Spiral arms

Defining feature of spiral galaxies - what causes them?

Observational clues

Seen in disks that contain gas, but not in gas poor S0 galaxy disks.

Defined by blue light from hot massive stars. Lifetime is << galactic rotation period.

When the sense of the galactic rotation is known, the spiral arms almost always trail the rotation.

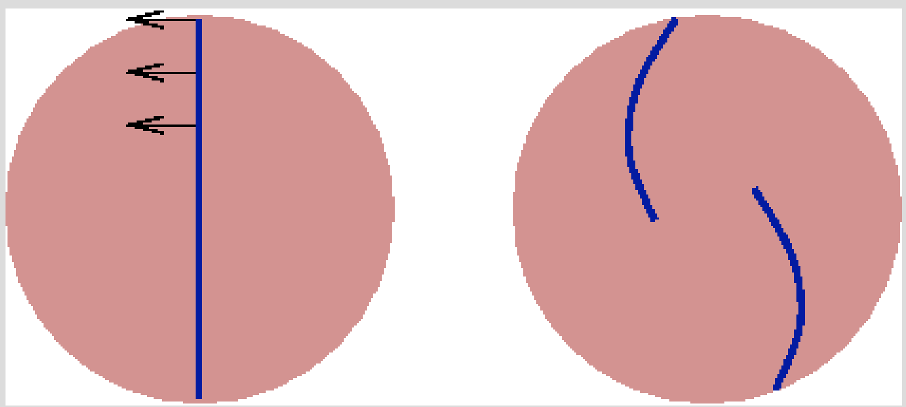
Differential rotation

First ingredient for producing spiral arms is differential rotation. For galaxy with flat rotation curve:

$$V(R) = \text{constant}$$

Angular velocity $\longrightarrow$ $\Omega(R) = \frac{V}{R} \propto R^{-1}$

Any feature in the disk will be wrapped into a trailing spiral pattern due to differential rotation:



Tips of spiral arms point away from direction of rotation.

Differential rotation is not enough to explain observed spiral structure. Again assuming a flat rotation curve:

$$\Omega = \frac{V}{R}$$

$$\frac{d\Omega}{dR} = -\frac{V}{R^2}$$

Two points in the disk, separated by ΔR in radius, and initially at the same azimuth, will be sheared apart over time. After time t, separated by an angle:

$$\left|\frac{d\Omega}{dR}\right| \Delta R t$$

Return to the same azimuth (one wrapping up) after a time given by:

$$\left|\frac{d\Omega}{dR}\right| \Delta R t = 2\pi$$

A spiral pattern will be wrapped up on a radial scale ΔR after a time t given by:

$$\frac{\Delta R}{R} = \frac{2\pi R}{Vt}$$

Using values appropriate for the Milky Way (R = 8.5 kpc, V = 200 km/s):

$$\frac{\Delta R}{R} = 0.25\left(\frac{1\ \mathrm{Gyr}}{t}\right)$$

This is already a **very tightly wrapped** spiral. Spiral arms would make an angle of ~2 degrees to the tangent direction.

In real galaxies, arms are not so wrapped up:

- Sa spirals, ~5 degrees
- Sc spirals, around 10 to 30 degrees

Implies spiral pattern must be continually renewed.

Properties of spiral arms can be explained if they are **not** rotating with the stars, but rather **density waves**:

- Spiral arms are locations where the stellar orbits are such that stars are more densely packed.
- Gas is also compressed, possibly triggering star formation and generating population of young stars.
- Arms rotate with a **pattern speed** which is not equal to the circular velocity - i.e. long lived stars enter and leave spiral arms repeatedly.
- Pattern speed is less than the circular velocity - partially alleviating the winding up problem.

In isolated disk, creation of a density wave requires an instability. **Self-gravity** of the stars and / or the gas can provide this.

Simplest case to consider is gas. Imagine a small perturbation which slightly compresses part of the disk:

- Self-gravity of the compressed clump will tend to compress it further.
- Extra pressure will resist compression.

If the disk is massive (strong self-gravity) and cold (less pressure support) first effect wins and develop spiral wave pattern.

Toomre's Q

For a disk of stars, `cold' means that the stars' random motions (in radial and vertical direction) are small compared to their circular velocity.

Define the velocity dispersion in the radial direction by:

$$\sigma_R^2 = \left\langle v_R^2 \right\rangle$$

Define the **epicyclic frequency** κ via:

$$\kappa^2(R) = \frac{1}{R^3}\frac{d}{dR}\left[\left(R^2\Omega\right)^2\right]$$

For a point mass gravitational field, $\kappa = \Omega$. See Section 3.3 of the textbook for derivation and interpretation of the epicyclic frequency.

For a disk of stars with surface mass density (mass per unit area) Σ, define Toomre's Q as:

$$Q \equiv \frac{\sigma_R \kappa}{3.36 G \Sigma}$$

Alar Toomre showed that if Q drops to ~1, a disk of stars is unstable to axisymmetric perturbations.

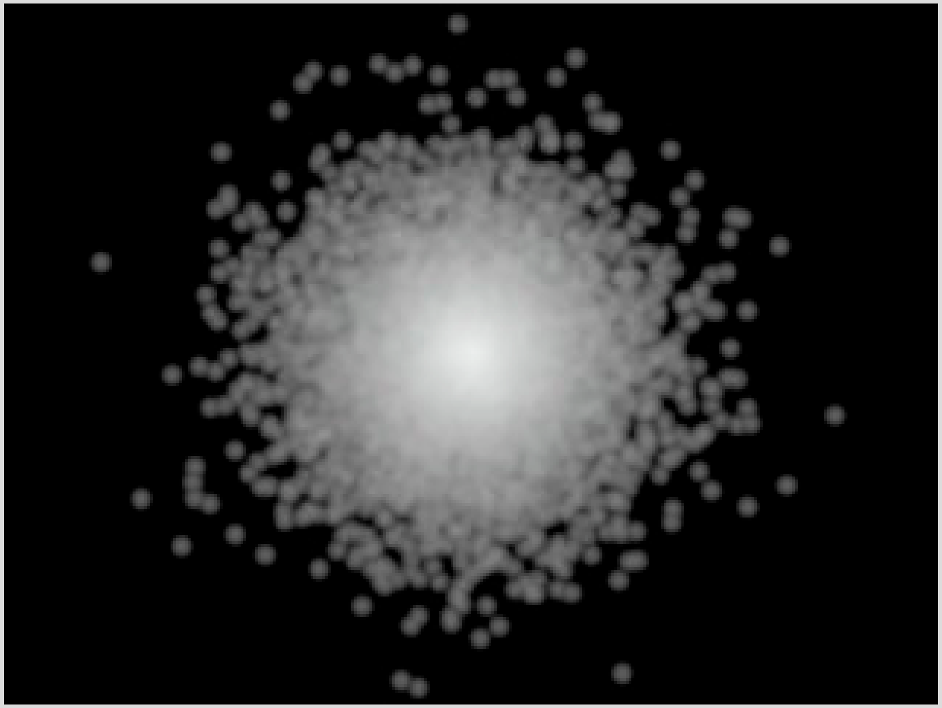
In practice, a spiral pattern generally grows if $Q < 1.2$ or so.

For the Milky Way's disk near the Sun, Σ is about 50 Solar masses per pc^2, and κ is about 36 km/s. Stars of Solar mass and below have σ_R = 30 km/s.

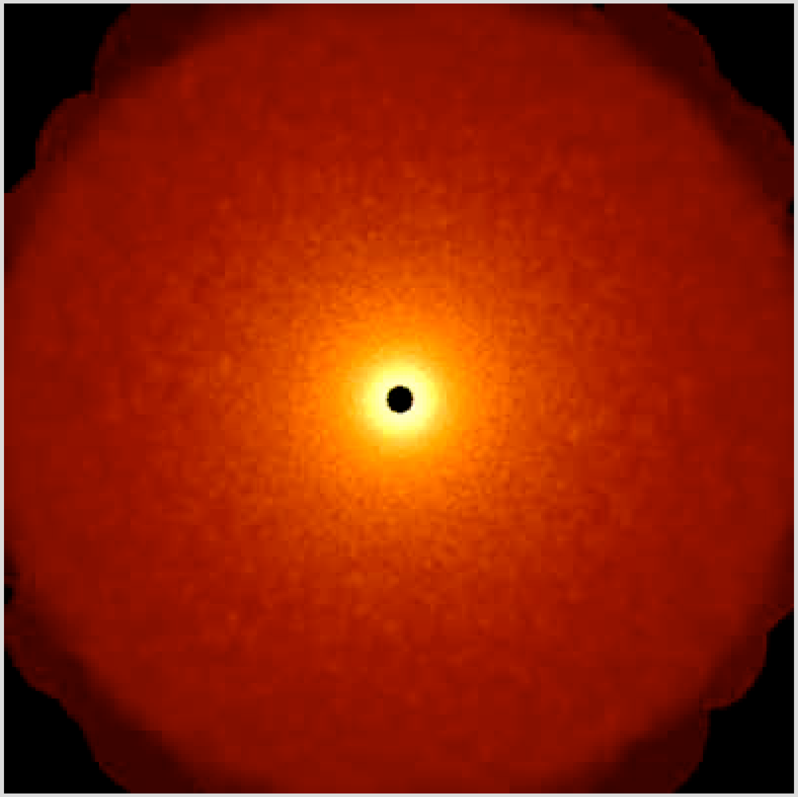
Suggests Q ~ 1.4 - close to critical value.

If Q ~ 1, disk of stars or gas will spontaneously develop spiral structure within a few rotation periods:

Stars



Gas



Note: these are trailing spirals. Persistence and strength depends upon how Q evolves. If the disk heats up, raising Q, then the spiral pattern dies away.

Observationally, clear that this is not the whole story:

<u>NGC 4622</u>

Galaxy with leading spiral arms

<u>NGC 1410</u>

Interacting galaxies with clear spiral structure that appears to have been triggered by the interaction