Galaxies: dynamics, masses, and formation

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Overview

• Spiral galaxies rotate; this allows us to measure masses
• But there is also a problem: spiral arm winding
• Elliptical galaxies do not rotate, but we can still estimate the typical random velocity to get masses
• In both cases we see evidence for dark matter
• How do galaxies form? We will look at some basic ideas

Measuring rotation

Using spectral features (e.g., stellar absorption lines, ionised gas emission lines, or neutral hydrogen radio emission) we measure the Doppler shift in different parts of the galaxy.

If we see a blueshift on one side and a redshift on the other, this is a sign of rotation.

Note: this only gives us the correct velocity if the galaxy is edge-on; a face-on rotating object has no motion in the line-of-sight.

If we know the inclination angle of the galaxy, we can correct for this effect.
Example of rotation seen in ionised gas

Place slit of spectrograph across galaxy and get a spectrum at each position.

emission lines from Earth’s atmosphere at fixed wavelength

starlight from central region of galaxy

wavelength

position along slit

redshifted Hα from this side of galaxy

blue shifted Hα from this side of galaxy

Hydrogen velocity profile

21cm observations versus frequency of edge-on galaxies show their rotation clearly.

Optical image of NGC891

Radio contours on sky, averaged over all velocities

Velocity versus position along the axis of the galaxy

Blueshifted (approaching) side

Redshifted (receding) side

From Richter and Sancisi 1994

Some typical results. These curves have been measured a very long way out, where stellar light is very faint but there is still a lot of HI. Note the initial steep rise, followed by long flat portion, very similar to the Milky Way result. Is this what we expect?
Types of rotation curve

A solid body, rotating with a fixed angular rotation speed, would have velocity following

\[ V \propto R \]

Material orbiting a large central point mass, like the planets orbiting the Sun, would have

\[ V \propto \frac{1}{R^{1/2}} \]

Galaxies show

\[ V \propto \text{const} \]

This is because the material is distributed... can we get a better prediction?

Distribution of stellar mass

We saw before how the starlight from galaxies fades out gradually in a well defined way. If we assume the starlight comes from a mix of stars similar to the Milky Way, then the mass-to-light ratio \( \gamma = \frac{M}{L} \approx 2 \) in solar units. Then the brightness profile \( I(R) \) gives us an estimate of the mass profile \( m(R) \).

Consider material at radius \( R \). The gravitational forces from material at radius \( >R \) cancel out. The material inside \( R \) acts as if it was all at the centre, so we can use the trusty formula \( V^2 = GM/R \), where \( M = M(<R) \), the sum of all the mass within \( R \).

What rotation velocity profile is then predicted?

Observed vs predicted rotation curve

In central regions, rotation agrees with starlight, but at larger distances rotation is much too fast.

Note the implied mass is \( M = RV^2/G \). At large distances, the rotation velocity is ~3 times larger than the stellar-light prediction, so the total mass is ~9 times larger than the stellar mass.

Most of the mass of a galaxy is dark matter. The stars are a centrally concentrated part of the total mass.
Differential rotation

The rotation period for material varies with radius:

\[ P(R) = \frac{2\pi R}{V(R)} \]

If \( V(R) \approx \text{const} \) then stars nearer the centre have much shorter rotation periods. This suggests that the spiral arms should gradually wind up tighter.

For the Sun, \( v = 223 \text{ km/s} \) and \( R = 8.5 \text{ kpc} = 2.62 \times 10^{20} \text{ m} \)

This gives a rotation period of 234 million years, much less than the age of the Milky Way. So we have been round many times!

This prediction of tightly wind spiral arms is clearly not what we see. Why not?

Spiral arm density waves

The answer is that spiral arms are not fixed pieces of material; they are a kind of wave, specifically a "density wave".

A familiar example is clumps of cars on motorways. Cars arrive at the back and peel off at the front. The clump moves much more slowly than the cars.

The extra feature with spiral arms is that the density wave compresses gas, and triggers new star formation. This is very likely why spiral arms are bluer.

Elliptical galaxies

- Elliptical galaxies do not rotate.
- Some individual stars maybe on circular orbits, but in many different directions; other stars are on highly elliptical orbits, or more complicated orbits. The result is no net rotation.
- However the typical stellar velocity is still given by \( V^2 = GM/R \)
- How do we measure this typical velocity?
Absorption line seen in the galaxy spectrum at radius $R$ comes from all the stars in the line of sight. Some are moving away from us and stretch the line to the red; some are moving towards us and stretch the line to the blue.

The velocity spread is $\Delta V \approx c \Delta \lambda / \lambda$

This tells us the typical random velocity at $R$, and then

$$M \approx R \Delta V^2 / G$$

Just as with spirals, we find $M_{\text{total}} \approx 10 \times M_{\text{stars}}$

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Hot gas haloes

- The argument about typical random velocities applies to *atoms* just as well as it does to *stars*
- You might expect that the hydrogen atoms in a galaxy should also be moving at $\sim 200$ km/s
- How hot would that make the gas?
  - If $E_{\text{kinetic}} = E_{\text{thermal}}$ then $mv^2/2 = 3kT/2$ so $T = mv^2/3k$
  - For $v = 200$ km/s and $m = m_H$ we get $T = 1.6$ million degrees
- This should produce X-ray emission ... but surely in spirals at least, we see that most gas is *cold*?
- This is a clue to galaxy formation, and the difference between spirals and ellipticals...

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The low spin case

- Galaxies must be produced by the collapse of large clouds of gas over the history of the universe.
- First consider a cloud of mass $M$ with no net angular momentum.
- As it collapses to typical galaxy size $R$, the typical gas velocity will be given by $v = (GM/R)^{1/2}$ and the gas is very hot.
- Gas that *cools* can collapse further and turn into stars.
- Those stars will continue to move randomly, with the same average velocity.
- This is fairly much what we see in ellipticals; mostly stars with $v = (GM/R)^{1/2}$, and a smooth halo of X-ray gas
- The star formation has been efficient, so $M_{\text{hot gas}} < M_{\text{stars}}$
The high-spin case

- Now add in gas with spin. Imagine the cloud starts with radius $R_{st}$ and is slowly rotating with velocity $v_0$ at its edge. A clump of gas of with unit mass will have angular momentum $L = v_0 R_{st}$.
- As the cloud collapses, $L$ stays constant. So at any given radius $R$, the clump has velocity $v = L/R$. Rotation gradually speeds up as $R$ shrinks, like an ice skater spinning up.
- But the clump cannot rotate faster than the orbital velocity given by $v_{orb} = (GM/R)^{1/2}$.
- The collapse therefore stops at the stalling radius given by $v = v_{orb}$: this gives $R_{min} = L^2/GM$.
- The result is a cold flat spinning disc.

Galaxy formation

- The simple analysis above seems to give a rough explanation of the features of galaxies:
  - An early generation of star formation "freezes in" a spheroidal structure.
  - Left over gas cools and forms a rotating disc.
  - Continuing star formation is in the cold disc.
- But there are two main complications...
- Galaxies are dominated by dark matter:
  - How does that behave?
  - How does gas behave sitting in a dark matter potential well?
  - What is dark matter anyway?
- As we shall see later, galaxies often collide:
  - Not a neat simple collapse!
  - Not an isolated cloud ... more stuff keeps falling in...
  - How does this change things?