\Omega_{\rm gp} = \Omega - \kappa/2$ for $n/m = 1/2$.

Corotation radius

When $\Omega_{\rm gp} = \Omega$

Outer Lindbladt resonance

When $\Omega_{\rm gp} = \Omega + \kappa/2$

These resonance locations could dramatically increase collisions of gas clouds, which would dissipate energy, and damp the spiral waves.