The Milky Way is a continuous band of diffuse light. The band is thicker and brighter in one part of the sky and 180° away it is thinner and fainter. The band is tilted about 60° with respect to the Celestial Equator.
The Milky Way

Telescopic observations show the band is composed of millions of stars.

What is this collection of stars of which the Sun is a member?

It is the **Milky Way Galaxy** or just **The Galaxy**.

Where Are We Located?

William Herschel (late 1700s) counted stars in 683 regions on the sky. He reasoned he should see the greatest number of stars toward the Galaxy’s center and a lesser number toward the Galaxy’s edge. He found about the same density of stars all along the Milky Way. Therefore he concluded that we are at the center of the Galaxy. Later, Jacobus Kapteyn came to the same conclusion and that the diameter is 17 kiloparsecs (17 kpc).
Interstellar Extinction

Both Herschel and Kapteyn were wrong about the Sun being at the center of the Galaxy. The reason for their mistake was finally discerned in 1930 by Robert Trumpler. While studying star clusters, Trumpler discovered that the more remote clusters appear unusually dim – more so than would be expected from their distances alone.

He concluded that interstellar space contains dust that absorbs or scatters light from distant stars.

Because of interstellar extinction, Herschel and Kapteyn were only seeing the nearest stars.

Dust and Gas

Most of the gas and dust is in the plane of the Milky Way.
The Solution

While interstellar dust in the plane of the Galaxy hides the sky covered by the Milky Way, we have an almost unobscured view out of the plane.

To find our location in the Galaxy, we need to locate (a) bright objects that are part of the Galaxy but lie outside its plane in unobscured regions of the sky and (b) the collection of which surrounds the center of the Galaxy.

Globular Clusters are just such objects.

Finding the Center of the Galaxy
Instability Strips

Why do some stars pulsate?

The structure of any star is determined in large part by how easily radiation can travel from the core to the photosphere – that is, by the opacity, the degree to which the gas hinders the passage of light through it.

If the opacity rises, the radiation becomes trapped, the internal pressure increases, and the star’s envelope expands.

If the opacity falls, radiation can escape more easily, and the star shrinks.

Under certain circumstances a star can become unbalanced and then regularly expand and contract about the balance point. \[ L \propto R^2 T^4 \]
Cepheids

These yellow supergiants have periods in the range of 3 to 50 days and absolute magnitudes (at median light) from -1.5 to -5.0 magnitudes. The amplitudes range from 0.1 to 2 mags. More than 700 are known.

Period-Luminosity Relation

Now we can try to find Cepheids in clusters or galaxies, and after determining the period and amplitude, we can calculate a distance.

Once we have the distance to that cluster or galaxy, we then have the distances to all of the various types of stars in that group. Some of these may be brighter (or more special) than Cepheids, and we use these for still further galaxies.
**Period-Luminosity Relationship**

The period-luminosity law can be used to determine distances. By using photometry to determine the period, one can deduce the star’s average luminosity, and therefore get its absolute magnitude.

With the apparent magnitude (also from the photometry), one can now compute the star’s distance.

\[ m - M = 5 \log (d/10) \]

**RR Lyrae Stars**

Shortly after Leavitt’s discovery, Harlow Shapley began studying a family of pulsating stars related to the Cepheids called **RR Lyrae** variables. The light curve of an RR Lyrae variable is similar to that of a Cepheid, and their period-luminosity relationship is similar to that of the short-period Cepheids.
Obtaining Distances

Most globular clusters contain at least a few RR Lyrae variable stars, whose absolute magnitudes are known. The distance to an RR Lyrae star in a globular cluster, and hence to the cluster itself, can therefore be calculated from its observed apparent magnitude. Shapley used this technique to obtain distances to the globular clusters.

Universe by Freedman, Geller, and Kaufmann

Obtaining Distances

RR Lyrae variables are commonly found in globular clusters. Using the period-luminosity relationship, Shapley determined the distances to 93 globular clusters. He found that some are as far away as 100,000 light years (~33 kpc).
Open clusters are rather uniformly spread along the Milky Way band. However, the majority of the 93 globular clusters that Shapley studied are located in one-half of the sky.

(Although this picture covers only 2% of the sky, it contains about one-fifth of the known globular clusters, which are circled.)

From the directions and distances to the 93 globular clusters, Shapley mapped out their 3D distribution. He concluded that the clusters form a huge spherical distribution centered about a point ~8 kpc away.

Shapley reasoned this point must coincide with the center of our Galaxy because of the gravitational forces between the disk and the “halo” of globular clusters.
Side View of the Structure

The Galaxy is a thin, circular disk of luminous matter distributed across about 50,000 pc (160,000 LY) in diameter, with a thickness of 600 pc (2000 LY). Dust and gas are closely confined to the galactic plane.

The disk is embedded in a halo of largely non-luminous or dark matter that extends to a distance of at least 50,000 pc from the galactic center. The globular clusters are also distributed in a much larger spherical halo around the galactic center.

Within 1000 pc of the galactic center, the stars are no longer confined to the disk but rather form a spheroidal nuclear bulge of old stars.
Side View

Components of the ISM

**Interstellar Gas**
- H II Regions
- H I Regions
- Cold Clouds

**Interstellar Dust**
- Reflection Nebulae
- Dark Nebulae
- Reddening

**Giant Molecular Clouds**
H II Regions

Interstellar gas near very hot stars is ionized by the UV radiation from those stars. All UV light of wavelength 91.2 nm or less can be absorbed by neutral hydrogen, which becomes ionized. An appreciable fraction of the energy emitted by the hottest stars lies at wavelengths shorter than 91.2 nm.

European Southern Observatory

H II Regions

If such a star is embedded in a cloud of interstellar gas, the UV radiation ionizes the hydrogen in the gas, converting it into a plasma of protons and free electrons. The detached protons are continually colliding with free electrons and capturing them, becoming neutral hydrogen again.

As the electrons cascade down through the various energy levels of the hydrogen atoms on their way to the lowest energy levels or ground states, they emit light in the form of emission lines.

Lines belonging to all the series of hydrogen are emitted – the Lyman, Balmer, Paschen, etc. Color photographs of H II regions appear red because of the strongest Balmer line.
H II Regions

When a proton in an H II region captures an electron, light is emitted as the electron cascades down to lower energy levels. The proton then loses that electron again almost immediately by the subsequent absorption of another UV photon from the star. Thus, although neutral hydrogen is responsible for absorbing and emitting light in H II regions, almost all the hydrogen, at any given time, is in the ionized state.

The process for producing clouds of glowing gas near hot stars is called **fluorescence**. The light emitted from regions of ionized gas consists largely of emission lines, so they are also called **emission nebulae**.
H II Regions

Besides ionizing hydrogen and other elements, the radiation from hot stars also heats the gas in the surrounding nebula. When atoms absorb enough energy to become ionized, the electrons carry away some kinetic energy. When they subsequently collide with other particles, the electrons share their energy, increase the velocities of those other particles, and so heat the nebula.

The gas is cooled by the radiation that escapes from the nebula, with oxygen emission being a particularly important source of cooling. The balance of heating and cooling leads to a steady-state temperature of about $10^4$ K for H II regions in our Galaxy.

H I Regions & Cold Clouds

Interstellar matter located at large distances from stars does not produce the strong emission lines that make H II regions visible.

A cold cloud of gas will, however, produce dark absorption lines in the spectrum of light from a star that lies behind it.

This was first seen in spectroscopic binaries, for the interstellar line does not change wavelength.
A hydrogen atom possesses a tiny amount of angular momentum by virtue of the electron’s spin and orbital motion.

In addition, the proton has a spin, too. If the spins are in opposite directions, the atom has a very slightly lower energy than if the two spins are aligned.

If a spin-opposed atom acquires a small amount of energy, the spins of the proton and electron can be aligned, leaving the atom in a slightly excited state.

If it then loses that energy, it returns to its ground state.

The amount of energy involved is that associated with a photon of 21-cm wavelength.
Mapping the Galaxy

Looking within the plane of the Galaxy from our position at S, the H clouds at different locations (shown as 1, 2, 3, and 4) along our line of sight are moving at slightly different speeds.

As a result, radio waves from these various gas clouds are subjected to slightly different Doppler shifts. This permits astronomers to sort out the gas clouds and thus map the Galaxy.

Neutral Hydrogen Map

This map shows the distribution of hydrogen gas in a face-on view of the Galaxy. The map suggests a spiral structure.

Details in the blank, wedge-shaped region are unknown. Cool gas in this part of the Galaxy is moving perpendicular to our line of sight and thus does not exhibit a detectable Doppler shift.
Interstellar Gas in the Disk

Observations at 21 cm show that the neutral atomic hydrogen is confined to an extremely flat layer. It extends to 25,000 pc from the center. At the position of the Sun, the layer is only about 125 pc thick.

Interstellar Dust

In the inner regions of the Galaxy, dust is typically found in the same places as neutral hydrogen. The thickness is also about 125 pc, and there is very little emission from dust lying outside the Sun’s orbit.
Dust

Reflection Nebulae

Some dense clouds of dust contain luminous stars within them and scatter enough starlight to become visible, which is called a reflection nebulae. Blue light is scattered more than red by the dust, so a reflection nebula usually looks bluer than the star.

Dust

Dark Nebulae

While dust clouds are invisible in the optical region of the spectrum, they glow brightly in the infrared. Small dust grains absorb optical and UV radiation very efficiently. The grains are heated by the absorbed radiation, typically to between 20 and 500 K, and reradiate this heat at IR wavelengths.

Barnard Atlas

Australian Astronomical Observatory/David Malin Images
Giant Molecular Clouds

The most massive objects in the Galaxy are not stars but agglomerations of interstellar gas and dust. Because of their size and composition, these massive structures are called giant molecular clouds. A typical cloud has a mass equal to 100 to 1,000,000 times the mass of the Sun, and the diameter of a typical cloud is 15 to 60 pc.

Molecular clouds contain both gas and dust, but their interiors are colder than is typical of most other interstellar clouds. Typical temperatures are about 10 K, so most atoms are bound into molecules. The giant molecular clouds are the birthplaces of most stars.

Important molecules include CN, CH, H$_2$, and CO.
Giant Molecular Clouds

In many cases, individual clouds have gathered into large complexes containing a dozen or more discrete clumps. Since the large molecular clouds and complexes are the sites where star formation occurs, most young stars are also to be found in spiral arms.

The Sun

The Sun orbits the center of the Galaxy at a distance of nearly 8500 pc.
Galactic Disk

Although the Sun lies far from the galactic center, the main disk of the Galaxy extends a nearly equal distance beyond the Sun. The young stars in the disk of the Galaxy are concentrated in a series of spiral arms. The luminous disk is gigantic – at least 50,000 pc (160,000 LY) in diameter.

Spiral Arms

The Galaxy has four spiral arms. The Sun appears to be near the inner edge of a spur called the Orion spur, which is about 5000 pc long. More distant are the Sagittarius-Carina and Perseus arms, located about 2000 pc inside/outside the Sun’s position with respect to the galactic center. These arms, and the Cygnus arm, are about 25,000 pc long. The fourth arm, Centaurus, is difficult to detect because emission from it is confused with strong emission from the central regions of the Galaxy.
Galactic Halo

The globular clusters are distributed in a sphere centered on the Galaxy. A sparse “haze” of individual stars—not members of clusters but far outnumbering the cluster stars—also exists in the region outlined by the globular clusters. This haze of stars and clusters forms the galactic halo, a region whose volume exceeds that of the main disk of the Galaxy by many times.

Individual RR Lyrae stars have been found as far away as 10,000 to 15,000 pc on either side of the galactic plane. A few globular clusters are as far as 80,000 pc.

Galactic Center

Because of the severe interstellar absorption at visual wavelengths, most information about the galactic center comes from IR and radio observations. The strongest IR emission comes from Sagittarius A, which is a grouping of several powerful sources of radio waves. One of these sources, Sgr A*, is thought to be the galactic nucleus. Hundreds of stars are crowded within 1 light years of Sgr A*.
What is Sgr A* 

It is neither a star nor a pulsar, from its high luminosity and radio spectrum. It also cannot be a supernova remnant because it is not expanding rapidly.

It is almost certainly an extremely massive blackhole!!

The strongest evidence comes from recent IR observations of the motions of stars in the vicinity of Sgr A*. Stars are orbiting around Sgr A* at speeds in excess of 1500 km/s.

A source of gravity must be keeping these stars in orbit about the galactic center. Using Kepler’s Third Law, this source must have a mass of $3 \times 10^6$ solar masses. All of this mass is contained in a volume no larger than our Solar System.
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

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 nucleosynthesis. So there are fewer “metals” in their spectra, and these are the high velocity stars.

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.
The 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.

\[ P = \frac{2 \pi r}{v} \]
\[ = \frac{2 \pi [(25,000 \text{ ly}) \cdot (9.46 \times 10^{12} \text{ km / ly})]}{(220 \text{ km/s})} \]
\[ = 6.5 \times 10^{15} \text{ sec} = 200 \times 10^6 \text{ years} \]

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

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

Keplerian Orbits and Rotation

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

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 Example

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

Spiral Density-Wave Theory

As gas and dust approach the inner boundaries of an arm and encounter the higher density of slower moving matter, they collide with it. It is here, where the shock of the collision occurs and that star formation is most likely to take place.

These regions (“arms”) rotate more slowly than do the actual material, so that the stars, gas, and dust pass slowly through the spiral arms.
Spiral Density-Wave Theory

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.

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 $200 \times 10^6$ years, so we have from Kepler’s 3rd Law:

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

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.

Can we compute the total mass in the Galaxy?

Yes, but first we need to rewrite Kepler’s Third Law.
Rotation Curve Derivation

\[ M \propto \frac{v^2 r}{G} \]

\[ M = \frac{4\pi^2 G r^3}{P^2} \]

\( P = \frac{2\pi r}{v} \) so \( \frac{1}{P^2} = \frac{v^2}{4\pi^2 r^2} \)

\[ M = \frac{4\pi^2 G r^3}{P^2} \cdot \frac{v^2}{4\pi^2 r^2} \]

\[ M = \frac{v^2 r}{G} \]

\( M \) is the mass inside a circular orbit of radius \( r \) and orbital speed \( v \).

Actual Rotation of the Galaxy

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.

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!!!*

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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

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