# Chapter 23 The Milky Way Galaxy

## Our Parent Galaxy

A *galaxy* is a huge collection of stars, nebulae, gas, dust and other things. They are usually isolated in space and they are held together by their own gravity. Our galaxy is known as the *Milky Way Galaxy* or just *the Galaxy*. The Sun lies in the galactic disk which is an immense, circular flattened region which contains most of the Galaxy's luminous stars and interstellar matter. As seen from the disk, if we look above or below we see few stars in the sky. If we look through the disk, the stars are so numerous that they join together to form a luminous cloud. From our position in the galaxy it is hard to decipher the large scale structure of the Galaxy. That is why we look to other galaxies that look lie the Milky Way. We use those galaxies to determine more about where we live since we can see them clearly. Figures 23.2 and 23.3 shows us 3 galaxies that are thought to look very much like our own galaxy. One is the Andromeda Galaxy which is the closest large galaxy to us at 2.5 million light years. When studying the Galaxy, we find that not only does it contain a disk of stars, but it also has the *galactic bulge* or *nucleus* at the center of the galaxy and a *galactic halo* which surrounds the galaxy. The other 2 photos show us a galaxy that is face on and the other one shows a galaxy that is edge on.

## Measuring the Milky Way

Before the 20$^{th}$ century the idea of galaxies did not exist. It was thought that everything that we saw was in the Milky Way. There was no "our Galaxy" and "the Universe."

### Star Counts

In the late 18$^{th}$ century, William Herschel tried to estimate the size and shape of our galaxy. He did this by counting the number of stars that could be seen in a particular direction. He assumed that all stars were of the same brightness and he concluded that the galaxy was somewhat flattened, roughly disk shaped. He placed the Sun at the center of the galaxy. We now know that the Milky Way is about 100,000 light years across and that the Sun is not in the center. Due to the interstellar dust objects more than a few kiloparsecs are obscured from us. The falloff in the number of stars is simply because we can no longer see through the haze. At this time we were only looking in the visible part of the spectrum.

### Spiral Nebulae and Globular Clusters

Looking through the disk of the galaxy means that we are hampered by all of the stars and the interstellar material. On the other hand if we look out the plane of the disk we can see much further. In the early 20$^{th}$ century we looked at 2 different classes of objects mainly found away from the galaxy: the globular clusters and the spiral nebulae. We know that the globular clusters are tightly packed swarms of old, reddish stars in the Milky Way. We know of about 150 of them in our galaxy. The spiral nebulae are now known to be *spiral galaxies* like our own galaxy. But one problem was how to measure distances to these objects. They are too far away to do parallax and the technology did not allow them to see individual stars. That meant that these objects were not clearly understood. It was assumed that the globular clusters were in our galaxy, which was thought to be quite small. It was originally thought that when they looked at the Andromeda *Nebula* that they were looking at eh beginnings of a new star with the disk of dust and gas swirling around it. They began to realize that Andromeda was too far away to measure much parallax making it at least 100 pc away. At this distance you wouldn't be able to see those details. ( the Andromeda Galaxy is much farther away than that) The big argument was whether these objects were small and within our galaxy or large objects that lay far outside the Milky Way. With out a way to measure distances it was impossible to tell.

A New Yardstick

At the turn of the century one of the things that was being looked at were the *variable stars*. These are stars that change their luminosities for whatever reason. We know that we have eclipsing variables in binary systems. But some stars just change their brightness. These are called *intrinsic variables*. An important class of these variables is the *pulsating variable stars*. They vary their luminosities in cycles that we can measure. Two types of these variables are the *RR Lyrae* stars and the *Cepheid* variables. They are recognized by the shape of their light curve. RR Lyrae is found to pulse between .5 to 1 day. Cepheids can pulse anywhere from 1 to 100 days. The big thing about these 2 kinds of stars is that we can recognize them just from their light curve. Why do they pulse? One idea was that their opacity increases, trapping the radiation until the outer layer puffs up and lets the radiation to escape. These pulsations are not found in stars on the main sequence. These stars are unstable internally. These stars became very important because when we understood them better, they allowed us to measure distances. In the early 1900's, a relationship was developed between the luminosity and period of a Cepheid variable star. It was put together by Henrietta Levitt. It is called the *period-luminosity relationship*. The longer the period, the brighter the star would become. Once we had this all we needed was the period and we could determine the luminosity. This led to Apparent brightness $\alpha$ luminosity/distance$^2$. So if we can measure the period of the star, we can determine the absolute magnitude. By looking at the star we can measure the apparent magnitude. Knowing those 2 numbers we can calculate distance. This allows us to see out to about 25 million pc. Figure 23.8 shows us the cosmic distance ladder which shows ways to measure distances.

The Size and Shape of our Galaxy

In the early 20$^{th}$ century Harlow Shapley made 2 very important discoveries. By looking at RR Lyrae stars in globular clusters he found that the clusters all lie at great distances from the Earth, many thousands of parsecs. He also produced a three dimensional distribution of the clusters in space. The clusters mapped out a gigantic, roughly spherical shape in space about 30 kpc across. But the important discovery was that they weren't around the Sun, but rather 8 kpc away in the direction of Sagittarius. Shapley realized that the clusters mapped out the extent of the stars in the Milky Way. They are found in the area that we now call the *galactic halo*. The central region that the clusters orbit is the *galactic center* or nucleus. From figure 23.10 you can see how they are distributed as well as seeing that we live in the suburbs. Up to now we thought that we were in the center of the galaxy but Shapley showed that not to be true.

## The Shapley-Curtis Debate

Unfortunately Shapley's discovery about the size of the Milky Way and our place in it helped strengthen his opinion that the spiral nebulae were in the Milky Way. He could not believe that there were other structures as large as the Milky Way out there. In 1920 there was a famous debate between Shapley and Heber Curtis. Here are some of the key parts of the debate:

1. Shapley correctly asserted the size of the Milky Way was much larger than thought, but incorrectly believed in the spiral nebulae. Curtis believed that the Milky Way was much smaller but that the spiral nebulae were actually outside the Milky Way.
2. Curtis noticed that the spiral nebulae were found away from the plane of the galaxy and that the galaxy had a ring of occulting material blocking the view. Shapley just said that there were no spiral nebulae in the plane of the galaxy.
3. Shapley argued correctly that the observed brightness of some "novae" seen in spiral nebulae implied enormous distances. Curtis suggested correctly that these novae might be members of a second, much brighter class of novae; we call them supernovae.
4. Shapley pointed out that the brightnesses and colors of the spiral nebulae were different from he expected the Milky Way to look like from great distances. Curtis had no answer for this.
5. Shapley said that the rotational speed of the spiral nebulae would need to be greater than the speed of light if they were really that far away. Curtis responded that the observations were in error. Curtis was right.

Both men were right and wrong about what they thought. At this time they couldn't be resolved due to the lack of technology.

## Galactic Structure

We have studied the Milky Way Galaxy in a number of different wavelengths. Our knowledge of the halo comes from optical observations of the globular clusters and halo stars. Due to the dust much has come from radio observations. Looking into the center of the galaxy we need radio telescopes to do this. The center coincides with the globular cluster system.

## The Spatial Distribution of Stars

The thickness of the disk out where the Sun is is relatively thin, only about 300 pc, or about 1000 light years. You will find that the clouds of dust and gas and the newly formed stars are much closer to the plane of the disk because after they are born, stars tend to drift away from the plane of the galaxy. This is due to gravitational interactions with other objects. This does not apply to the halo objects. These objects predate the formation of the disk. We have recently discovered another class of stars that are between the halo stars and the newly formed stars. They are about 7 – 10 billion years old and they make up the *thick-disk component* of the disk. It probably measures 2-3 kpc from top to bottom. That is too far out for the drift to account for, so it is thought that they are remnants of early star formation. The central bulge measures 6 kpc across and 4 kpc thick. All of the dust makes it very hard to see inside with optical telescopes. Long wavelengths are not affected by the dust and gas, so we can use radio telescopes to see down inside. From observations, we now believe that we live in a barred spiral galaxy.

Stellar Populations

The 3 components of the galaxy have several properties that distinguish them from each other. For example, the halo contains almost no dust or gas in it while the other 2 parts are full of it. There are also differences in appearance and composition of the stars that are found in the 3 parts. Stars in the halo and the nucleus are much redder than stars in the disk. Other spiral galaxies show this same trait. The bright blue stars are found in the disk of the galaxy. Cooler, redder stars are found evenly distributed throughout the disk, halo, and nucleus of the galaxy. The disk appears much bluer because of the abundance of O and B class stars that you find there. The main difference is this: there is ongoing star formation in the disk because of the dust and gas while the nucleus has no such material and that means that those stars are old. It is also true for the halo. Here star formation must have stopped about 10 billion years ago. The halo and nuclear stars have a much lower abundance of heavy elements (heavier than helium) than the stars in the disk. That is because the disk stars live, age and die and redistribute the material that becomes the next generation of stars. The young disk stars are called *Population I* stars while the older, redder stars of the halo and nucleus are called *Population II* stars.

Orbital Motions

Let's look at the motion of everything in the Milky Way. On a small scale the motions appear very random, but when you look at the big picture the motions all follow a very orderly pattern. Looking at the shift in the light from different parts o the galaxy, we find that some parts are coming towards the Sun and other parts are moving away. All of this information has led us to 2 conclusions: 1) we are rotating. The orbital speed out where the Sun is is about 220 km/sec around the nucleus. 2) The rotational period depends on where how far out you are from the nucleus. This means that the galaxy does not rotate as a solid object. This data only applies to the disk, not the halo or the nucleus. These stars move in rather random motions. The halo stars regularly move in and out of the disk as they go around the nucleus. Some well known stars like Arcturus are halo stars that are just passing through.

The Formation of the Milky Way

Our galaxy formed over 10 billion years ago. Astronomers don't agree on all of the details, but they do agree on the overall picture. Figure 23.14 shows the current view of the formation. The general idea is that there were several clouds spread out over a large area As the stars and globular clusters formed the gas had not accumulated into a disk. It was spread out over an irregular and quite extended region of space. The first stars were spread out over the entire region. The first stars ended up being the halo now. The gas clouds and gas began to collapse. Since then the rotation has flattened the gas into a thin disk. The halo is ancient and the disk is young, blue stars. When the halo stars formed the rotation was not very orderly. That is why the stars in the halo appear to move in random fashion. As the disk contracted, the conservation of angular momentum caused the disk to rotate faster. The stars that formed here inherited the same rotation as the disk. After al that has been done, the early Milky Way is poorly understood.

## Galactic Spiral Arms

In the 1950's astronomers developed spectroscopic radio astronomy to delve into the heart of the Milky Way.

### Radio Maps of the Milky Way

The key to studying the Galactic interstellar dust is the 21 cm radio emission produced by atomic hydrogen. The radio waves allow us to see farther than with optical devices. Since hydrogen is the most abundant element in the universe, the 21 cm radiation is strong enough that a large portion of the disk can be seen in this way. The distances to the clouds are not well known. Astronomers pull all the information together to make a mathematical model of the rotation of the stars and gas throughout the Galaxy. Radio astronomers combine the model with their observations to turn their measurements into detailed information about the distribution of gas. The distance from the center of the galaxy determines the velocity of the stars.

### Spiral Structure

As you move towards the center, you will find that the gas fattens markedly. Gas has been measured out to about 50 kpc from the galactic center. As you move outward in the disk the thickness thins out to a few kpc. The gas shows signs of being warped due to gravitational attraction of 2 nearby galaxies. The radio studies show us the best evidence that we live in a spiral galaxy. Figure 23.16 is an artist's conception of our Galaxy. You can clearly see the spiral arms in the drawing. Our Sun lies near the edge of one of the arms. The structure of the galaxy is about 30 kpc, which is fairly typical of spiral galaxies.

### Persistence of the Spiral Arms

In the arms of the galaxy we find O and B class stars, recently formed open clusters, and emission nebulae. This says that this is where star formation is taking place. A big problem facing astronomers is why the spiral arms persist. Differential rotation makes it impossible for the arms to survive. They should wrap around the nucleus. Figure 23.17 shows how the arms should wrap up as the galaxy rotates. How do the arms keep their shape? One theory is that *spiral density waves* cause this to happen. These waves sweep through the galaxy and maintain the shape of the arms. This happens just like a sound wave moving through the air. Near the nucleus the density wave moves more slowly than the arm. As the arm catches up to the density wave it is compressed and the gas is compressed and stars form. We are unsure of just how many arms the Milky Way has. A different theory is that the formation of the stars drives the density waves. As the gas is compressed by a newly formed star, more new stars are formed which causes a wave which can compress more gas. This is called the *self-propagating star formation*. There may very well be more than one process going on at the same time.

### Origin of Spiral Structure

We really don't know what caused the spiral arms. Some ideas are the gravity of companion galaxies, instabilities in the gas near the bulge, or the possible bar-like asymmetry within the bulge.

The Mass of the Milky Way Galaxy

We have used Kepler's third law to determine the mass of the Milky Way. It comes out to be about 90 billion $M_{sun}$. This is only the mass inside of our Sun and does not take into consideration of the mass outside the Sun's orbit.

Dark Matter

To better measure the mass of the galaxy, we need to measure the orbital motions of the stars farther out to the edge of the galaxy. The plot of rotation speed versus distance from the center is called the *Galactic rotation curve*. We know that out to about 15 kpc from the center the total mass is $2 \times 10^{11}$ $M_{sun}$. If all the mass were contained within the visible edge, then the speed of the stars and gas beyond 15 kpc would drop off. The dotted line on figure 23.21 shows what that would look like. The red line shows what it is really like. That means that there is mass out there we can't see. We now think that what we see as the halo as marked by the globular clusters is only the tip of the ice berg. There must be a much larger *dark halo*. It has been determined that most of the mass of the galaxy must be *dark matter*. It is called dark because it is invisible in all wavelengths. We just don't know what it is. One possibility is called MACHO's which stands for MAssive Compact Halo Object. A different type of particle is called WIMP's which is Weakly Interacting Massive Particle. It has been estimated from gravitational studies that maybe as much as 90 % of the universe is dark.

The Search for Dark Stellar Matter

There is a large effort to find the stellar mass dark matter in the universe. The problem is how to find it. One of the ways to do this is by *gravitational lensing*. That is where a small body passes in front of a distant star. As it does it causes the light to be spread out and the star appears to get brighter for an instant. See figure 23.23. The small object can't even be seen, just the effect. Astronomers use automated equipment to look at millions of stars every few days for years to watch for these events. We have now seen a number of these events which has allowed astronomers to calculate the amount of dark matter in the galactic halo.

The Galactic Center

Theory says that the bulge of the galaxy should consist of billions of stars, but with all of the interstellar dust between us and it we can't see them. Figure 23.2 shows what we see when we look in the direction of the center which is in Sagittarius. Infrared observations shows us that the stellar density in the center is about 50,000 stars per cubic pc which is about 1 million times denser than in our solar neighborhood. We have also detected huge clouds rich in dust. There is also a ring of molecular gas nearly 400 pc across containing some 30,000 $M_{sun}$ of material. It is rotating around at about 100 km/sec. Figure 23.25b shows a region called Sagittarius A (bright radio source). It is thought to be in the center of the galaxy. There are filaments that extend about 100 pc which says that there is a strong magnetic field. There appears to be a ring that is only a few pc across and in X-rays it appears to be a supernova remnant. Figure 23.25d The object has a huge mass and is very small physically and that means that it must be a what?

An accretion disk around the hole is the source of the energy coming from the hole. As material falls in, it heat up and emits in X-rays. A strong magnetic field may act like particle accelerators and causes cosmic rays. At the center of the galaxy is an object called Sag A* (Sag A star). Sag A* is can't be more than 10 AU across. Several stars near this object have been observed for several years and their *proper motion* has been mapped. It is thought to be a black hole with a mass of 2.6 million $M_{sun}$ and an event horizon that is .02 AU across. The last few decades has seen an explosion in our knowledge of the center of the galaxy. Even so we are only now we are beginning to appreciate the realm of the center of our galaxy.