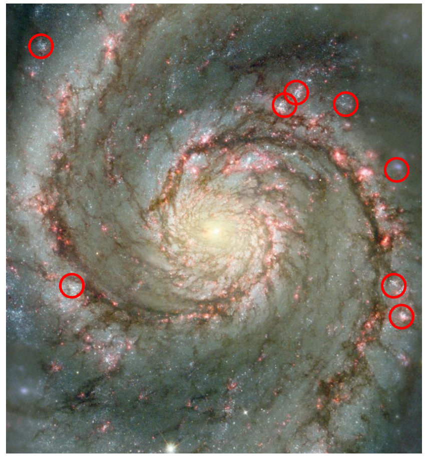
Spiral Structure of Disk

Most big galaxies are spirals. Spiral arms best traced by:

Young stars and clusters
Emission Nebulae
Atomic gas
Molecular Clouds
(old stars to a lesser extent)

Disk not empty between arms, just less material there.

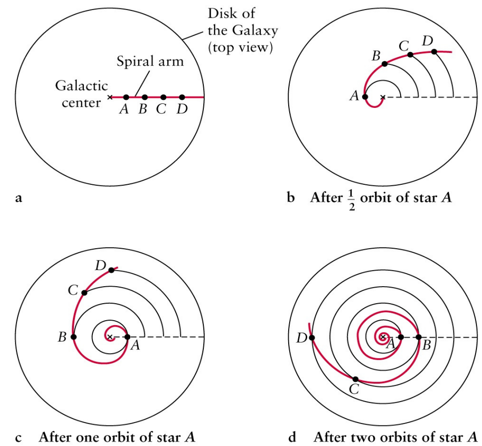


Inner disk of M51 with HST – note dust lanes, HII regions, young blue clusters concentrated to arms.

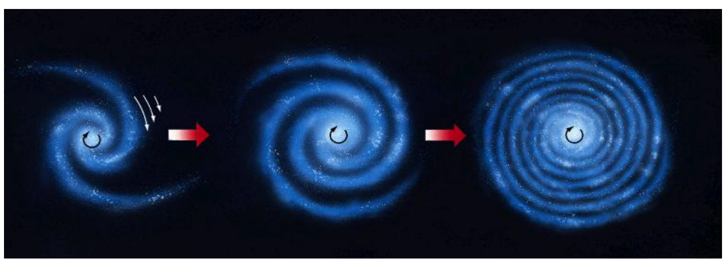
Recall: disk has "differential rotation", not rigid-body.

Problem: How do spiral arms survive?

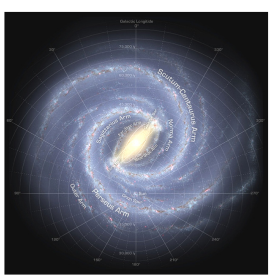
Given differential rotation, if arms always contain same material, should be stretched and smeared out after a few revolutions (Sun has made 20 already):



So if spiral arms always contain same material, the spiral should end up like this after just a few orbits:



Real structure of Milky Way (and other spiral galaxies) is more loosely wrapped.



Proposed solution:

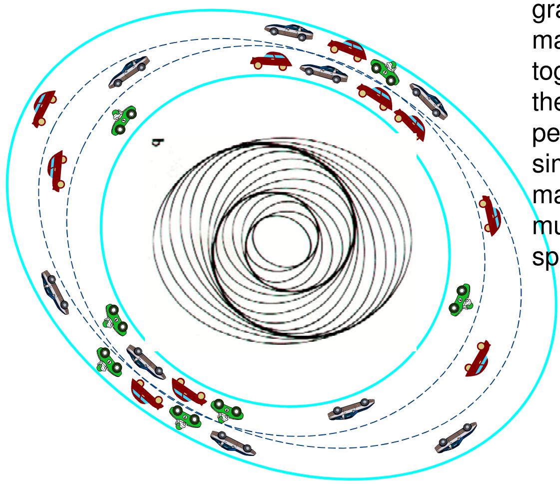
Arms are not material moving together, but mark peak of a compressional wave circling the disk:

A Spiral Density Wave (Lin & Shu 1964)

Traffic-jam analogy

Traffic jam on a loop caused by merging

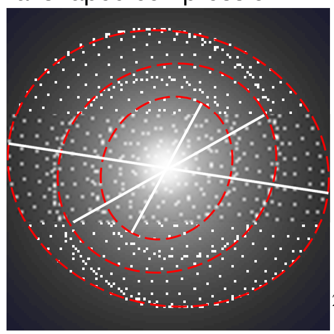
circular traffic jam simulation

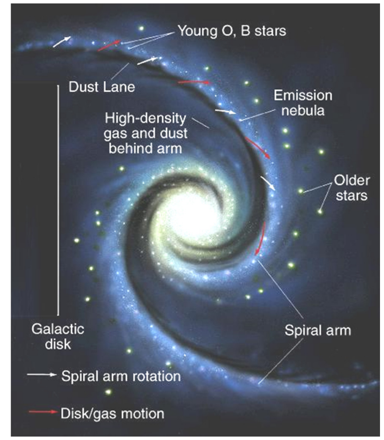


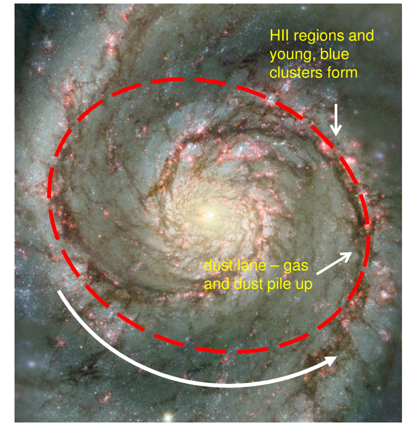
Not shown: whole pattern rotates slowly. Rigidly? Can it survive for billions of years? Waves may be transient and recurrent.

Another animation

Replace cars by stars (ignore gas clouds for now). Traffic jams are due to the stars' collective gravity: higher gravity of jams makes star orbits crowd together, which in turn maintains the enhanced gravity –> self-perpetuating. Calculations and simulations suggest this may be maintained for a long time. How must orbits be arranged to make spiral shaped compression?





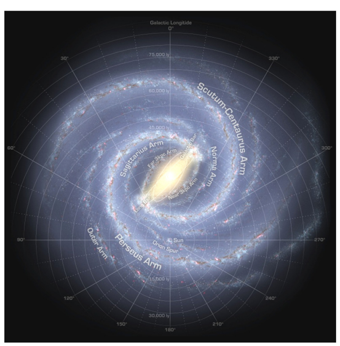


Gas clouds pushed together in arms too => high density of clouds => high concentration of dust => dust lanes.

Also, squeezing of molecular gas clouds initiates collapse within the denser ones => star formation. Bright young massive stars live and die in spiral arms. Emission nebulae mostly in spiral arms (animation).

So arms always contain same <u>types</u> of objects, but <u>individual</u> objects come and go.

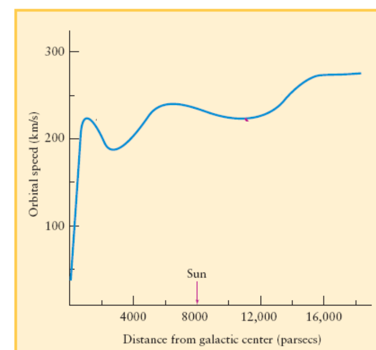
A bar is a pattern too, like a spiral.

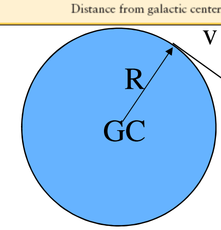


Bar simulation

Estimating the mass of the Galaxy, and Dark Matter

- Most radiating matter runs out at about R=12 kpc.
- Rotation speed there is V = 225 km/s.
- Use Newton's laws to deduce mass within this radius.





For object moving at speed V in a circular orbit of radius R the acceleration is:

$$a(R) = \frac{[V(R)]^2}{R}$$

If a small mass m orbits a mass M (e.g. Earth and Sun), with centers separated by R, then from Newton's second law, $F=ma$, along with law of gravitation,

$$\frac{GMm}{R^2} = m\frac{[V(R)]^2}{R}$$

But in a galaxy, M is extended in radius, and m is within it. For a spherical mass distribution, Newton showed you can ignore mass outside R, and treat mass inside R as all being at the center. So if $M_{int}(R)$ is the mass of the Galaxy *within R*, then,

$$\boxed{M_{int}(R) = \frac{[V(R)]^2 R}{G}}$$

Putting in numbers, we get the mass within R=12 kpc.

$$M_{int}\,(12\ kpc) \sim 10^{11}\ M_\odot$$

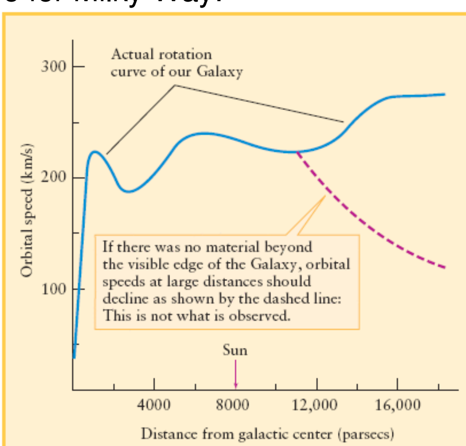
Little radiating material beyond R~12 kpc. But is there significant mass beyond 12 kpc? First, rearrange:

$$M_{int}(R) = \frac{[V(R)]^2 R}{G} \Rightarrow V(R) = \sqrt{\frac{GM_{int}(R)}{R}}$$

If almost all mass within 12 kpc, then for the few stars and gas clouds beyond 12 kpc, M_{int} ~ const., and thus:

$$V(R) \propto \sqrt{\frac{1}{R}}$$

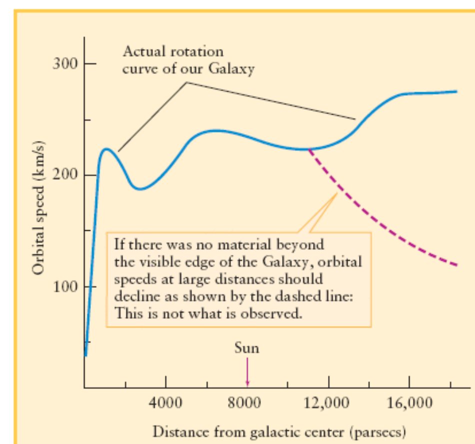
This is *Keplerian motion* (as for the planets). But recall rotation curve for Milky Way:



Stays flat instead of Keplerian out to at least 16 kpc (may even rise a bit). So $M_{int}(R)$ must grow with R. But this matter is not radiating! (Other spirals: same result).

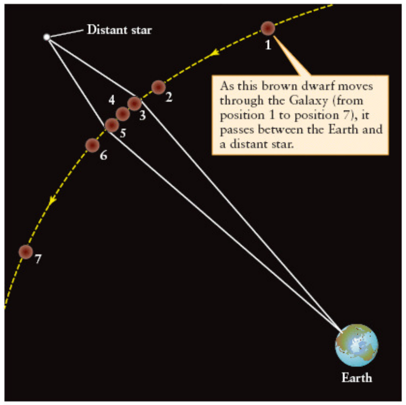
Dark Matter

- Needed to explain flat rotation curve. Inferred by its gravity, even though it does not radiate. Inferred to be a quasi-spherical halo via various observations.
- Total mass of Milky Way from V at largest R we have measured is at least ~10^{12} $M_\odot$.
- Only about 5% is radiating normal stuff, e.g., stars, gas, dust.

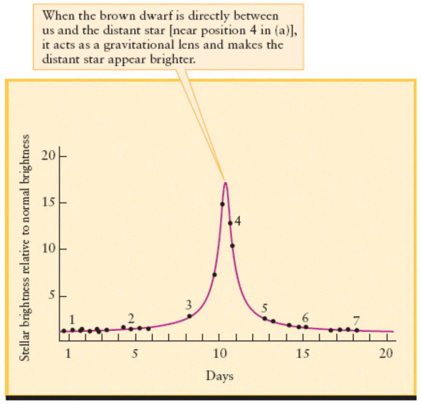


What is dark matter?

- Some consists of dim objects (brown dwarfs, white dwarfs, neutron stars, black holes, i.e. "MACHOs"), but not all. Limits on this from "gravitational microlensing" in the halo. Result: few to 20% of dark matter at most.



(a)



(b)

- Most is likely to be an as yet unidentified particle(s). A small amount is in neutrinos.

- True nature is not yet known – but this material is most of the mass of the Universe.