The Milky Way

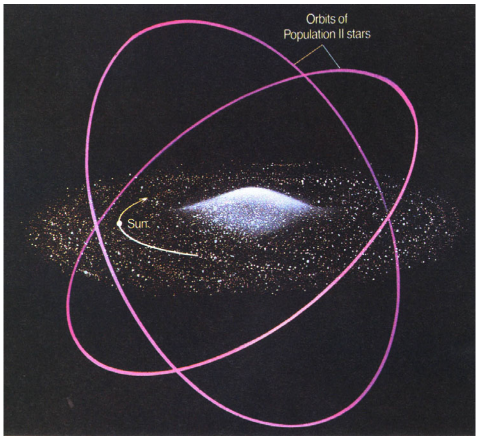
Stellar Orbits

Stars are in orbit around the Galactic Center. There are basically two types of orbits, which are described by their speeds.

1. low velocity	40 to 50 km/s	nearby, circular orbits
2. high velocity	greater than 80 km/s	highly eccentric orbits

The term "high velocity" or "low velocity" refers to the speed of an object *with respect to the Sun*. Most high velocity stars lag behind the Sun in its motion about the galactic center and hence are actually revolving about the Galaxy with speeds less than those of the low velocity stars.

Orbits Diagram



Exploration of the Universe, Abell (et al.)

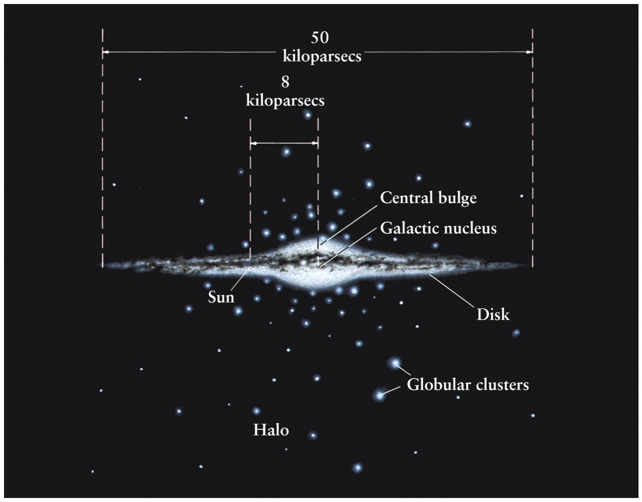
Most of the high velocity stars have high vertical component velocities, which carries them to large distances above and below the plane.

Populations

Population I comprises stars of many different ages, including very **young ones**. These are also the stars with high metal contents, can have high masses, and are located in the galactic disk and arms. These are the **low velocity** stars.

Population II consists entirely of **old stars**, formed early in the history of the Galaxy before there had been much enrichment of the original hydrogen and helium by heavy elements produced by stellar nucleo-synthesis. So there are fewer "metals" in their spectra, and these are the **high velocity** stars.

Side View



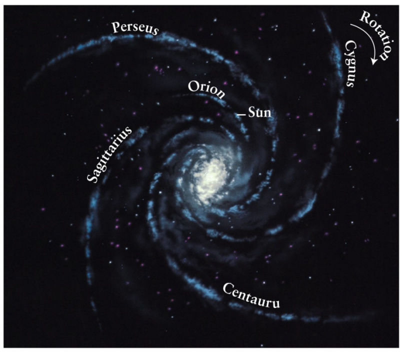
Universe by Freedman, Geller, and Kaufmann

Populations and Nuclear Bulge

It is an over-simplification to think that all stars can either be characterized as either old, with low abundances of elements heavier than helium, or young and rich in heavy elements.

Nuclear bulge stars have twice the abundance of heavy elements than does the Sun, but their mean age ranges from 11 to 14 billion years old. It is thought that star formation in the nuclear bulge occurred very rapidly shortly after the Galaxy was formed, so even the stars 11 to 14 billion years old were enriched.

Galactic Rotation and Galactic Year



The Sun is moving in its galactic orbit with a speed of 220 km/s, about 90° from the direction toward the galactic center.

$P = 2 \pi r / v$

$= 2 \pi [(25{,}000 \text{ ly}) (9.46 \times 10^{12} \text{ km / ly})] / (220 \text{ km/s})$

$= 6.5 \times 10^{15}$ sec $= 200 \times 10^{6}$ years

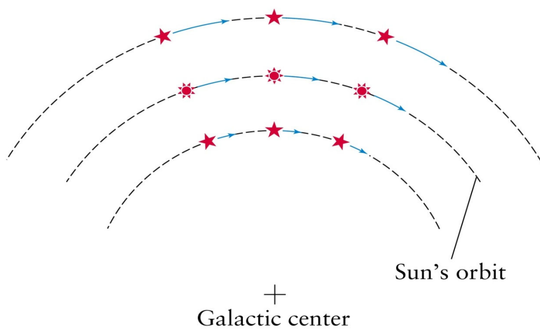
The galactic year for the Sun is ~200 million years.

Permanence of Spiral Structure

At the Sun's distance, the Galaxy rotates once in about 200 million years, but its current age is believed to be 5 billion years, in which case there should have been at least **25 rotations**.

No matter what the original distribution of the material might have been, the **Differential Rotation** of the Galaxy would be expected to form spiral arms. However, it is harder to understand **why the arms do not become tightly wound together.**

Solid Disk Rotation



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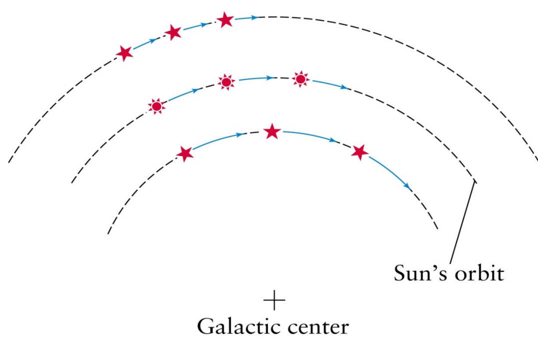
This type of solid-body rotation would not produce spiral arms. Rather the Galaxy would look like a Ferris Wheel.

Keplerian Orbits and Rotation



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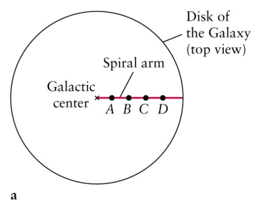
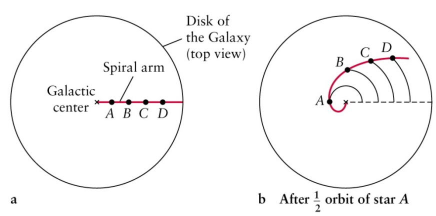
These types of orbits – slower periods as radial distance increases – will produce spiral arms. But there is a problem with this type of rotation.

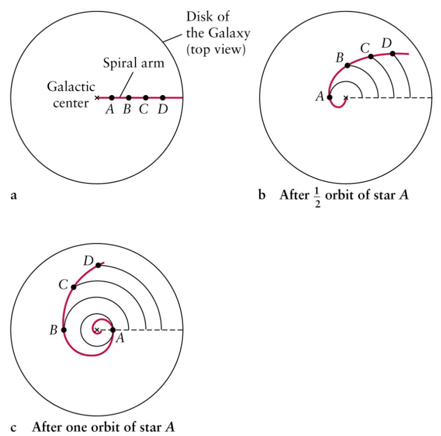
Arms Winding Tighter



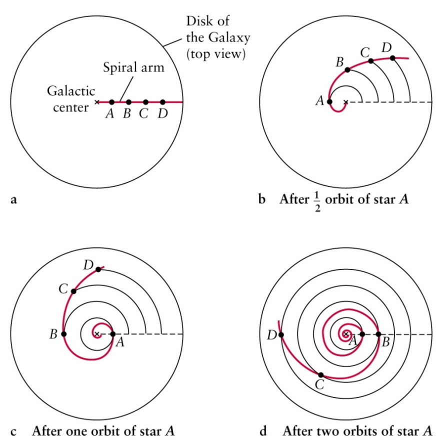
Arms Winding Tighter



Arms Winding Tighter



Arms Winding Tighter



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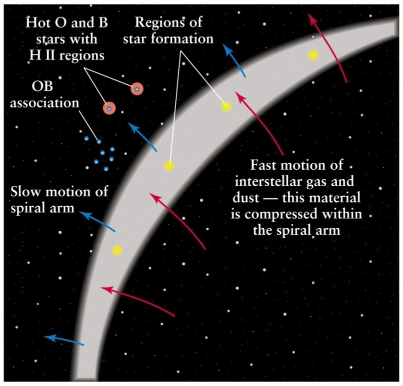
Rotation of Spiral Arms



Universe by Freedman, Geller, and Kaufmann

The **youngest stars** are in the spiral arms. In some other galaxies, where the spiral arms can be viewed face on, we see young stars, along with the densest dust clouds, near the inner boundaries of spiral arms.

Can we accurately describe the motion of spiral arms?

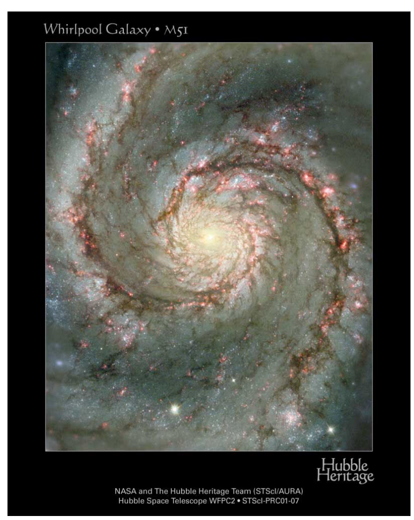
Why Spiral Arms?

Spiral structure looks so stunning because they are outlined by brilliant, young OB stars.

Such OB stars have main sequence lifetimes of only a few million years.

This is very short compared to the ~10 billion year lifetimes of galaxies.

Odds are that we did not just happen to see all these galaxies at just the right time. Rather, star formation must be an on-going activity.



Why Spiral Arms?

Why should new stars be born in a grand spiral pattern?

Spiral arms are usually very skinny and yet very long.

What is the mechanism that causes star formation throughout such arms?

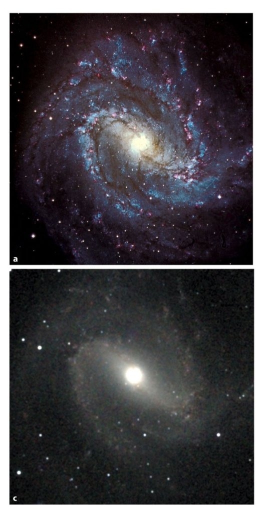
Possible Answer – Is it because the gas and dust clouds that produce stars are always/only located in spiral arms?

No – differential rotation makes it impossible to have arms that are always made of the same material.

Density Enhancements

Improved observations show that there are many stars between the spiral arms. In fact, there is only a 5% increase in number in the spiral arms.

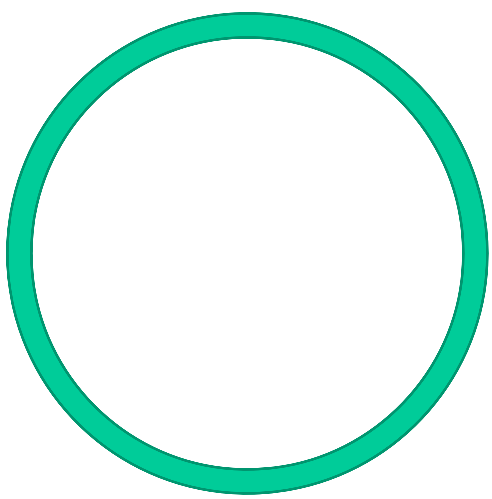
Time for a new theory that allows for the permanence of spiral arms.

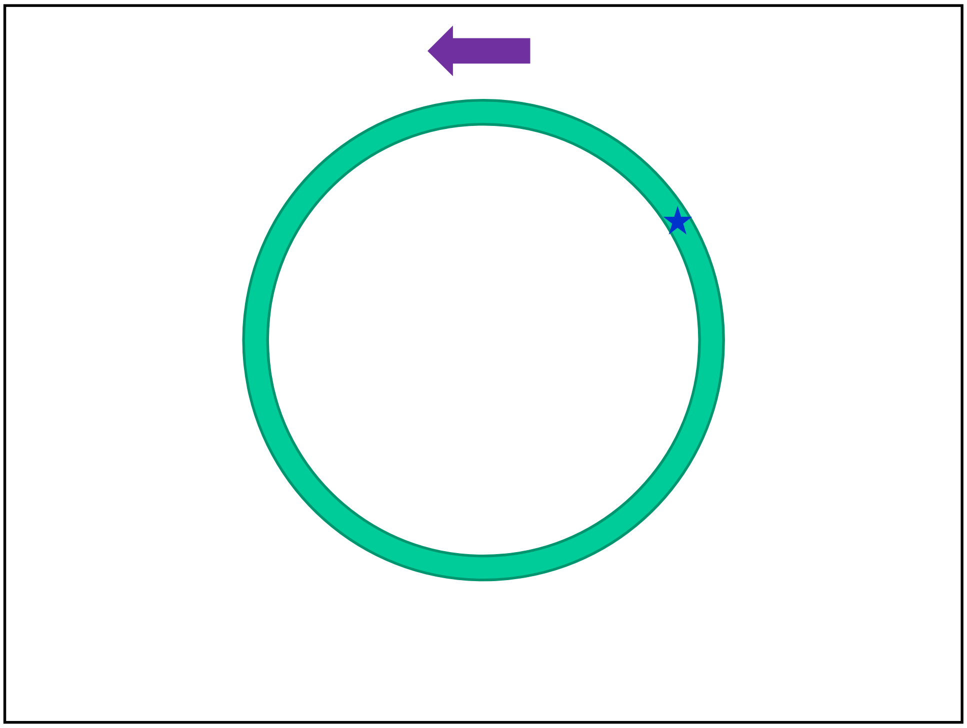


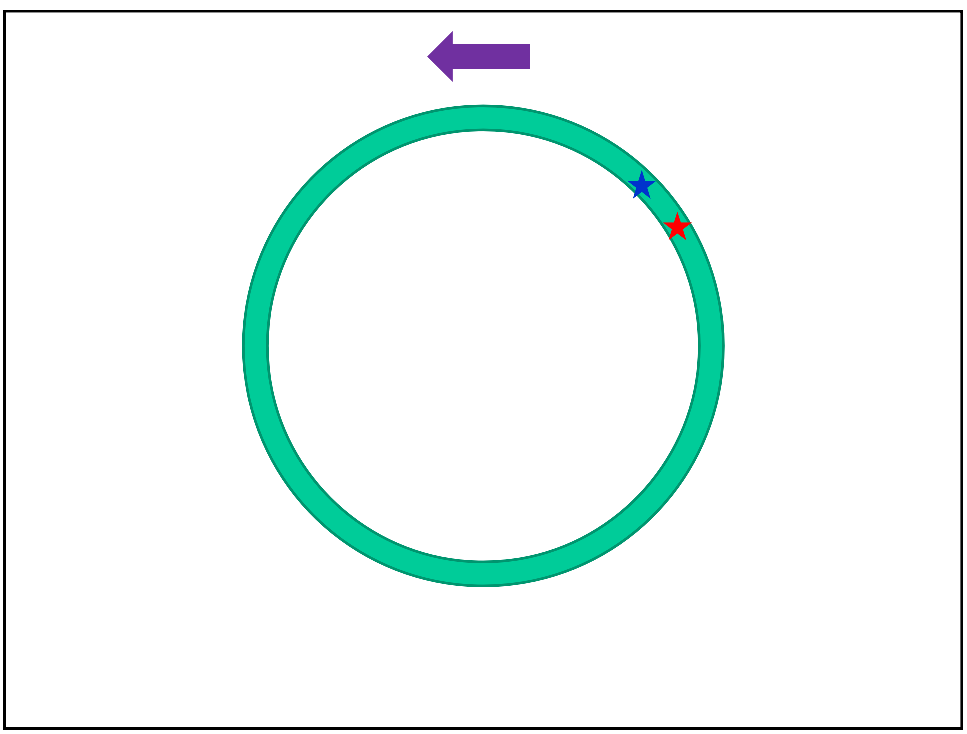
Density Wave Theory

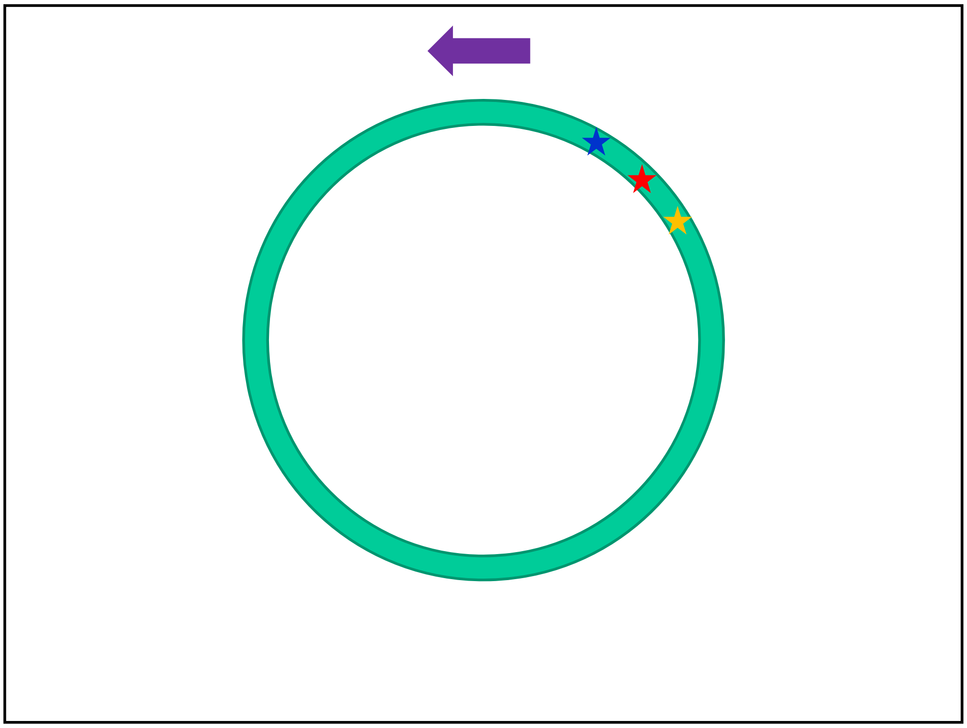
Spiral structure in disk galaxies is a density wave phenomenon, maintained by the self-gravity of the large-scale distribution of matter.

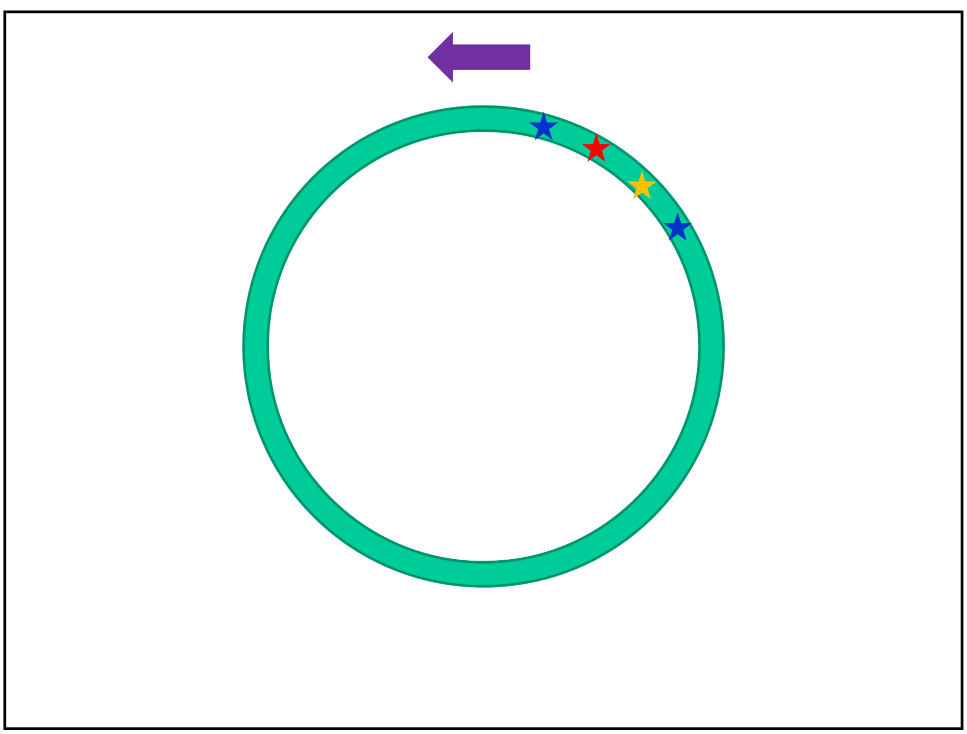
The motions/orbits of stars and gas clouds are deflected by the gravitational field, because spiral galaxies do not have a perfect distribution of matter.

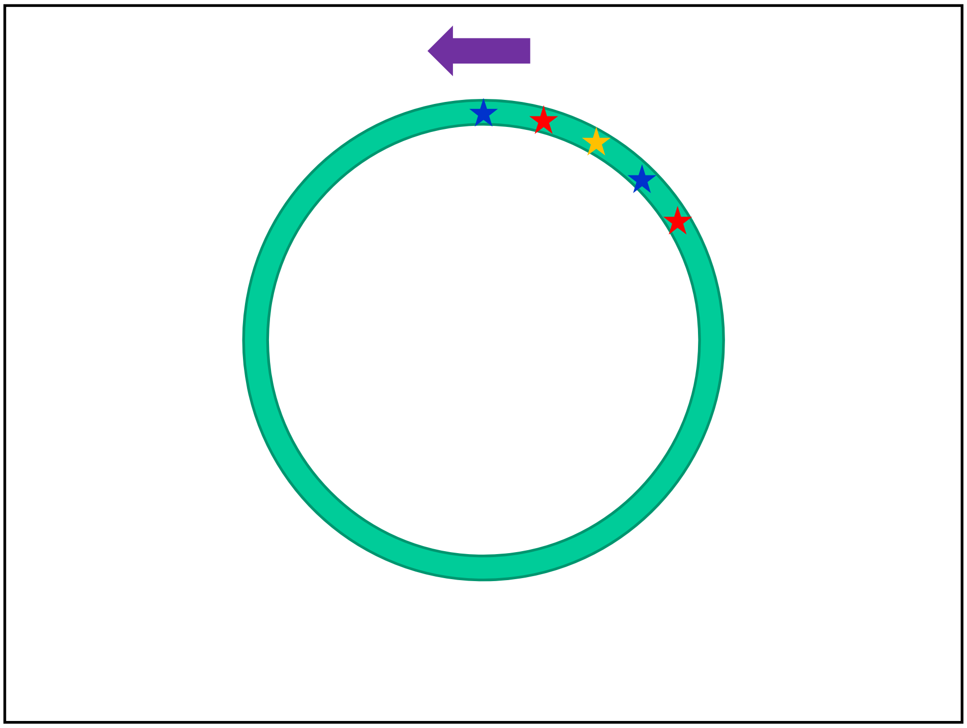


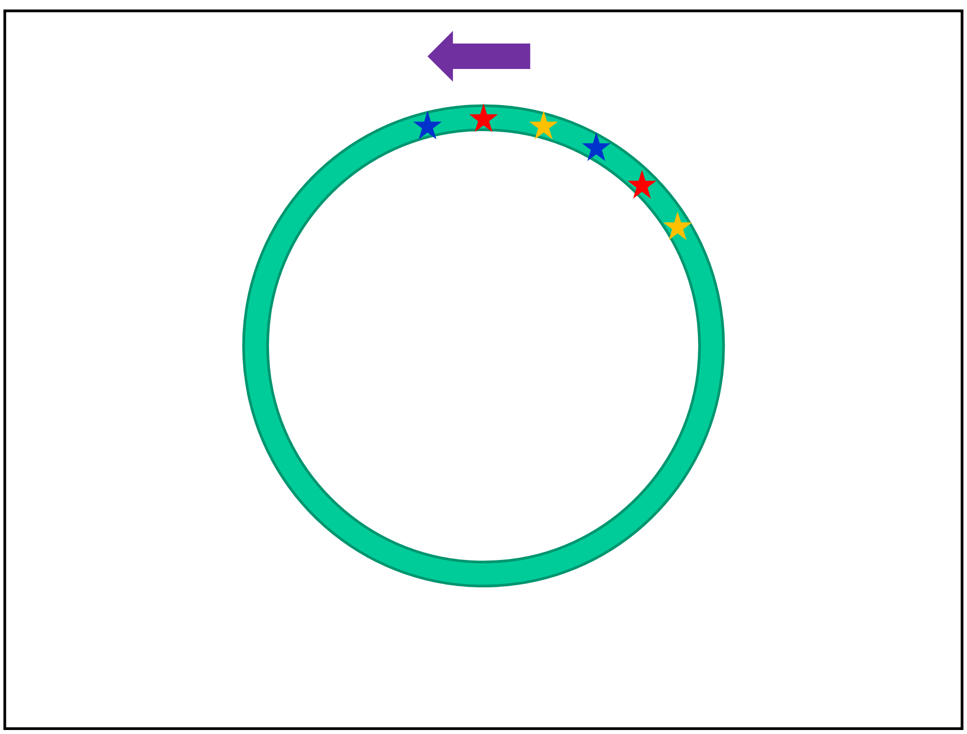


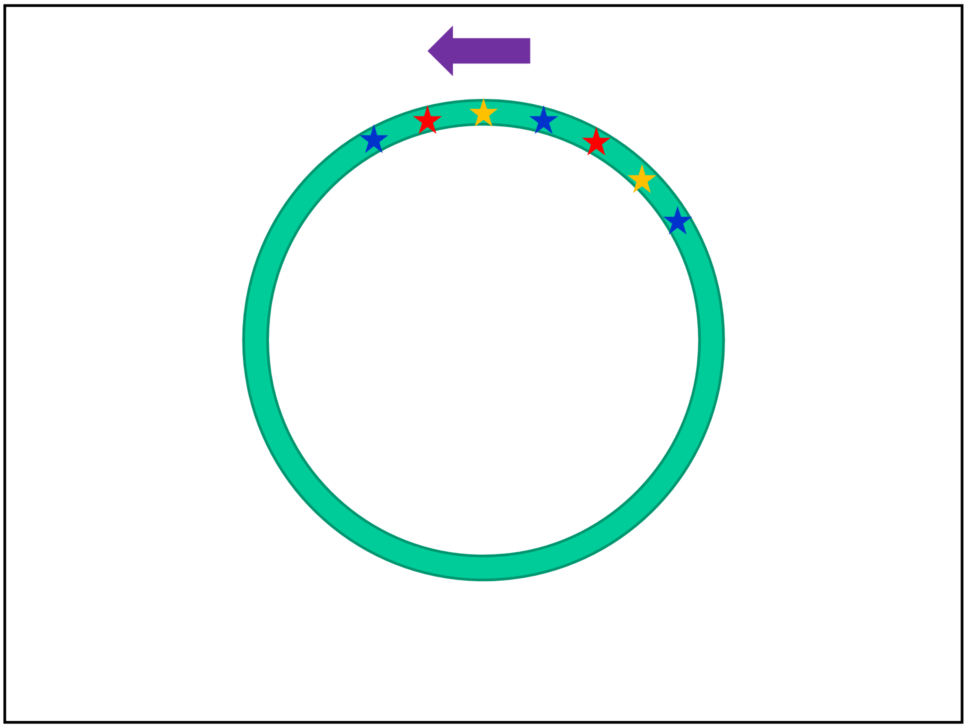


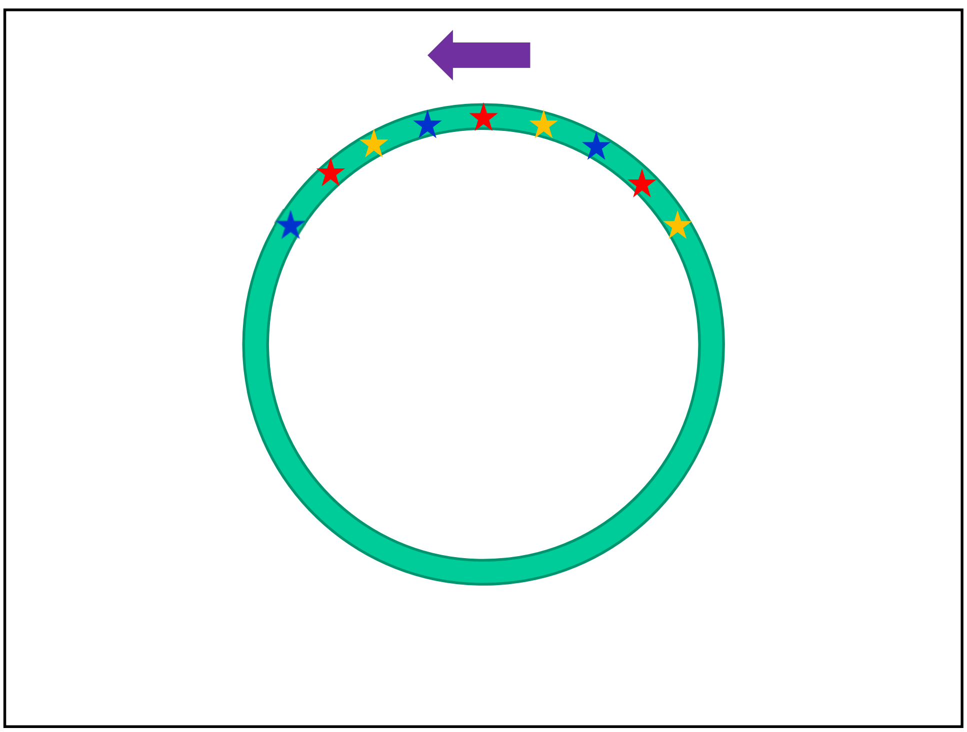


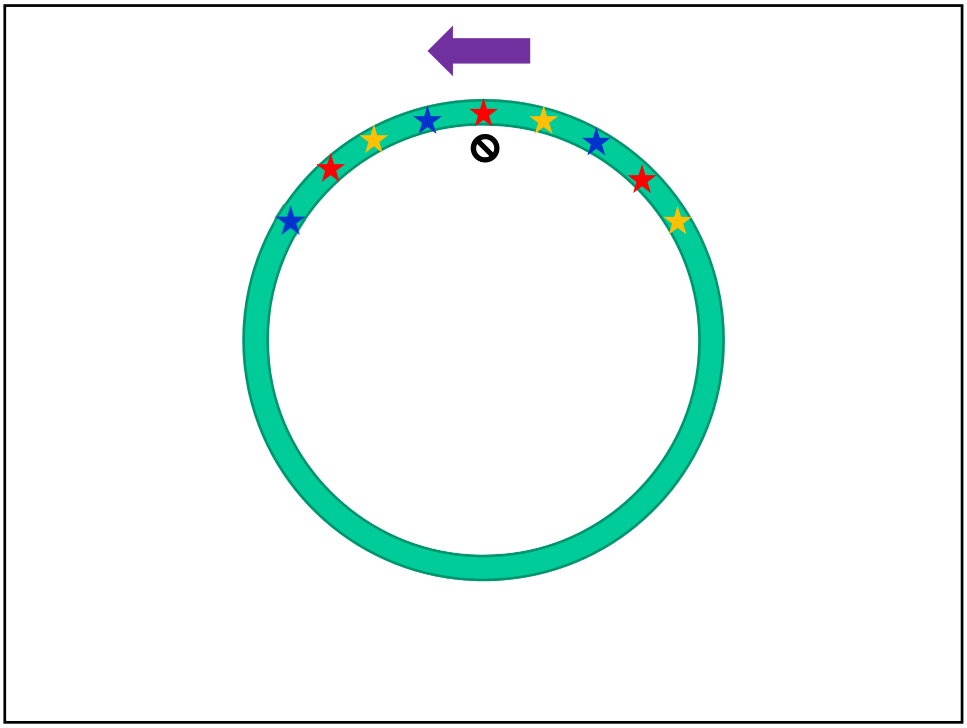


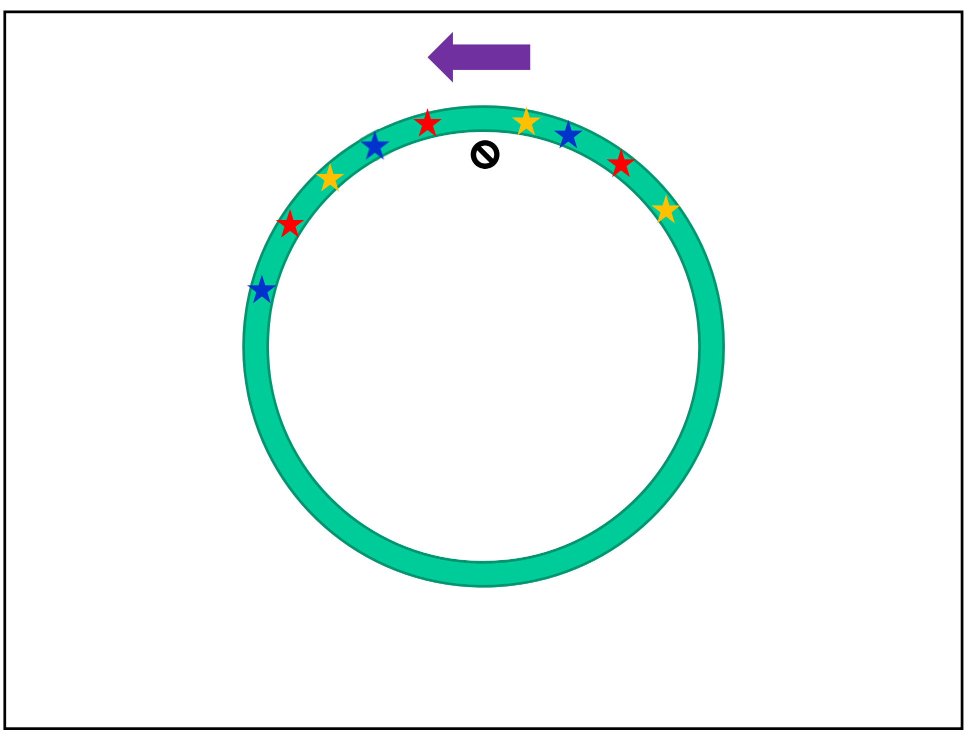


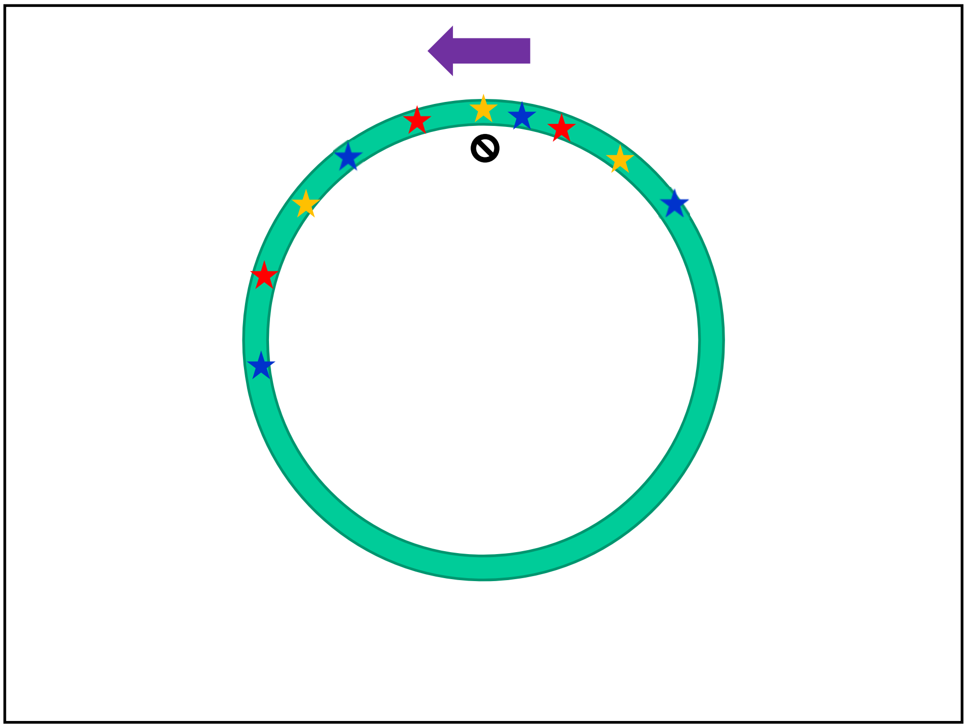


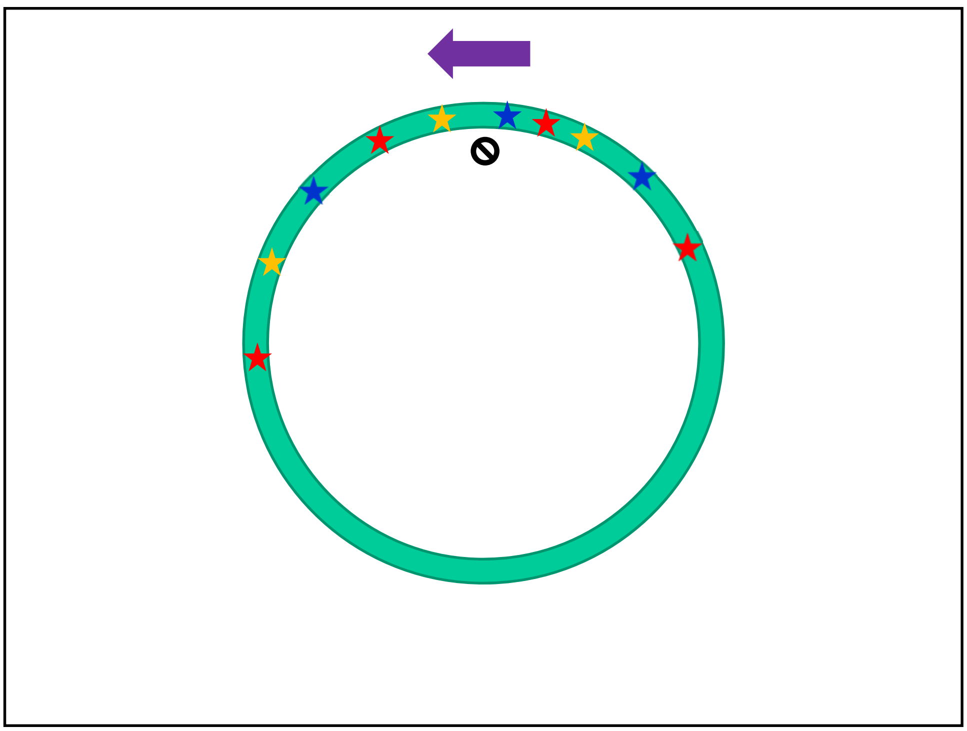


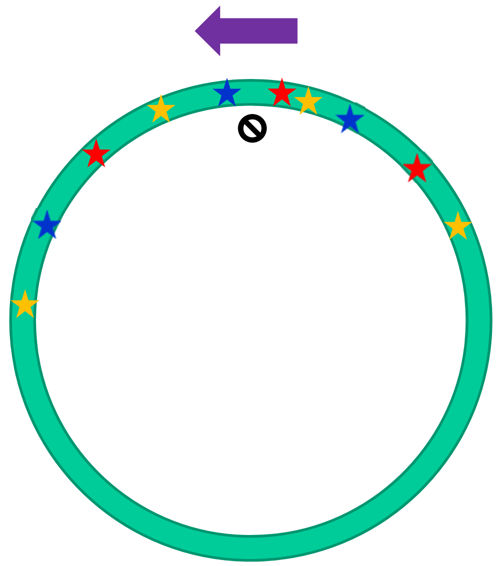




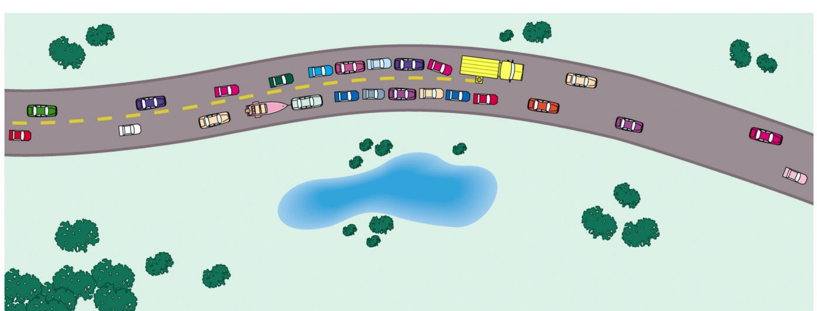








Density Wave Example



Universe by Freedman, Geller, and Kaufmann

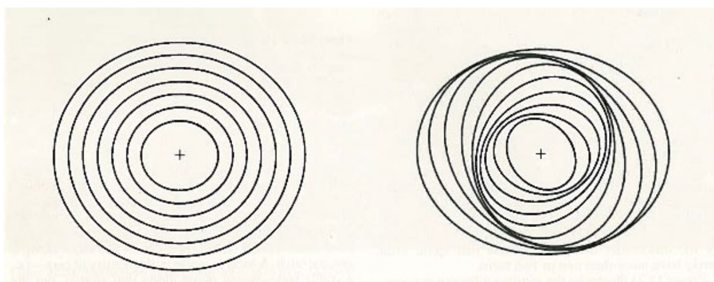
The density enhancement persists even though the specific cars involved in the pile-up eventually pass through the region.

Perturbations

Except for small random motions, the mean orbit of a star in an unperturbed disk galaxy describes a **circle**.

But if this object is moving in a perturbed gravitational field that is periodic in time and angle, then the orbit is more **oval**.

If the angular phase changes as a function of distance, then the spiral arm structure is produced.



Mass of the Galaxy

Assume the Sun's orbit is circular and the Galaxy is spherical. Thanks to Isaac Newton, we can treat the total mass inside the Sun's orbit as being concentrated at a point.

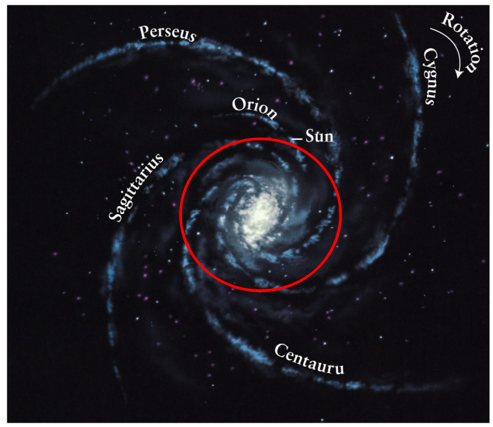
Its distance to the Galactic center is 8500 pc and period is 200 x 10^6 years, so we have from Kepler's 3rd Law:

$$\text{Mass}_{\text{Galaxy}} = (8500 \times 206265\ \text{AU})^3\ /\ (200 \times 10^6\ \text{yr})^2 = 10^{11}\ \text{solar masses.}$$

This is only the mass **inside** the Sun's orbit.

Total Mass

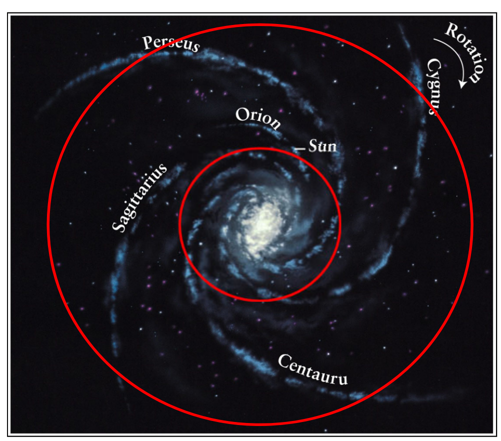
The mass of the Galaxy inside the Sun's orbit is 10^{11} solar masses.



Total Mass

Can we compute the total mass in the Galaxy?

Yes, but first we need to rewrite Kepler's Third Law.



Rotation Curve Derivation

$\mathcal{M}\ \ P^2 = 4\pi^2/G\ r^3$ (Kepler's 3rd Law)

$\mathcal{M} = 4\pi^2/G\ \ r^3/P^2$

$P = 2\ \pi\ r\ /\ v$ so $1/P^2 = v^2/4\pi^2 r^2$

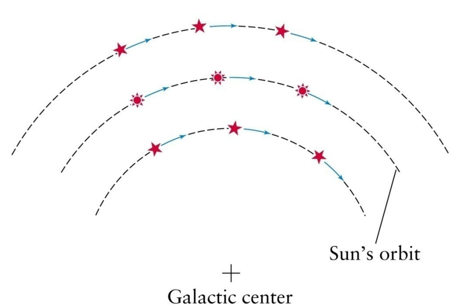
$\mathcal{M} = 4\pi^2/G\ \ r^3\ \ v^2/4\pi^2 r^2$

$\mathcal{M} = v^2\ r\ /\ G$

$\mathcal{M} \propto \mathbf{v^2\ r}$

$\mathcal{M}$ is the mass inside a circular orbit of radius **r** and orbital speed **v**.

Actual Rotation of the Galaxy



Universe by Freedman, Geller, and Kaufmann

OBSERVATIONAL DATA SHOW THAT ALL STARS – outside the Sun's distance from the Galactic Center – have the same orbital speed.

This is NOT what Kepler's 3rd Law gives.

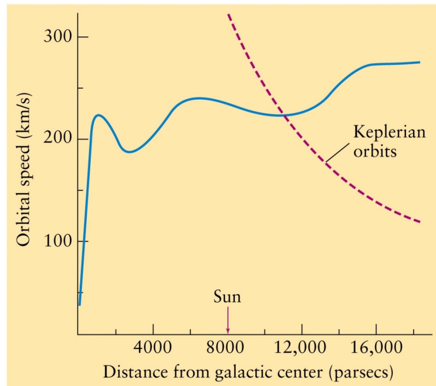
Flat Rotation Curve

$\mathcal{M} \propto v^2 r$

If all (or most) of the mass is inside the Sun's orbit, then as one moves farther out to larger values of **r**, the rotational velocity **v** must decrease.

But, stars at large distances from the luminous boundary of the Milky Way Galaxy **are not moving more slowly**.

Stars between 10,000 and 50,000 pc from the Sun have orbital speeds that **remain constant at about 250 km/s**.



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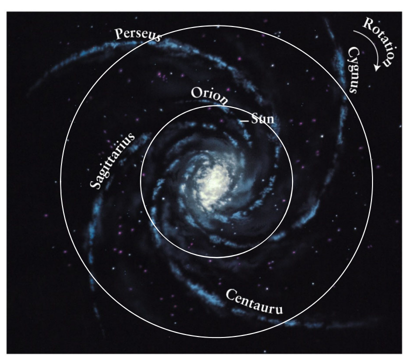
Unseen Additional Mass

Stars between 10,000 and 50,000 pc from the Sun have orbital speeds that remain constant at about 250 km/s.

$\mathcal{M} \propto v^2 r$

The only way this can happen is if there is a huge amount of additional mass beyond the visible boundary of the Galaxy – matter that, except for its gravitational force, is entirely invisible and undetectable.

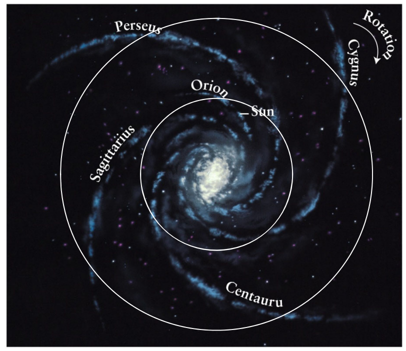


Dark Matter

The mass of the Galaxy out to 50 kpc is about 10^{12} solar masses, which is 10 times greater than the amount of mass within the Sun's orbit.

Theoretical arguments suggest that this **Dark Matter** is distributed in a spherical halo.

About 90% of the mass in our Galaxy is invisible!!!



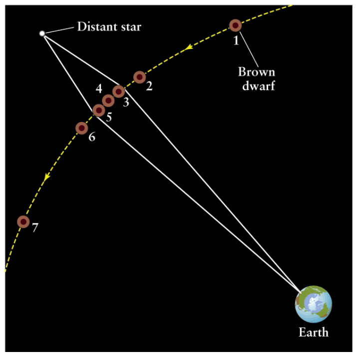
Dark Matter Possibilities

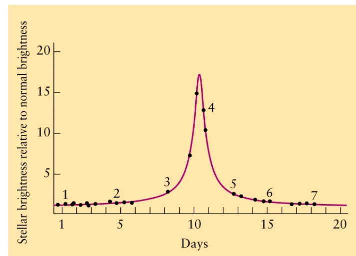
It cannot be:
- (a) gas in any form, for there is no radiation from it
- (b) dust, because it would block light

Probably not:
- (a) low-mass brown dwarfs or red dwarfs
- (b) white dwarfs that are now black dwarfs
- (c) neutron stars that are no longer pulsars
- (d) stellar-sized black holes, for there is no X-ray emission
- (e) black holes with masses millions of times that of the Sun

Might be:
- (a) exotic subatomic particles
  - WIMPS – Weakly Interacting Massive Particles
- (b) low-mass black holes
  - MACHOS – MAssive Compact Halo Objects

MACHOs





Universe by Freedman, Geller, and Kaufmann

Massive Compact Halo Objects can cause stars to brighten
(by gravitational bending of light) as they move in front of it.