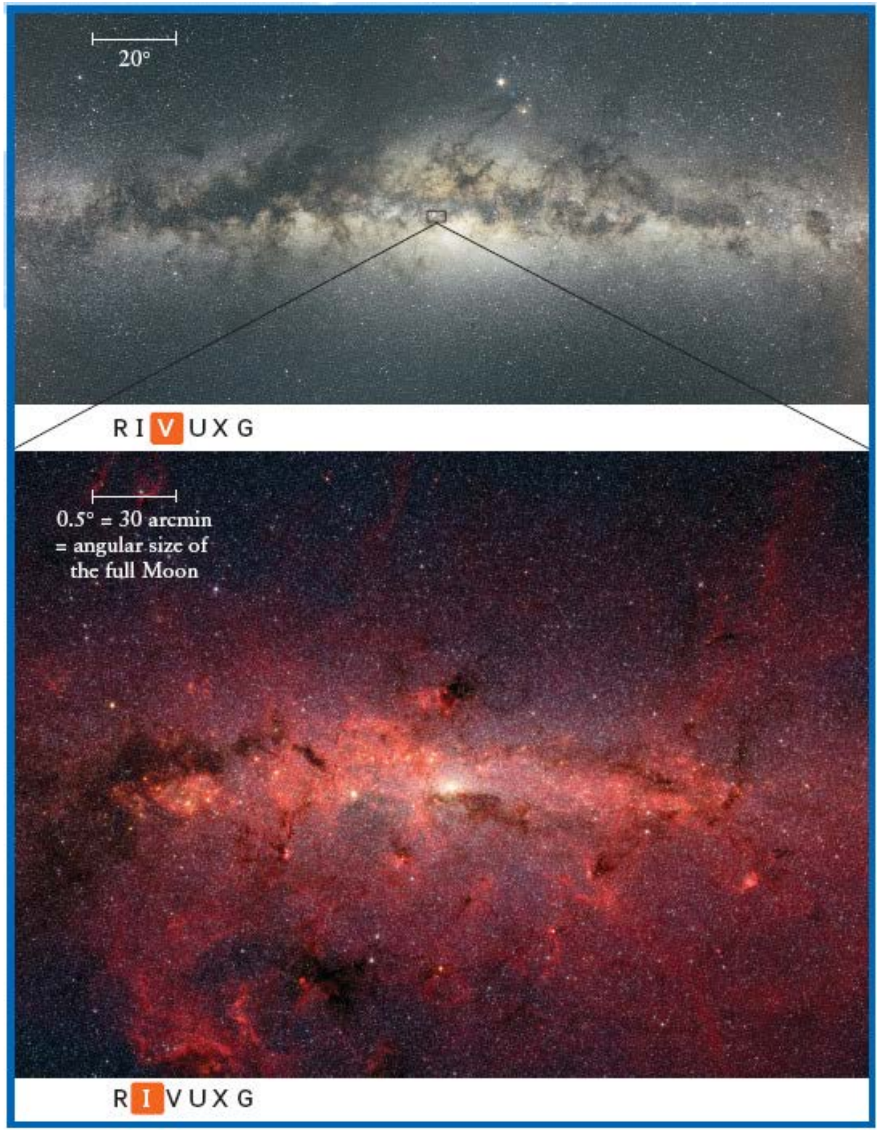
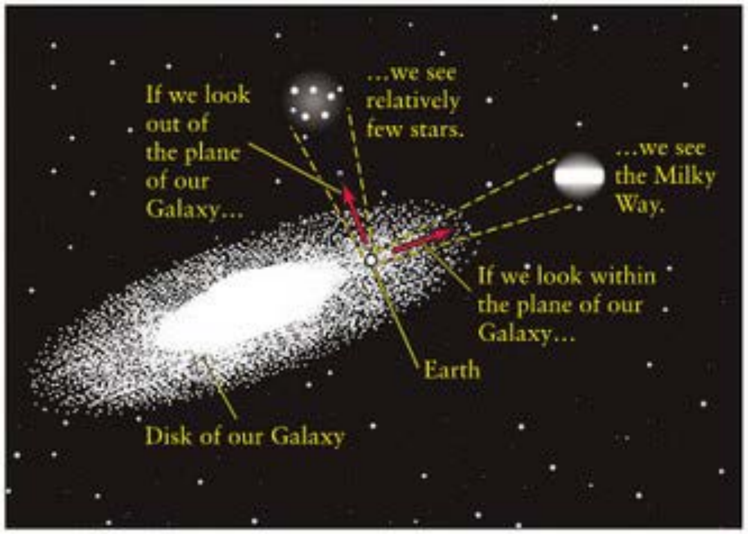
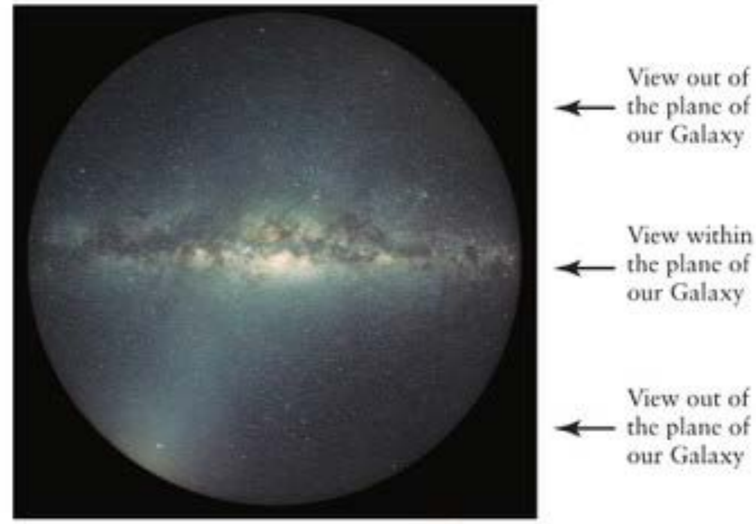
Our Galaxy



Our Galaxy



(a)



(b) R I V U X G

We are located in the disk of our galaxy and this is why the disk appears as a band of stars across the sky.

Early attempts to locate our solar system produced erroneous results. The main **problem was that interstellar extinction** allows one to only see the nearby stars and **makes distant objects appear dimmer**.

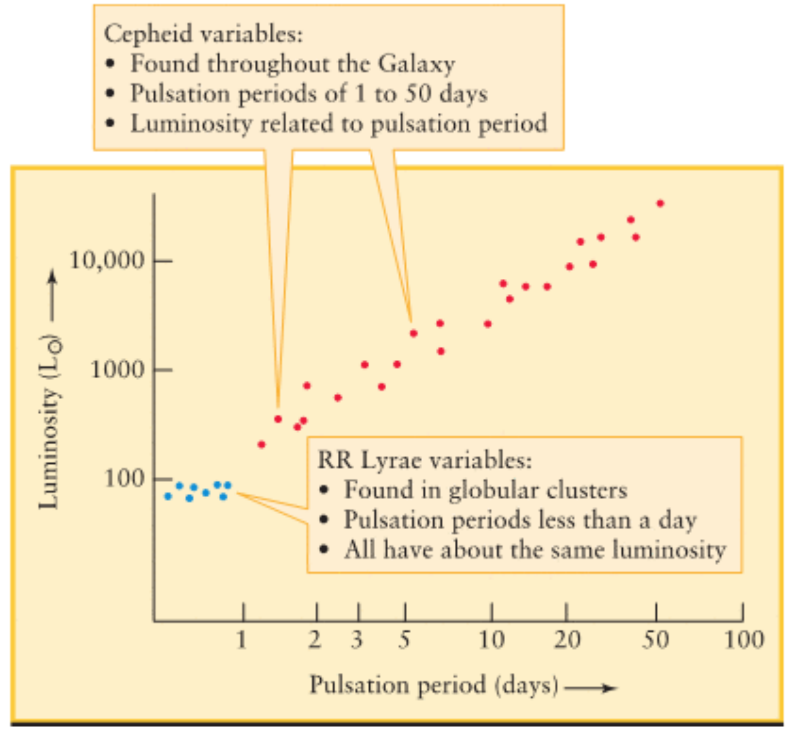
The key to finding our location in the galaxy is locating bright objects out of the plane of the galaxy. Astronomers use **globular clusters** to locate the position of our solar system with respect to the Galaxy.

Our Galaxy

To find the **positions of the globular clusters** of our galaxy astronomers measured their coordinates and distances.

Shapley measured the positions of **globular clusters** and found that they **form a spherical distribution** that is not **centered on** Earth but around a point in our galaxy several kpc away in the direction of **Sagittarius**.

Today, the generally accepted distance from Earth to the center of our galaxy is 26,000 ly +/- 3,000 ly



Cepheid and RR Lyrae variables are used to determine distances.

RR Lyrae are found in globular clusters and measuring their distances provides the distances to the globular clusters.

Our Galaxy

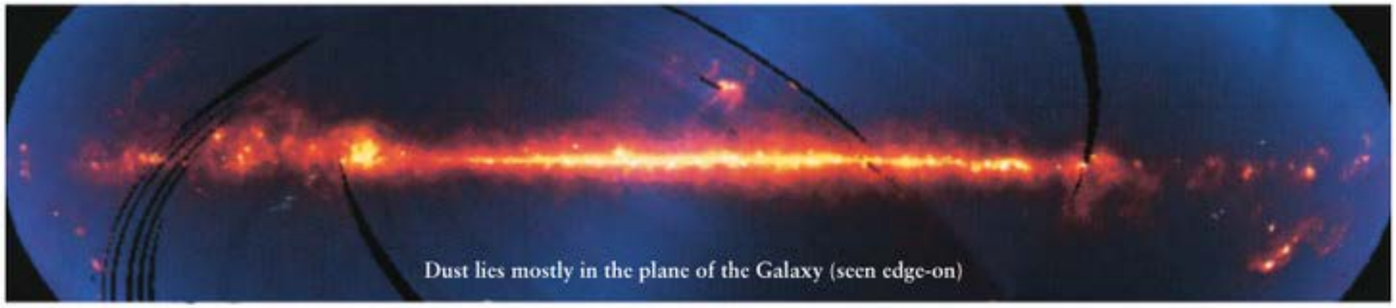
Interstellar extinction is roughly inversely proportional to wavelength. As a result we can see farther into the disk in radio and IR wavelengths than at visible wavelengths.

Starlight warms **dust grains** to temperatures of about 10K - 90K and thus they **emit predominately at far-infrared** wavelengths between 30 μm – 300 μm.

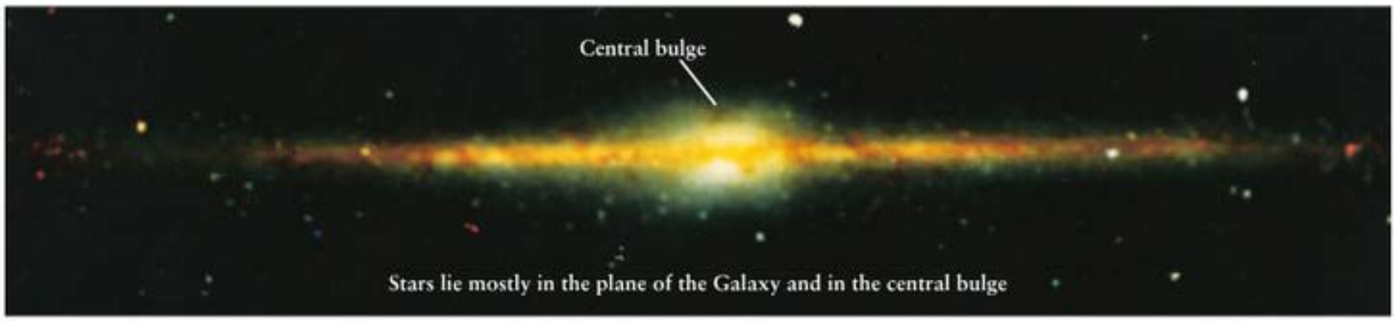
- **Far-infrared** light from our galaxy **traces interstellar dust.**

- **Near-infrared** light from our galaxy **traces mostly stars**.

Our Galaxy



(a) Infrared emission from dust at wavelengths of 25, 60, and 100 μm

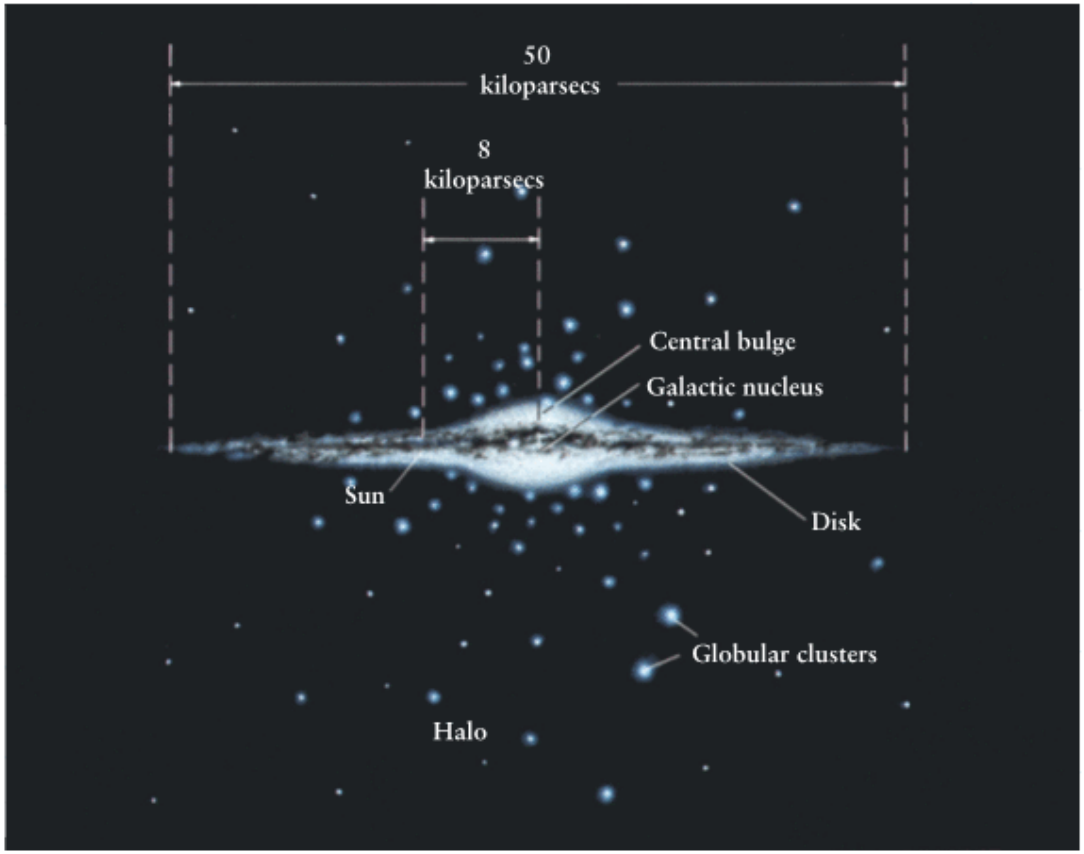


(b) Infrared emission from dust at wavelengths of 1.2, 2.2, and 3.4 μm

(a) **Far-infrared image of the Milky Way** taken with the IRAS spacecraft. **Interstellar dust**, which is mostly confined to the plane of the Galaxy, is the principal source of radiation in this wavelength range.

(b) **Near-infrared image of the Milky Way** taken with the COBE observatory. We can see farther through interstellar dust by observing in near-infrared wavelengths than at visible ones. Light in the near infrared range comes **mostly from stars** in the plane of the Galaxy and in the bulge at the Galaxy's center.

Our Galaxy



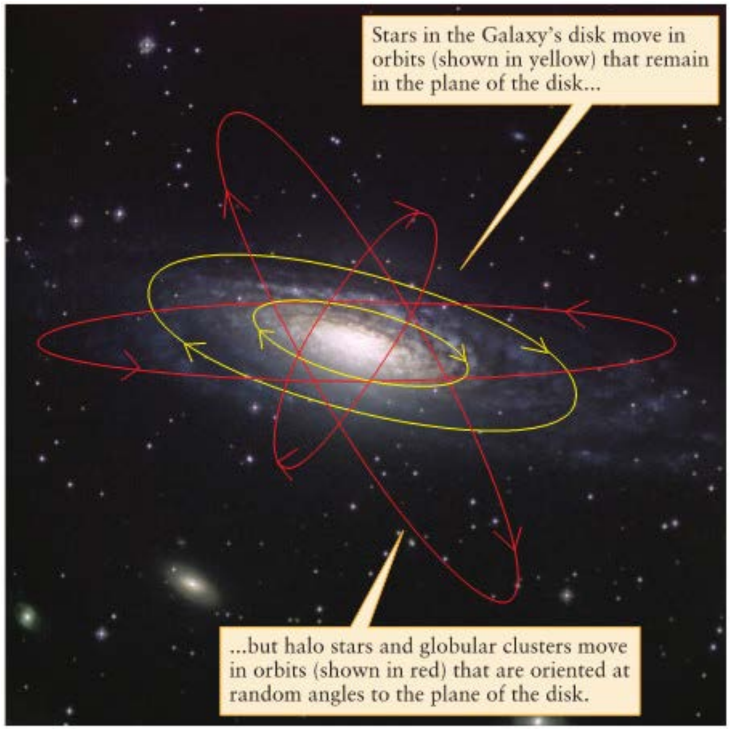
There are three major components of our Galaxy: a disk, a central bulge, and a halo. The **disk** contains gas and dust along with metal-rich (Population I) stars. The **halo** is composed almost exclusively of old, metal-poor (Population II) stars. The central **bulge** is a mixture of Population I and Population II stars.

Stars in our Galaxy

There are an estimated 200 billion stars in our galaxy.

Stellar populations:
Metal poor and very old stars reside in the halo. These are called **Population II stars**. There is no recent star formation in the halo and you don't expect to find massive stars in here!

Only 1 % of the stars in the halo reside in globular clusters. Most halo stars are isolated and are often called **high velocity stars** because of their high speed compared to the suns.

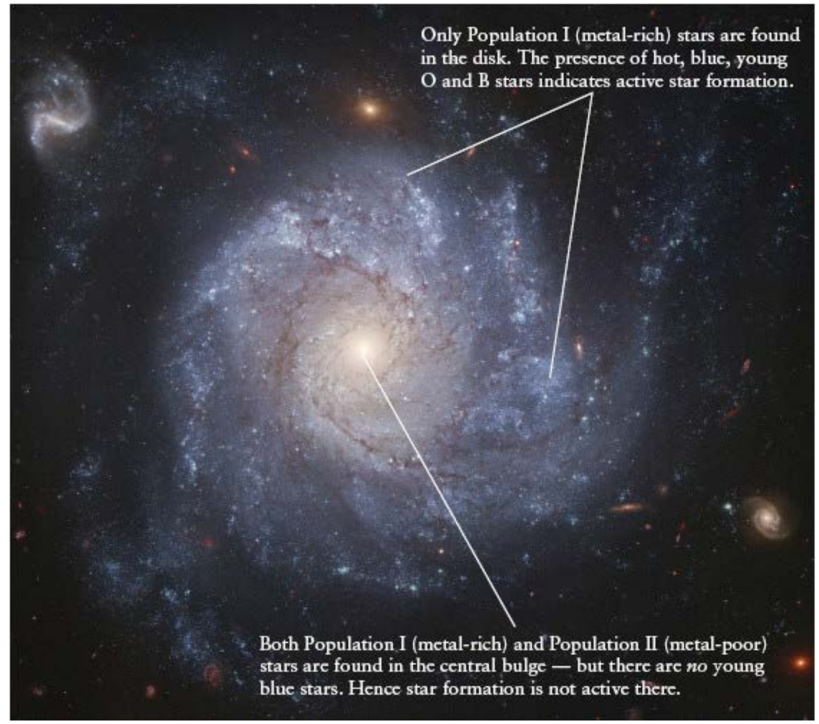


The different populations of stars in NGC 7331 (similar to our Galaxy) travel along different sorts of orbits.

Stars in our Galaxy

Stellar populations:
Metal rich and mostly young stars reside in the disk. These are called **Population I stars**. The disk contains many O and B stars which give it a bluish color. Since O and B stars do not live long there must be continuous star formation in the disk to replenish them.

The bulge contains both Population I and II stars and mostly red giants and supergiants but no O and B stars (no star formation here).



Pop I stars in the disk and Pop I and II stars in the bulge.

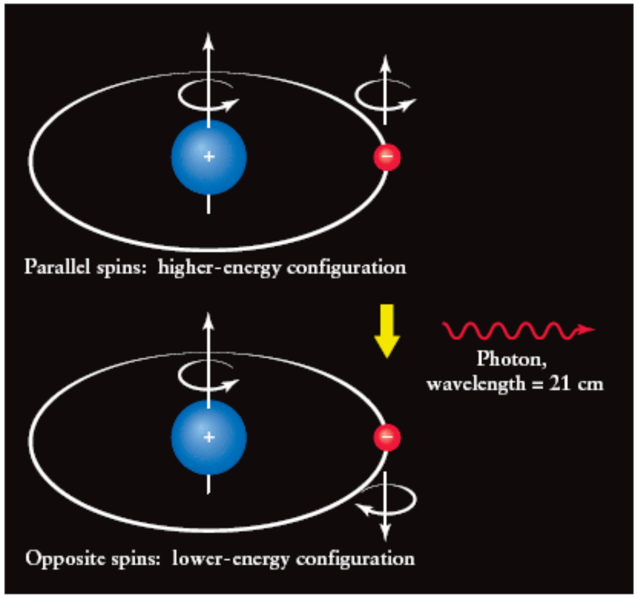
Mapping our Galaxy in Radio Wavelengths

A large fraction of the matter in the galaxy is made of hydrogen but most of it cannot be detected in the visible.

Radio wavelengths can penetrate the interstellar medium of our Galaxy easily and is ideal for mapping out cold hydrogen (H I → not ionized).

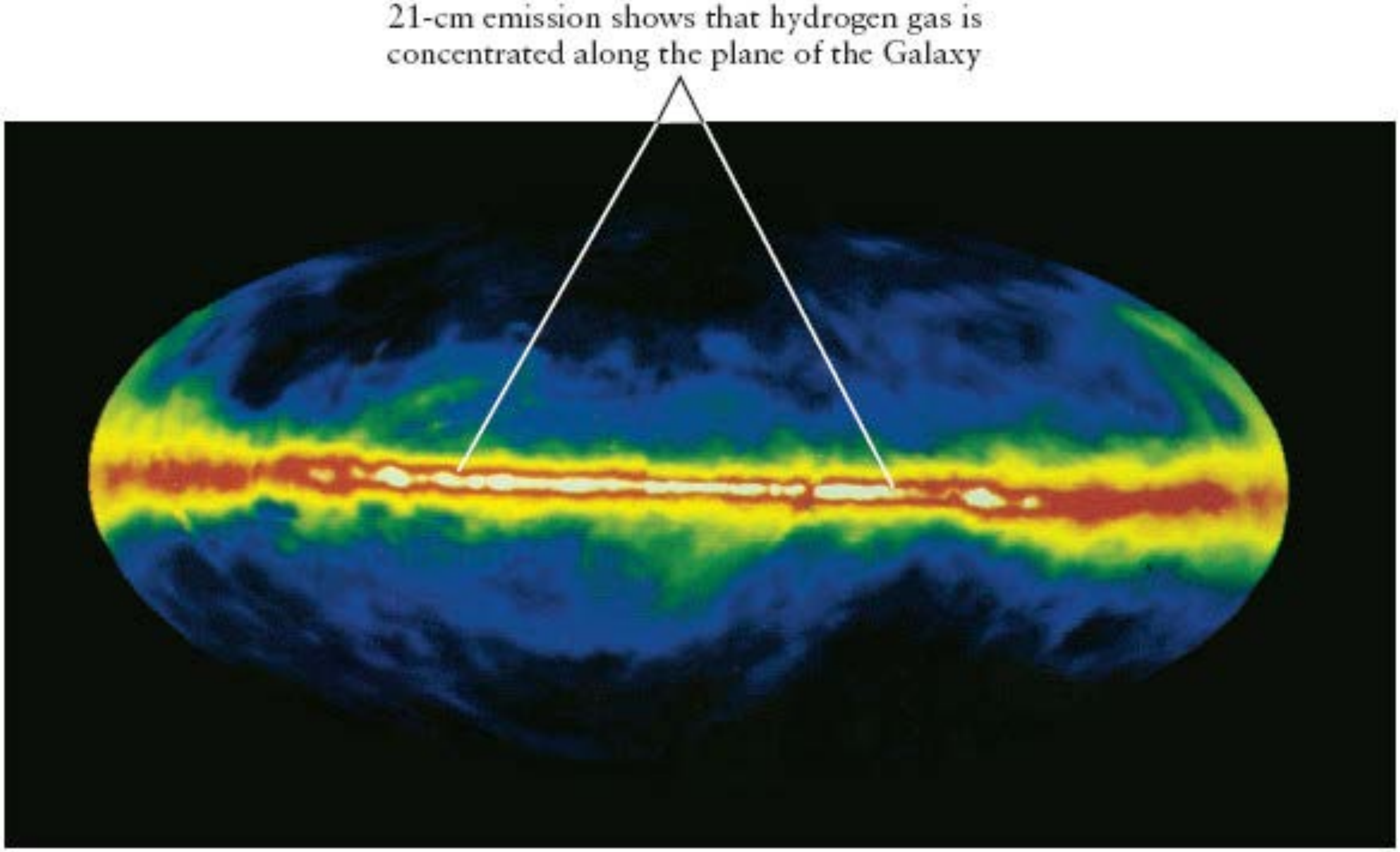
A photon with a wavelength of 21 cm is emitted by a hydrogen atom when the electron flips its spin orientation.

Observations at 21 cm provide maps of the cold H in our Galaxy.



In the higher-energy configuration the electron has its spin in the same direction as the proton's spin.

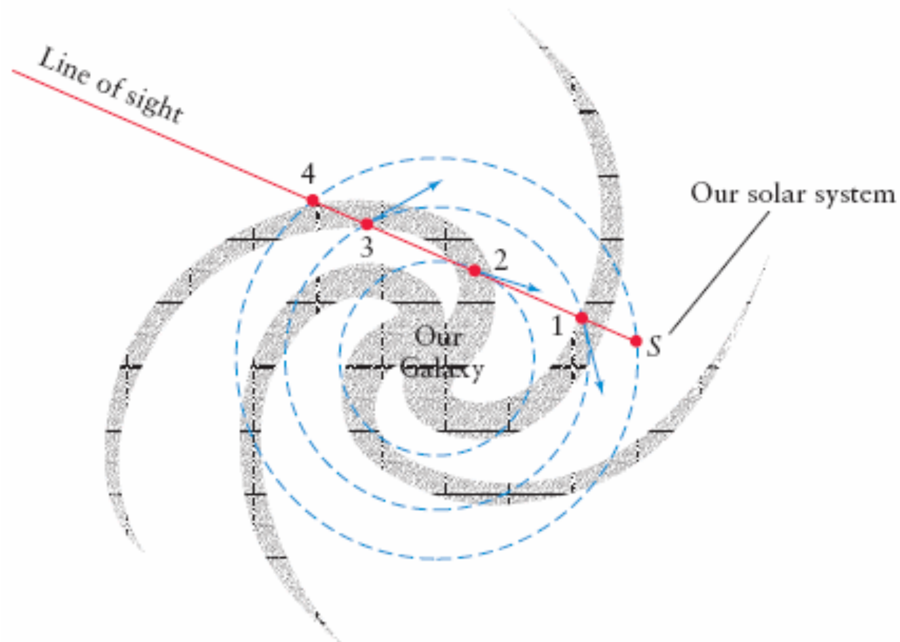
Mapping our Galaxy in Radio Wavelengths



The distribution of neutral H in the disk is not uniform but frothy. Our sun is located in a low density (10^{-3} cm^{-3}) hot bubble of gas (local bubble) with a temperature of $\sim 10^6$ K, possibly created by a supernova explosion ~ 300,000 years ago.

Mapping our Galaxy in Radio Wavelengths

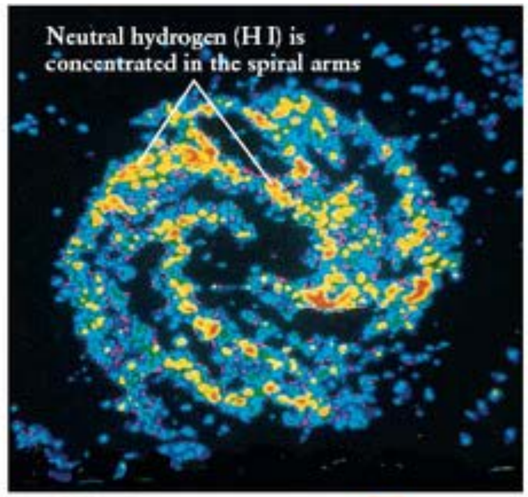
The spirals of our galaxy were mapped out using Doppler shift measurements of the 21 cm emission originating from neutral H in the spiral arms.



- Hydrogen clouds 1 and 3 are approaching us: They have a moderate blueshift.
- Hydrogen cloud 2 is approaching us at a faster speed: It has a larger blueshift.
- Hydrogen cloud 4 is neither approaching nor receding: It has no redshift or blueshift.

Spiral Arms

(a) Visible-light view of M83 R I V U X G



(b) 21-cm radio view of M83 R I V U X G

(c) Near-infrared view of M83 R I V U X G

The images of spiral arms may lead to the false impression that the spiral arms have a much larger density of stars. In reality the density of stars is only about 5% higher in the spiral arms.

The reason the spiral arms appear brighter is that they contain more luminous O and B stars than the rest of the disk.

An image of the disk in the near infrared that is not sensitive to interstellar extinction reveals a smooth distribution of stars.

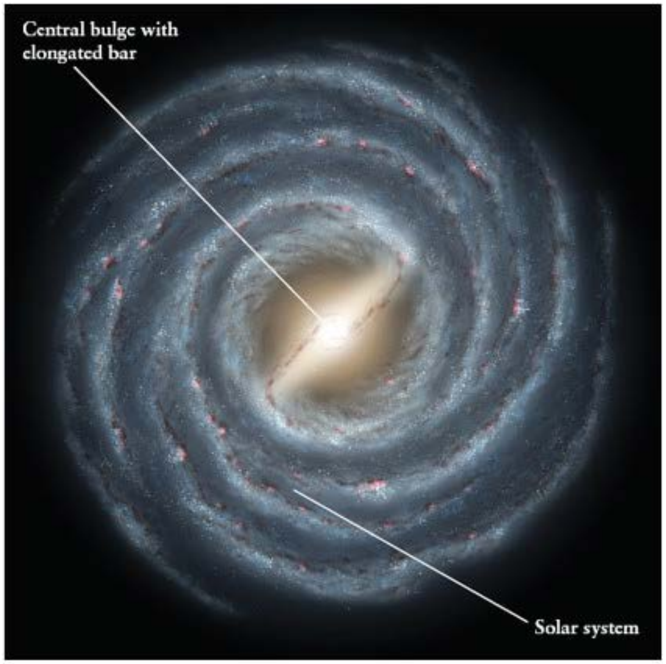
Spiral Arms in our Galaxy

Our galaxy has at least four major spiral arms as well as several short arm segments.

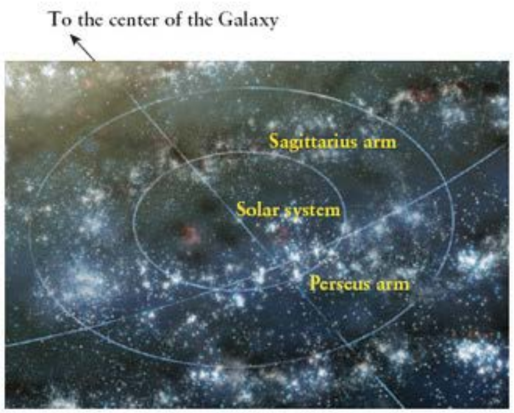
Our solar system is located between the Sagittarius and Perseus arms.

Infrared images show that our Galaxy's **bulge is elongated like a bar**.

Spiral arms are places where matter piles up as it orbits around the center of the Galaxy.



(a) The structure of the Milky Way's disk



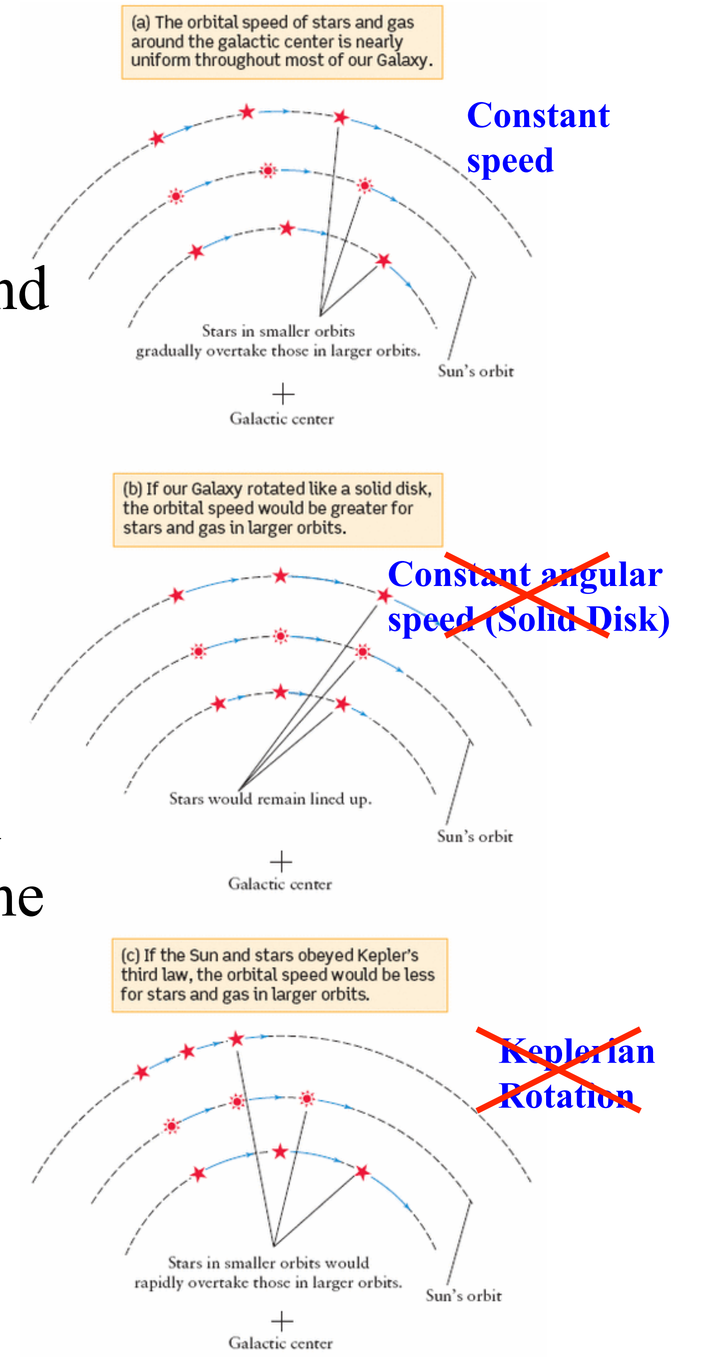
(b) Closeup of the Sun's galactic neighborhood

Our Galaxy

Doppler measurements indicate that the **stars, gas and dust in the disk rotate** around the galactic center **with similar velocities**.

The rotational speed is almost the same as a function of radius. This means that **the disk does not move as a solid body**.

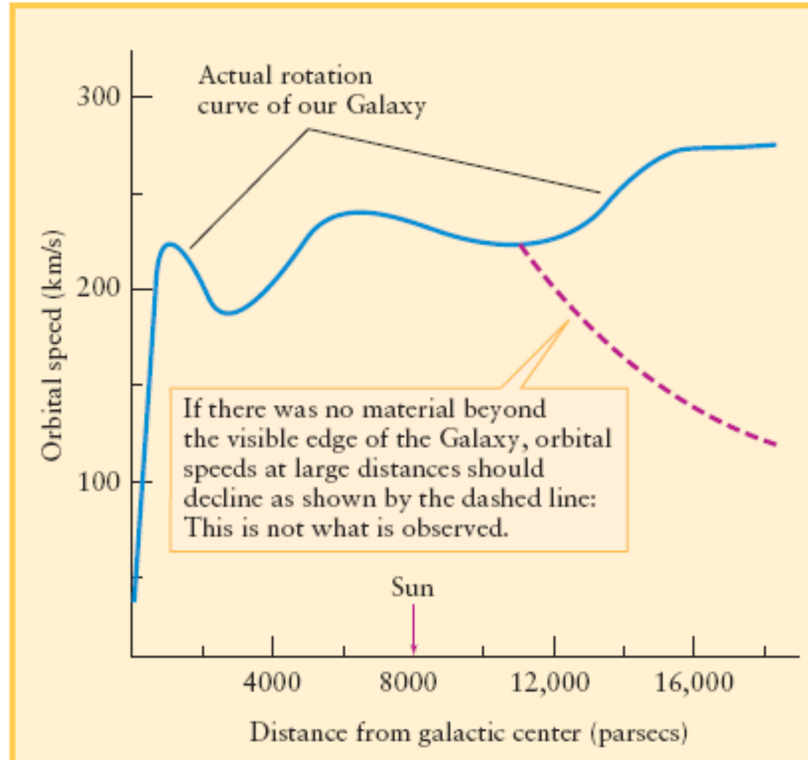
One of remarkable findings of the rotational measurement of our galaxy is that most of the mass of our galaxy is not visible but dark (**dark matter**) and we infer its presence from its gravitational effects.



Rotation Curve of our Galaxy

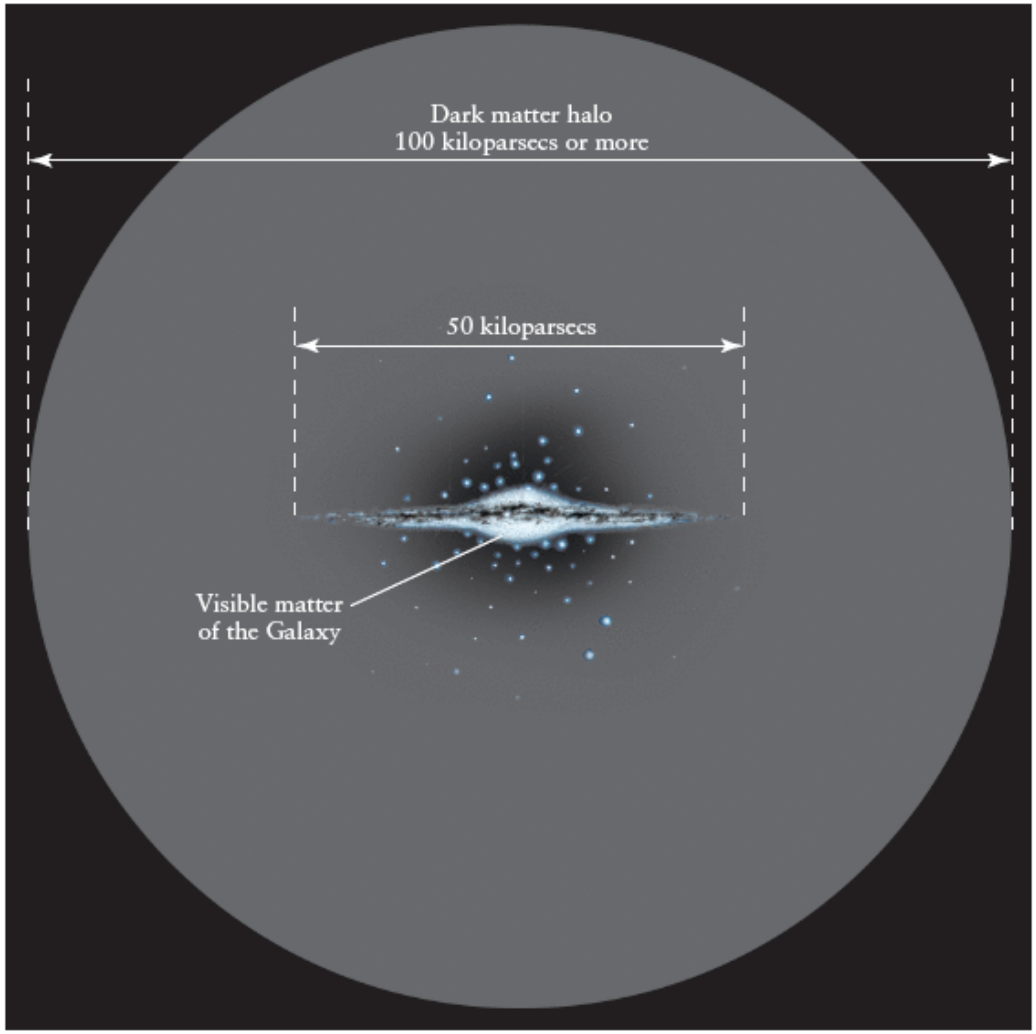
On the right is a plot of the **rotational speed** of stars in the galaxy as a function of radius. The orbital velocities were inferred from Doppler measurements and from the absolute measurement of the Sun's velocity around the center.

One expects, based on Kepler's third law, that objects outside most of the mass to have orbital velocities that decline with distance.



The fact that the rotation curve does not decline beyond the visible edge of the galaxy implies the presence of **dark matter.**

Flat rotation curve implies dark matter in our Galaxy



Our Galaxy

Example: Sun's rotation period around the Galactic center

$$P = \frac{2\pi R}{\mathrm{v}} = 2.2 \times 10^{8}\,\text{years!}$$

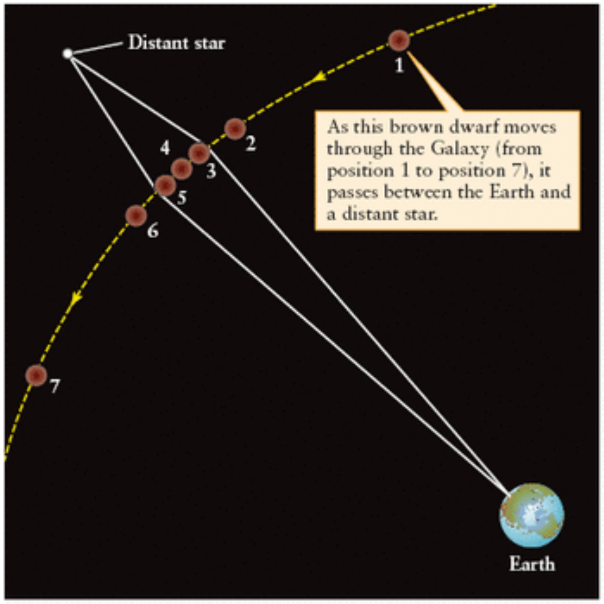
v = speed of sun aroung galactic center = 220 km/s from Doppler shift measurements of distant galaxies and globular clusters in the halo.

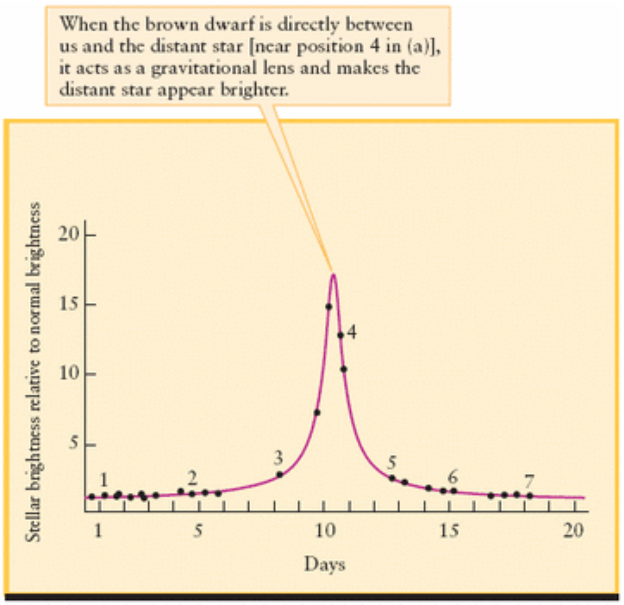
R = distance of sun from Galactic center = 26,000 ly

(1 light year ~ 9.46×10^{15} meters)

How many times has our Sun orbited our Galaxy?

Dark Matter in our Galaxy





One speculation for dark matter is that it is composed of dim objects with masses less than 1 $M_{\odot}$. These objects which would include **brown dwarfs** (object not massive enough to sustain H fusion), **white dwarfs, and black holes** are called **massive compact halo objects (MACHOs)**.

When a MACHO passes between a background star and us it will magnify the light from the star. The degree of magnification and the length of the event provide constraints on the mass of the MACHO object. Astronomers estimate that MACHO's can only account for about half of the dark matter halo.

Dark Matter in our Galaxy

Various dark matter candidates recently proposed are made of more exotic forms of matter. One suggestion is that dark matter is made up of **weakly interacting massive particles** (**WIMPs**).

WIMPs do not interact with electromagnetism (photons) and they don't interact with the strong nuclear force but they do interact with the weak force and gravity.

WIMPs are predicted by some particle theories and are expected to have masses between 10 to 10,000 times that of a proton.

Density-Wave Model of Spiral Arms

Most of the stars, gas and dust in our Galaxy rotate around the center of the galaxy at almost the same speed. Any rigid pattern of stars could not persist after some time.

The **density-wave model** posits that the spirals are actually density-waves that travel around the disk just like ripples on water. These waves move around the galaxy more slowly than do stars, dust and gas.

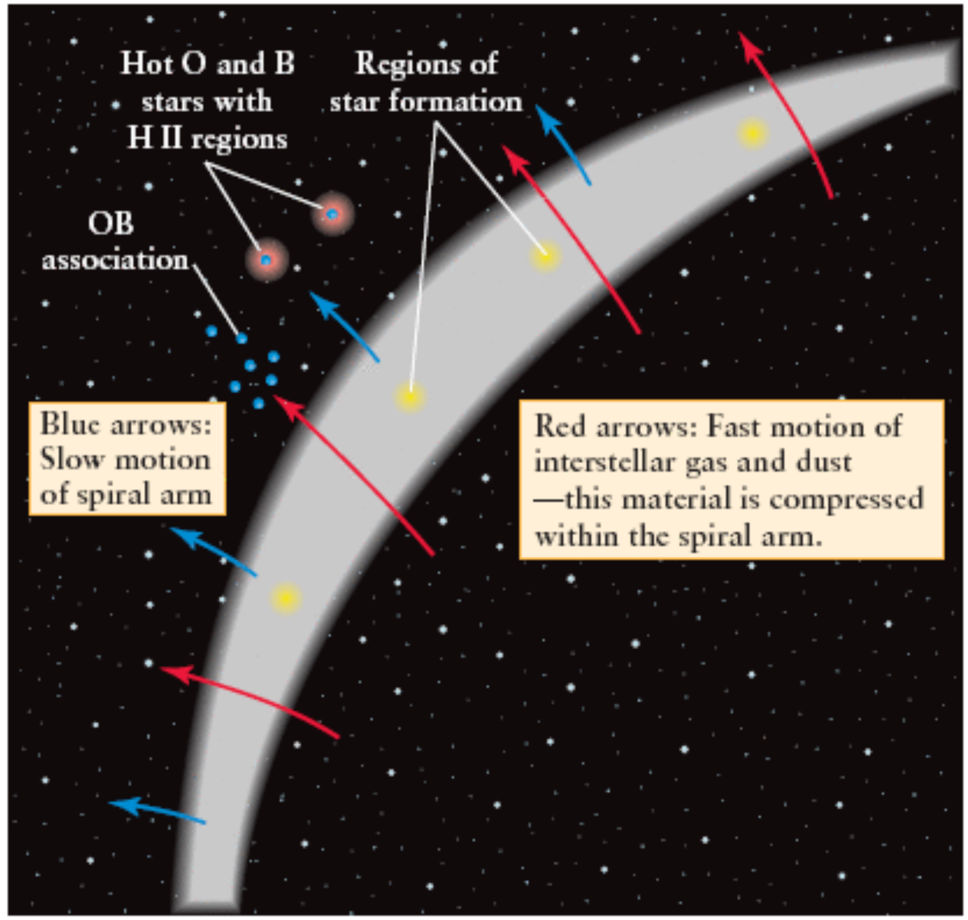
A density wave compresses the gases in the interstellar medium and this **leads eventually to star formation**.

Density-Wave Model of Spiral Arms

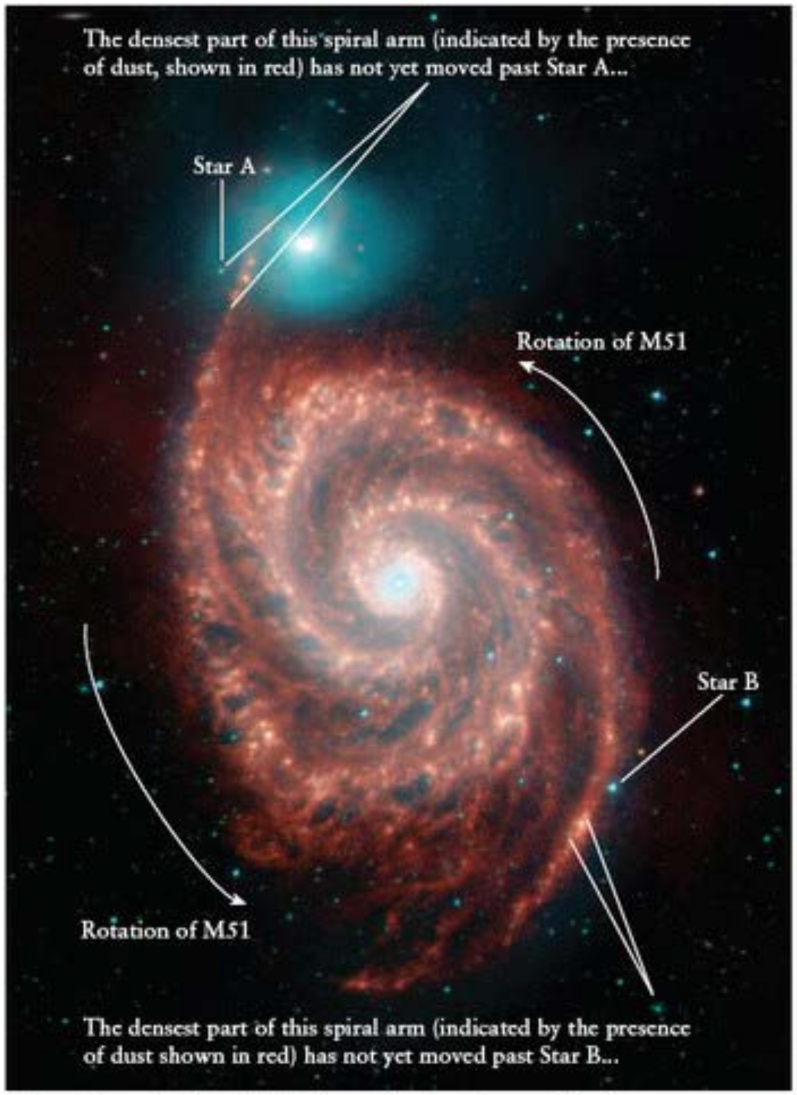
A spiral arm is a region where the density of material is higher than in the surrounding parts of a galaxy.

Interstellar matter moves around the galactic center rapidly (shown by the red arrows) and **is compressed as it passes through the slow-moving spiral arms** (whose motion is shown by the blue arrows).

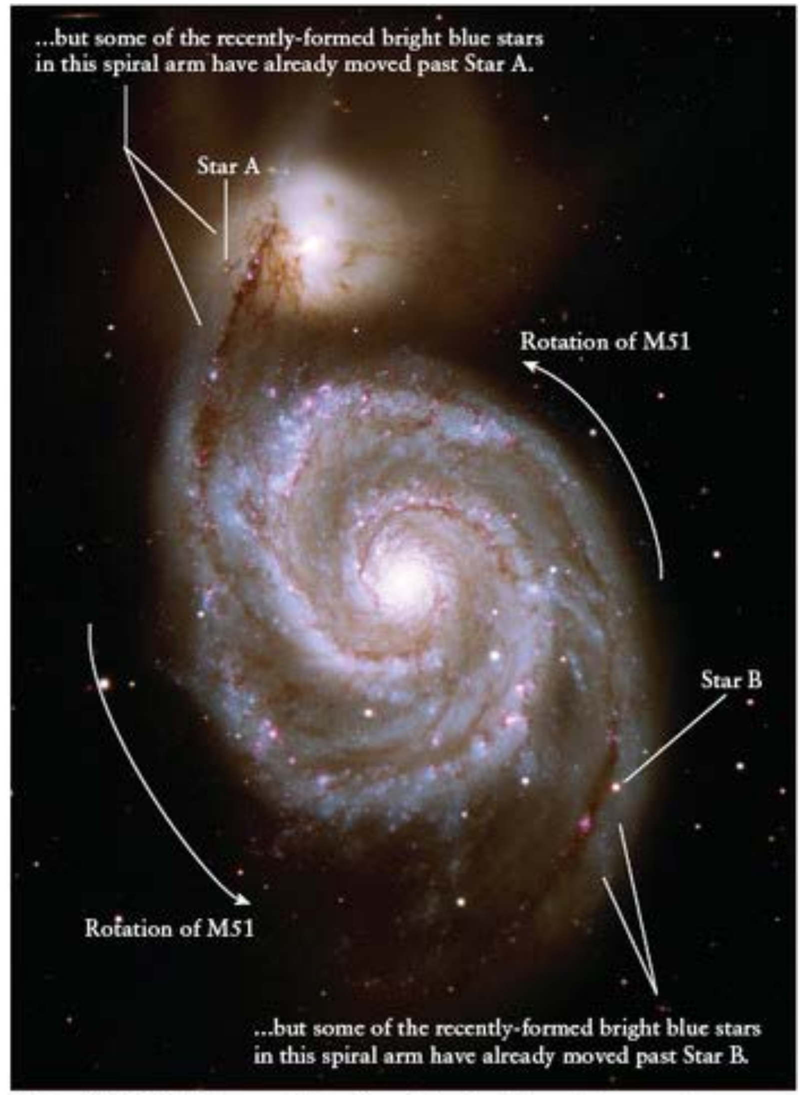
This **compression triggers star formation** in the interstellar matter, so that new stars appear on the "downstream" side of the densest part of the spiral arm.



Density-Wave Model of Spiral Arms



(a) An infrared view of M51 shows the locations of dust



(b) A visible-light view of M51 shows the locations of young stars

Self-Propagating Star-Formation Model of Spiral Arms

(a) Grand-design spiral galaxy

(b) Flocculent spiral galaxy

In the density wave model well defined spiral arms produce star formation.

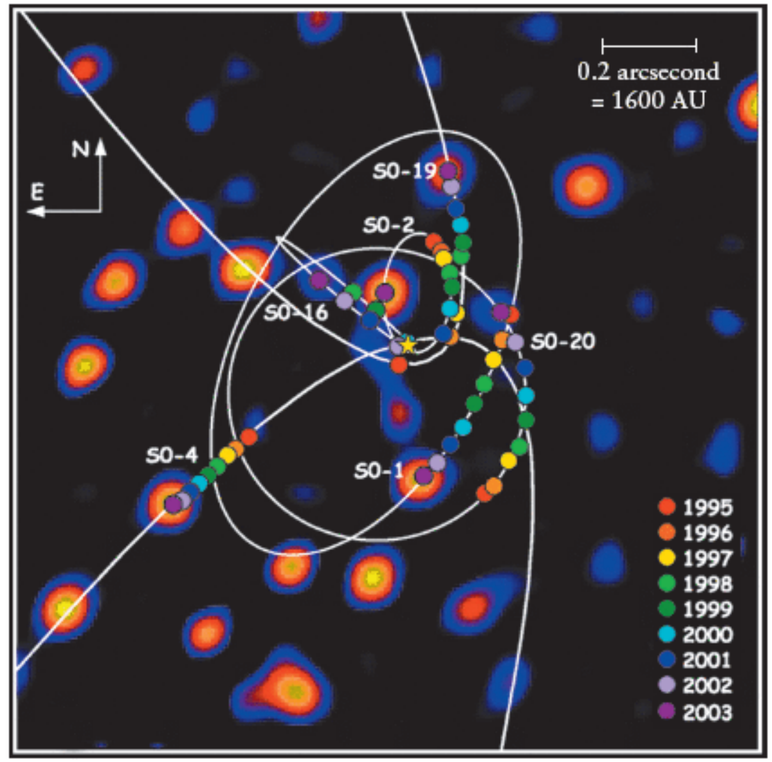
In the self–propagating model chaotic looking spiral arms are produced by star formation.

Galactic Center: Sagittarius A*

At the center of our galaxy resides a supermassive black hole named Sagittarius A*.

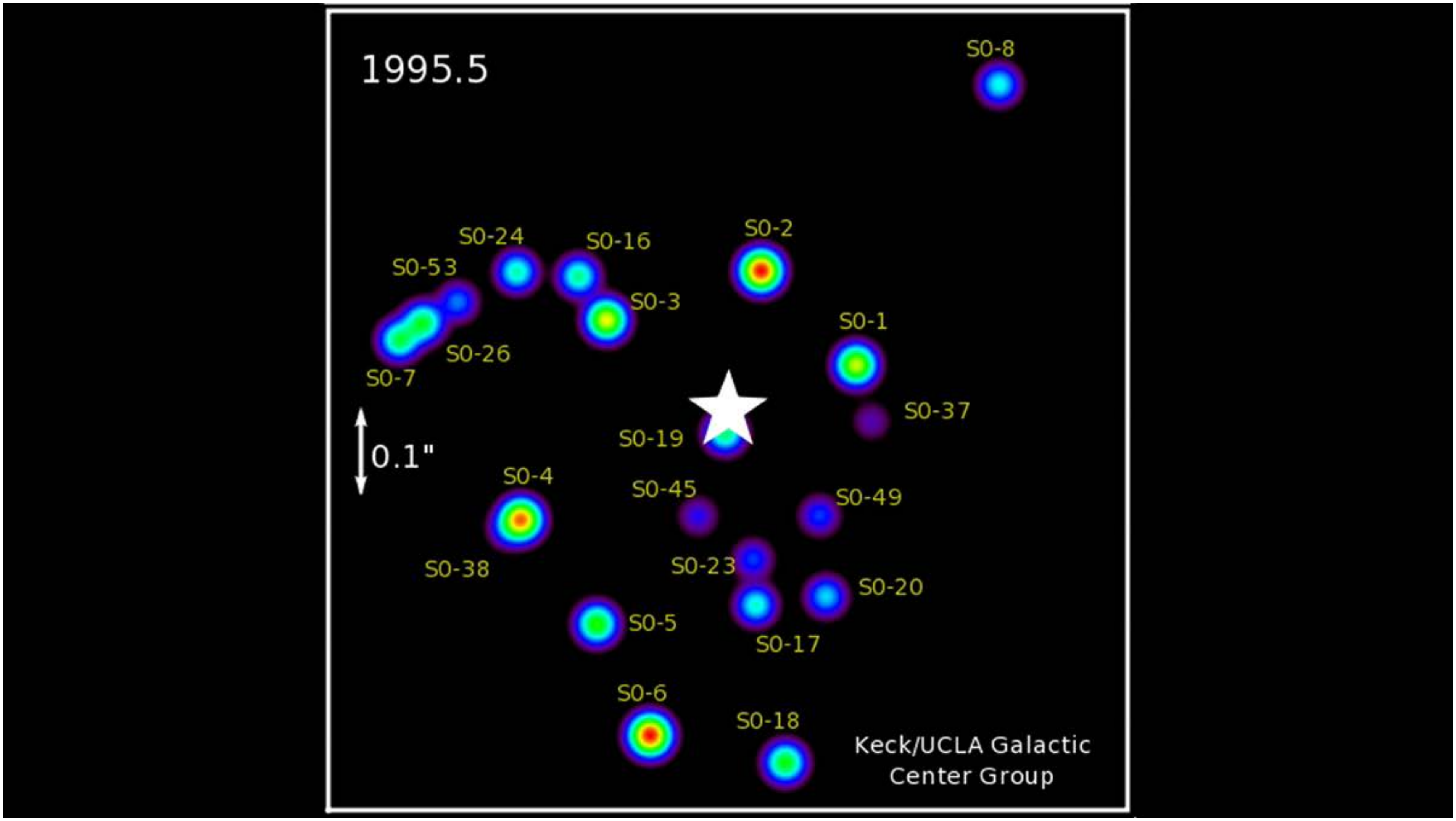
Because of interstellar extinction most of our information on Sgr A* comes from IR and radio observations.

Radio observations of Sgr A* indicate that it is located very close to the center of our galaxy.



Observations in the IR show many stars orbiting Sgr A*. One of these stars got as close as 45 AU to Sgr A*.

Using Kepler's 3rd law the mass of the BH at the Galactic center has been determined to be $\sim 4.2 \times 10^6\ M_\odot$.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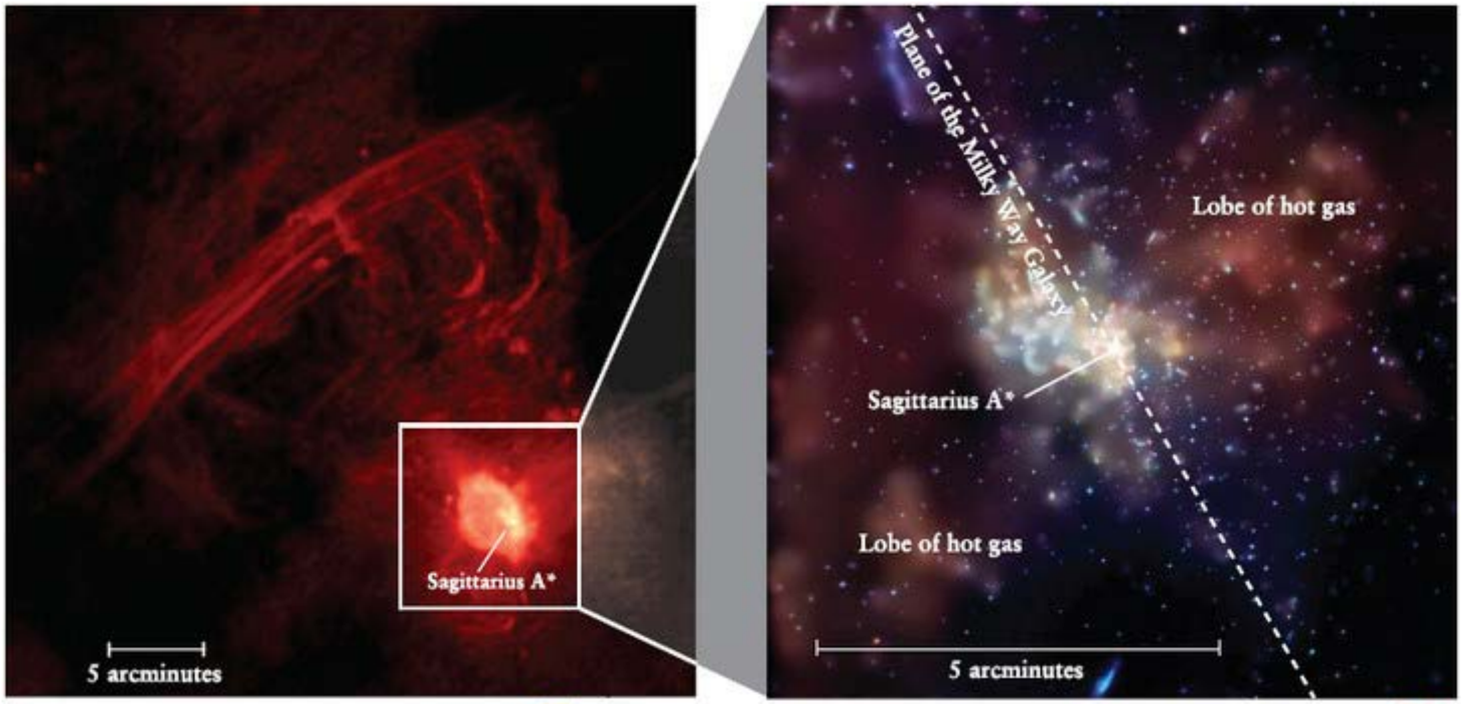
Keck/UCLA Galactic
Center Group

Galactic Center: Sagittarius A*



(a) A radio view of the galactic center R I V U X G (b) An X-ray view of the galactic center R I V U X G

X-ray observations of Sgr A* revealed **X-ray flares on timescales of 10 min** which indicates that the emission region must be smaller than the distance travelled by light in 10 min. The **X-ray emission** from Sgr A* **is very feeble** indicating that the fuel supply is very limited. The immediate vicinity of Sgr A* contains lobes of hot, ionized X-ray gas. It is thought that many **explosions** may have taken place here that perhaps **cleared away most of the gas** leaving only a small amount to fall into the black hole.

Our Galaxy

Example: Mass of our Galaxy within the Sun's orbit.

$$\text{Virial Theorem}: \ 2\,\mathrm{E_K} = -\mathrm{E_P} \rightarrow 2 \times \left(\frac{1}{2} m \mathrm{v}^2\right) = \frac{G M_G m}{R}$$

$$M_G = \frac{\mathrm{v}^2 R}{G}$$

$$\mathrm{G} = 6.67 \times 10^{-11} \ \text{Newton m}^2/\text{kg}^2$$