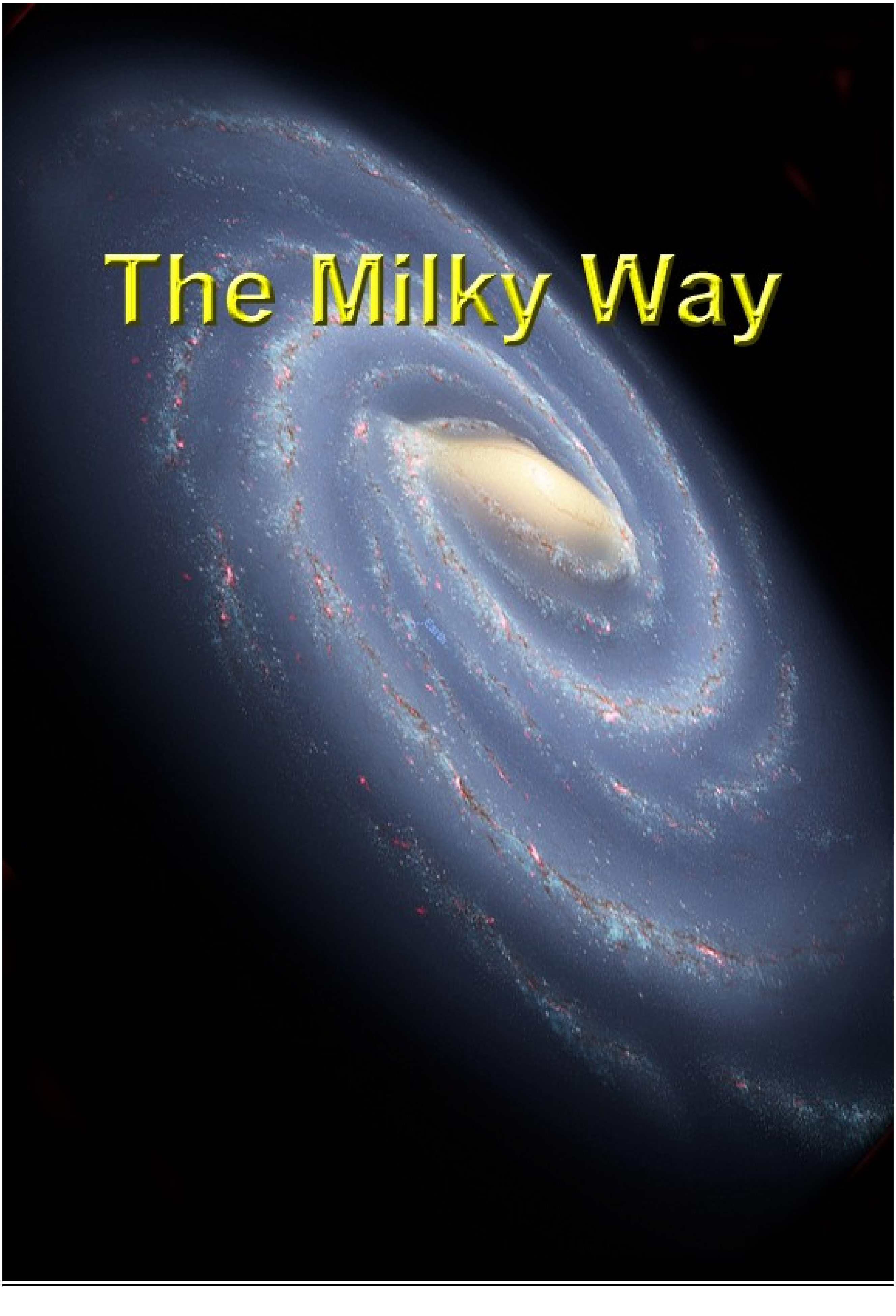

The Milky Way

The Milky Way

*{**Abstract** – In this segment of our "How far away is it" video book, we cover the structure of the Milky Way galaxy.*

After a brief history of what we thought going into the 20^{th} century and how that changed, we give a high-level description of the three main components: the galactic center with its black hole, the galactic disk with its spiral arms, and the galactic halo stretching far out in all directions.

Using the full power of the Hubble, Spitzer, and Chandra space telescopes, we take a deep dive into the center of our galaxy with its central bulge. We detail the evidence for the existence of a supermassive black hole, Sagittarius A, at the very center of the galaxy's core. We cover and illustrate the work done by the UCLA Galactic Centre Group in conjunction with the new Keck observatory on top of the Mauna Kea volcano in Hawaii, and the Max Plank Institute for Extraterrestrial Physics in Germany. This includes the obits of S0-2 and S0-102 as they approach Sag A*. A look at the G2 Gas Cloud as it approaches Sag A* is also included.*

Next, we go a level deeper into the nature of a Black Hole singularity. We review electron exclusion pressure and neutron exclusion pressure forces that hold back gravity for White Dwarfs and Neutron stars respectively. When that isn't enough, we get a total collapse. We cover the Schwarzschild radius, event horizon, accretion disk and gamma-ray jets. In addition to the supermassive black hole Sag A, we show a few of the solar mass black hole candidates including A0620-00, and GRO J1655-40.*

We then cover the structure of the galactic disk including: the bar core, the two 3 Parsec arms, Scutum-Centaurus, Perseus, Sagittarius with its Orion Spur, Norma and the Outer Arm. We review the locations of various celestial objects we've seen in previous Milky Way segments, to show how close to us they are. We also cover the disk's rotation and the Sun's orbit. We end the galactic disk coverage by illustrating how far one would have to go to take a picture that would include what we see in our illustrations.

Next, we cover the galactic halo. We start with Sharpley's globular cluster map that first showed that we were not at the center of the galaxy. We cover the size of the halo, the inner and outer halos orbital motion, and recent discoveries of massive amounts of Hydrogen in the halo and this findings impact on the Dark Matter debate.

*We conclude with another look at the distance ladder that took us across the galaxy.***}**

Introduction

> **[Music:** *Beethoven - Symphony No.9, 'Choral' _ III – Completed in 1824, this was Beethoven's last and best symphony. Accompanied by the poem "Ode to Joy" written by Friedrich Schiller in 1785 and adjusted by Beethoven for his 9th. This most wonderful of symphonies is most appropriate for covering the scope and structure of our magnificent Milky Way galaxy.***]**

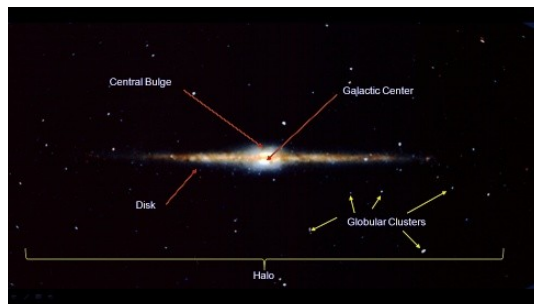
Welcome to our final segment on the Milky Way. In this segment:

- We'll go over our current understanding about the structure and size of the Milky Way as a whole, and our place in it.
- We'll examine the galactic center with its supermassive black hole. We'll go a little deeper into the nature of a black hole and show a few of the black hole candidates we have found.
- We'll explore the galactic disk with its spiral arms.
- And we'll cover the latest information on the galactic halo.

And, as usual, we'll discuss how we came to know these things from our viewpoint deep inside the galaxy itself.

Galaxy Overview

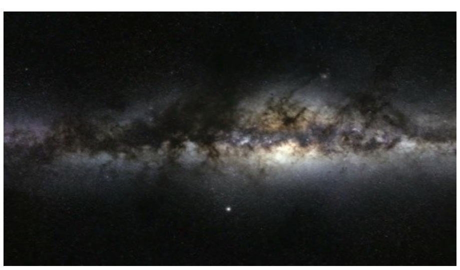
On January 1st, 1990, from its orbit around Earth, the Goddard Space Flight Center's Cosmic Background Explorer captured this edge-on view of our Milky Way galaxy in infrared light. The galaxy has a center with a central bulge, a disk of rotating stars and dust and a halo with lots of globular clusters. The disk is around 100,000 light years in diameter, and the halo is much larger than this.



We'll go into each of these galaxy components, starting with the galactic center.

Galactic Center - 26,000 light years

Here we have one of the most detailed images of our galaxy ever created. It is constructed from over a thousand photographs taken from the darkest places on earth and painstakingly stitched together.



We exist inside the galaxy, so we have to view it all around us as we rotate each day. As we look into the plane of the galaxy, we see that the stars are so closely packed together that it looks like a bright glow. We also see tremendous dust clouds obscuring most of the stars.

As we look above and below the center line, the number of stars decreases to the point where they are readily seen as individual stars and the dust clouds are gone.

The central area

The world's Great Space Observatories — the Hubble Space Telescope, the Spitzer Space Telescope, and the Chandra X-ray Observatory — have collaborated to produce this unprecedented look at the central region of our galaxy.

- Hubble documented vast arches of gas, heated by stellar winds from very large stars.
- Spitzer's infrared picked up the pervasive heat signals of all these stars.

- Chandra detected x-ray sources from ultra dense neutron stars and small black holes.

Together, they produced this spectacular image.

[Additional info: Observations using infrared light and X-ray light see through the obscuring dust and reveal the intense activity near the galactic core.

Note that the center of the galaxy is located within the bright white region to the right of and just below the middle of the image.

Each telescope's contribution is presented in a different color:

- Yellow represents the near-infrared observations of Hubble.

- Red represents the infrared observations of Spitzer.

- Blue and violet represent the X-ray observations of Chandra.

When these views are brought together, this composite image provides one of the most detailed views ever of our galaxy's core.**]**

<u>The Supermassive Black Hole at the center of the Milky Way</u>

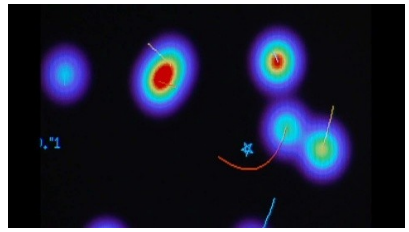
The central object in the Milky Way is known as Sagittarius A* or Sag A* for short. It lies approximately 26,000 light-years away. It is surrounded by so many stars and gas and dust that it is almost impossible to see.

[Additional info: Our first look at Sag A* came with the advent of broadcast radio in the 1930s. Karl Jansky was asked to locate the radio interference to Bell Labs early trans-Atlantic transmissions. He built the first radio antenna and located the source at the center of the galaxy. He named it Sagittarius and is credited with starting the entire field of radio astronomy.

Flashing forward – we now have the Hubble space telescope which was designed in part to study what we now call Sagittarius A*.**]**

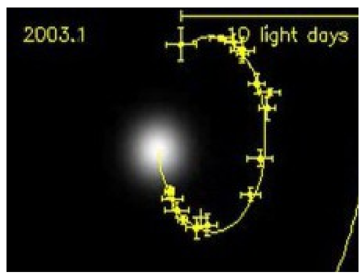
Teams of astronomers have been working on understanding Sag A* for over 20 years. The UCLA Galactic Centre Group is one. In conjunction with the new Keck observatory on top of the Mauna Kea volcano in Hawaii, and the Max Plank Institute for Extraterrestrial Physics in Germany, they have made dramatic progress in advancing our understanding of this critically important part of our galaxy.

By the turn of our new century, after years of carful observation, the speeds and trajectories for these stars were calculated. This enabled measuring the precise location of the point they are all orbiting around. But, when we look at this point, we don't see anything.



The measured orbits also identified the gravitational pull from this point which in turn gave us its mass at 4 million times the Sun's mass. This was strong evidence that Sag A* was a black hole because stars are known to be unstable at much smaller masses.

Further observations of the star S0-2 showed that its orbit takes it to within 11 billion miles of Sag A* without bumping into anything. That puts Sag A*'s 4 million sun mass into a very small place.



For many astrophysicists, this constituted proof that it was indeed a supermassive black hole. But others pointed out that an extremely dense dim star cluster could produce these results.

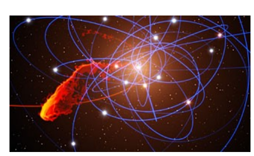
In 2002, S2 made its closest approach to Sag A*. If Sag A* were a cluster, S2's orbit would wobble. It did not wobble. This was the final proof point. 500 years after Copernicus put the sun at the center of our solar system, this team identified Sagittarius A* as a supermassive black hole at the center of our galaxy!

[Additional info: It is interesting to note that the star S0-102's orbit is just 11-and-a-half years — the shortest known orbit of any star near this black hole. S0-2, orbit is 16 years. It is moving at about 3,000 miles a second. It will go through its next closest approach to the black hole in 2018. It is the tango of S0-102 and S0-2 that will reveal the true geometry of space and time near a black hole for the first time," This will test Einstein's theory of general relativity.**]**

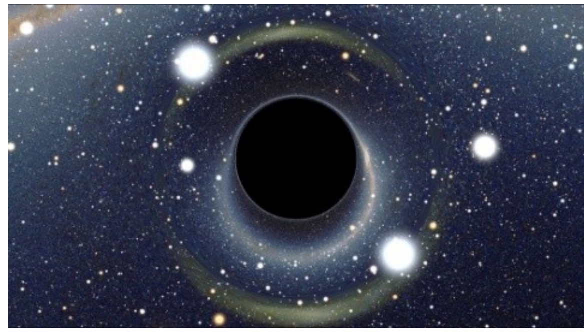
G2 Gas Cloud

The gas cloud G2 was first seen in 2002. Observations confirmed that it is on a course to Sag A*. It will have its closest approach to the black hole in mid to late 2013. At this time the gas cloud will be at a distance of just over 36 light hours from the black hole.

If this is the case, a significant amount of it may be sucked into Sag A*. This should lead to a significant brightening of X-ray and other emission from the black hole that could last several decades. This is the first time ever that the approach of such a doomed cloud to a supermassive black hole has been observed.



Black Holes

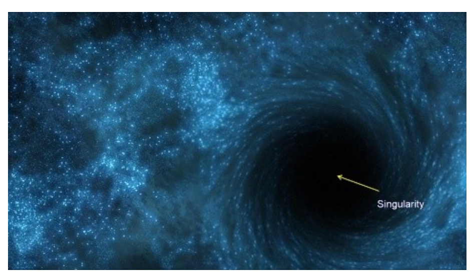


The black hole at the center of our galaxy is called a supermassive black hole. This kind of black hole usually contains the mass of millions or even billions of suns. The other kind of black hole is the Stellar-mass black hole. These are created when massive stars reach the ends of their lives and run out of fuel, exploding in powerful blasts called **gamma ray bursts**, or **hyper-novas**. A typical stellar-mass black hole contains the mass of about 10 suns.

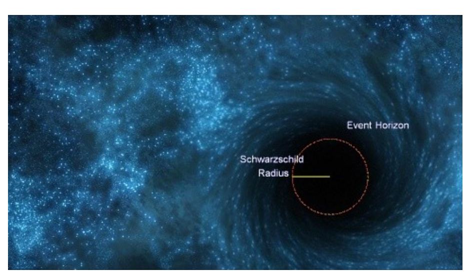
You'll recall that nova explosions at the end of life for stars less than 5 times the mass of the sun leave behind a white dwarf. In these stars, electron exclusion pressure is enough to counteract the inward force of gravity.

Supernova explosions at the end of life of stars more than 5 times the mass of the sun leave behind a neutron star. In these stars, electron exclusion pressure is insufficient to overcome the force of gravity, but neutron exclusion pressure is.

But if a star is greater than 30 times the mass of the sun, even neutron exclusion pressure won't do the trick. In fact, there is no known force that will counteract the inward force of gravity for such a supernova or hyper nova exploding star.



According to Albert Einstein's general theory of relativity, the star will collapse into zero volume and infinite density – called a singularity. This defines a black hole. It gets its name from the fact that such a singularity would create a gravitational pull that not even light could escape. The object literally becomes invisible.



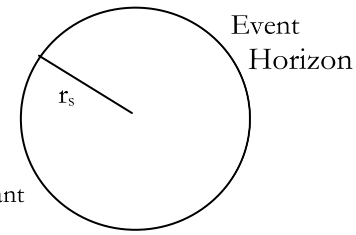
Karl Schwarzschild, a contemporary of Einstein, solved his equation for the special case of a non-rotating sphere. He found that although the diameter of the singularity is zero, the radius at which light would be captured depends entirely on the mass of the black hole. This is called the Schwarzschild radius and it defines the Event Horizon.

Schwarzschild Radius

$r_s = 2Gm/c^2$

Where:

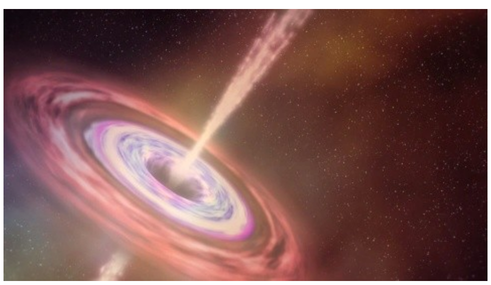
r_s = Schwarzschild radius
c = the speed of light
G = Newton's gravitational constant
m = mass of the object



For the Sun we get:

$r_s = 2Gm_{sun}/c^2 = 1$ mile

[Additional info: For the Sun, the Schwarzschild radius is 1 mile. That means that if the Sun were to shrink to a 2 mile diameter, it would disappear!**]**



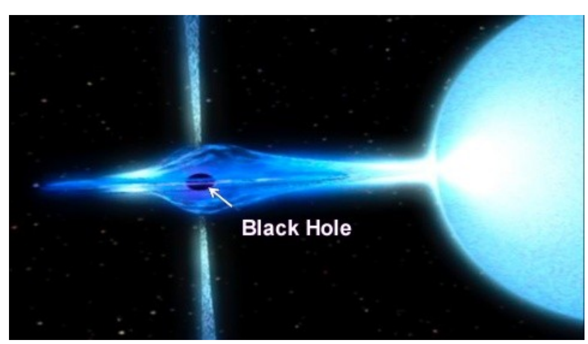
One thing all rotating black holes have in common besides the fact that we can't see them, is that matter flows in via an **accretion disk**. The exact mechanism is not yet fully understood, but we know that gamma-ray jets shoot out at the polls carrying a percentage of the falling matter with it at speeds approaching the speed of light.

Stellar Black Hole Candidates

Our Milky Way galaxy contains several stellar-mass Black Hole Candidates which are closer to us than the supermassive black hole in the Galactic center region. **[**These candidates are all members of X-ray binary systems in which the compact object draws matter from its partner via the accretion disk.**]**

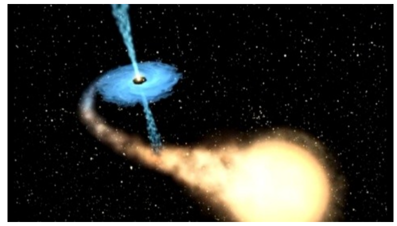
A0620-00 – 3,500 light years

This is a low mass x-ray binary star and black hole candidate. One of the stellar structures in this binary system is known to be a large dark compact stellar structure between three to five times the mass of the Sun with a diameter of around 25 miles! We calculate this by measuring the motions of gas in the accretion disk and studying the X-ray emission profiles. At a distance of around 3,500 light-years, this is the nearest black hole to Earth.



<u>GRO J1655-40 – 11,000 light years</u>

GRO J1655-40 is a binary star consisting of an evolved primary star and a massive, unseen companion. They orbit each other once every 2.6 days.



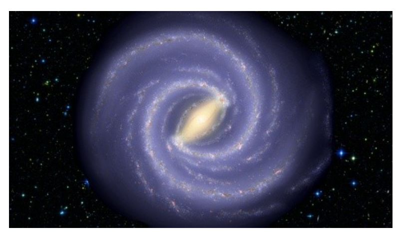
[Additional info: GRO J1655-40 produces several interesting phenomena.

> First, it has two strong jets of material flowing away from its poles. The jets consist of material in the accretion disk that is accelerated to almost the speed of light by the disk's strong magnetic field.
>
> Second, GRO J1655-40 and its companion are moving through the galaxy 4 times faster than all the other stars in their vicinity. This supports the idea that the black hole formed from the collapse of the core of a massive star. As the core collapsed, its outer layers exploded as a supernova. The explosion was a little off-centered, though, so it sent the system racing through the galaxy.**]**

<u>The Galactic Disk</u>

Based on detailed analysis of star distances, star motions, and neutral hydrogen radiation from spiral arms, we believe that the galaxy is a relatively flat rotating 100,000 light years wide disk of some 400 billions of stars.

This image, out of the Spitzer Science Center and the University of Wisconsin, represents an attempt to synthesize over a half-century of work on the Galactic Disk's structure based on data obtained from the literature at radio, infrared, and visible wavelengths.



[Additional info: The Milky Way was dubbed as a spiral galaxy in 1951 when William Morgan of the Yerkes Observatory presented his results showing the galaxy's three arms of hot stars, which he named Perseus, Orion and Sagittarius.

There were three methods traditionally used to map the disk structure of our Galaxy.

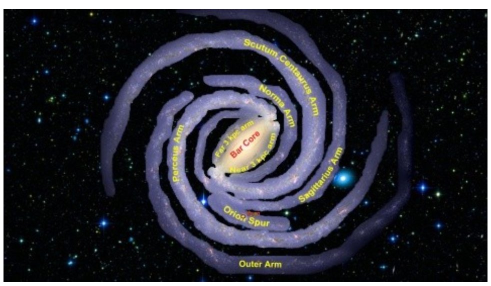
- Starting in 1958, the first method studied the density of the neutral hydrogen in the plane of the Galaxy.
- Starting in the 1960s the second method used radio astronomy to map out the Milky Way's structure.
- Starting in 1976, the third method plotted the giant HII regions. These were usually formed in the spiral arms.**]**

The galactic center itself, with the supermassive black hole that we discussed earlier, is shaped like a bar. Although most parts of the Milky Way galaxy are relatively uncrowded, roughly 10 million stars are known to orbit within just a single light-year of the galactic center in a region known as the central bulge.

Recent surveys discovered the two 3-kpc Arms, named for their length. They are now generally thought to be associated with gas flow roughly parallel to the central bar.

Using infrared images from Spitzer, scientists have discovered that the Milky Way's elegant spiral structure is dominated by just two arms wrapping off the ends of a central bar of stars. One is named Scutum-Centaurus and the other is named Perseus.

Each of these major arms consists of billions of both young and old stars.



Three thinner arms spiral out between the two giant main arms called Sagittarius, Norma and the Outer Arm. These are primarily filled with gas and pockets of star-forming activity.

There is also a spur off the Sagittarius arm called the Orion Spur.

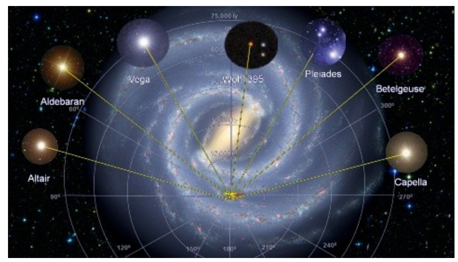
- It's 3,500 light-years across; 2,000 light years deep; and approximately 10,000 light-years long.
- We are located on the inner edge half-way along this spur around 26,000 light years from the galactic center.

When we fill in the space between the arms, we get the full picture.

It's interesting to note that the number of stars per unit volume of space in the regions between arms is the same as the number in the arms themselves.

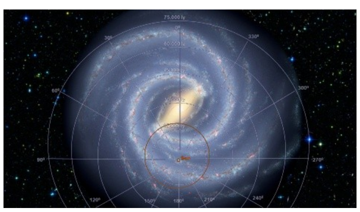
What distinguished the arms is that they have a far greater number of younger stars. In fact, all the known H II star forming regions in the galaxy exist inside the arms. We don't find any in the area between the arms.

If we lay a grid over the galaxy, we can locate some of the stars, nebula and H II regions we have seen in this chapter.

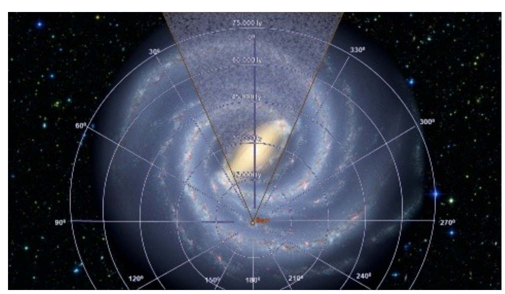


Actually, all the local neighborhood stars would fit into the red circle I used to locate our Solar System. That would be stars like Wolf 395, Altair, Vega, Polaris, Capella, Aldebaran, the Pleiades, and Betelgeuse. They are all with us in the **Orion Spur**, as is the Orion, Horsehead, Cone, Witch's Head, Veil and many other Nebulae.

In **Sagittarius**, we see the Jewel Box star cluster and the Trifid, Omega, Lagoon, Eagle, and Cat's Paw nebulas among other. In **Perseus**, we see the Rosetta, Heart and Soul Nebulae as well as the Crab Supernova to name just a few.

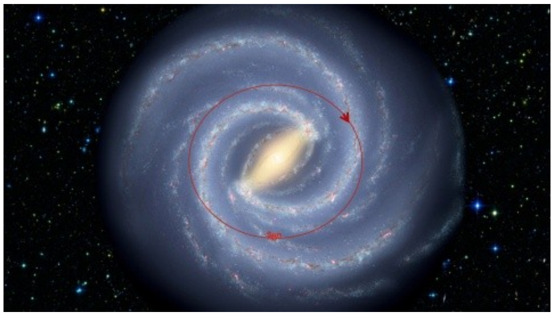


In fact, except for the hyper-velocity stars and a few of the supernova remnants, everything we have seen in this chapter is within this circle. As vast an area as we have covered, it is only a fraction of the Milky Way galaxy.



Another point that ought to be covered is that we cannot see through the galactic core into the other side. The core is simply too dense with stars and gas and dust to penetrate. So this slice of the disk has not been seen or analyzed. But our understanding of spiral galaxies is that they are symmetric, so this picture makes that assumption and fills in the blanks accordingly.

Viewed from "above" – what would be North on Earth – the Milky Way spins in the counter-clockwise direction. Of course, if you were to view it from the other side, it would spin clockwise.



Here we see the Sun's orbit around the galactic center. Our orbital speed is approximately 138 miles per sec. It takes the Solar System about 225 million years to complete one orbit. The last time we were in the same place in our orbit, dinosaurs were just starting to appear on the Earth. We have traveled around 1/1000th of a revolution since the origin of humans.

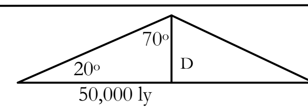
[Also, as the Sun orbits, it oscillates up and down relative to the plane of the galaxy approximately 2.7 times per orbit. It will be many millions of years before we pass through the plane again.**]**

Whenever you see any picture of the whole Milky Way, remember that it is an artist drawing. The size of the galaxy is so large, that the distance one must go to see it all is way too far. Here's what I mean:

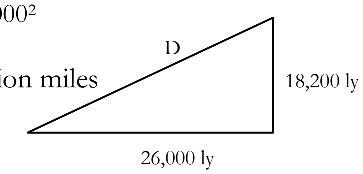
If we assume that our field of view is 140 degrees, we can use trigonometry to find the distance to a point where such a picture could be taken. That point is approximately 186,500 trillion miles from the Sun's current location.

Voyager I left on its journey in 1975 and is traveling at 38,185 miles per hour. It has already gone 12 billion miles. If we aim it at the photographic point, at its current velocity, Voyager won't reach this point for another 558 million years.

$d = 50{,}000 \text{ ly} \times \tan(20^o)$
$= 18{,}200 \text{ ly}$



$D^2 = 18200^2 + 26000^2$
$D = 31{,}737 \text{ ly}$
$D = 186{,}500 \text{ trillion miles}$



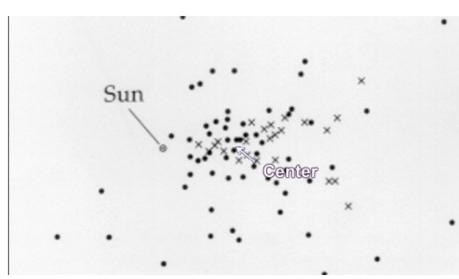
Voyager velocity = 38,185 mi/hr
= 334 million mi/yr

$\frac{186500 \text{ trillion mi}}{334 \text{ million mi/yr}} = 558 \text{ million years}$

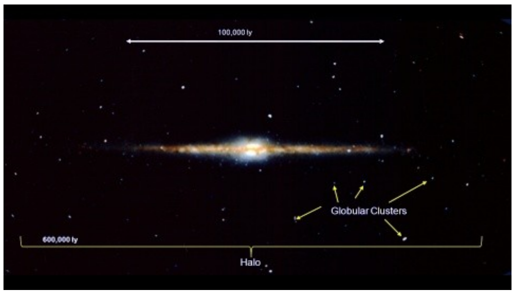
If some future generation were to ever take such a picture, they would see our entire solar system as little more than a single pixel.

The Milky Way Halo

At the turn of the 20th century, astronomer Harlow Sharpley, studying a large number of RR Lyrae stars inside globular clusters, found that the center of the galaxy was far from the Sun. He mapped 93 globular clusters. They formed a spheroidal shape with their own center – not near the Sun. He concluded that these giant clusters formed the "bony frame" of the galaxy.

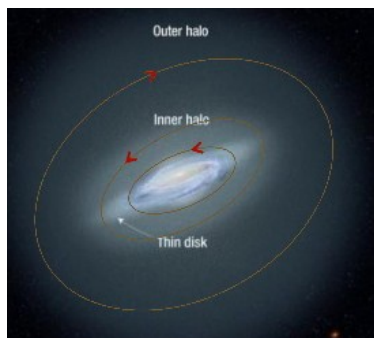


[Additional info: His distances were off because he did not know about and therefore could not correct for large amounts of **interstellar dust**. Dust absorbs light (called '**extinction**'), so it makes everything look dimmer than it otherwise would appear. In the 1930s, when the effects of dust were realized and corrected for, studies of galactic structure entered the modern era.**]**



This area around the disk is called the galactic halo or corona. It holds a large number of old stars and 158 globular clusters. The Galactic Halo itself has a diameter of at least 600,000 light years based on the locations of the globular clusters, although it may extend much further. There is no star formation out in the halo.

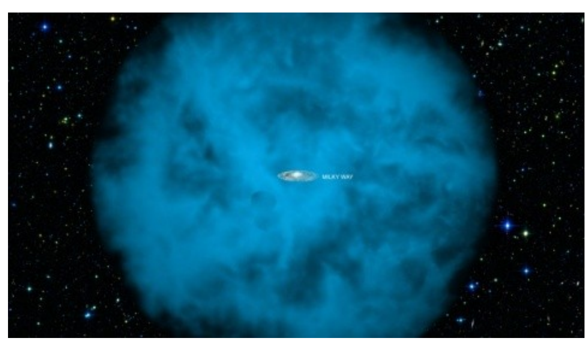
In 2007, using 20,000 stars observed by the Sloan Digital Sky Survey, an international team of astronomers discovered that the outer Milky Way is a mix of two distinct components rotating in opposite directions.



The inner halo, located well outside the disk, rotates in the same direction, but more slowly, at 50,000 miles per hour. In the outer halo, the most components spin in the opposite direction, at about 100,000 miles per hour.

On September 24, 2012, Chandra found evidence that the Milky Way Galaxy is embedded with a large amount of hot gas in the halo. Counting this vast amount of gas, the mass of the halo is estimated to equal the mass of the stars in the galaxy!

The stars in the outer regions of the galaxy are orbiting faster than Newton's and Einstein's equations predict. To explain this phenomenon, astrophysicists speculate that there must be a large amount of dark matter around the galaxy. They call it **dark matter**, because it does not interact in any way with the matter and electromagnetic energy we see with our instruments. Its only interaction is through gravity.



If these Chandra findings about the hot gas in the halo are confirmed, it could be the solution for star orbital speeds and eliminate the need for dark matter.

Conclusion

[Additional info: At the turn of the 20th century, most people understood that:

- there were a lot of stars
- they were very far away
- they shined with their own light
- and they are formed into a system called the Milky Way Galaxy

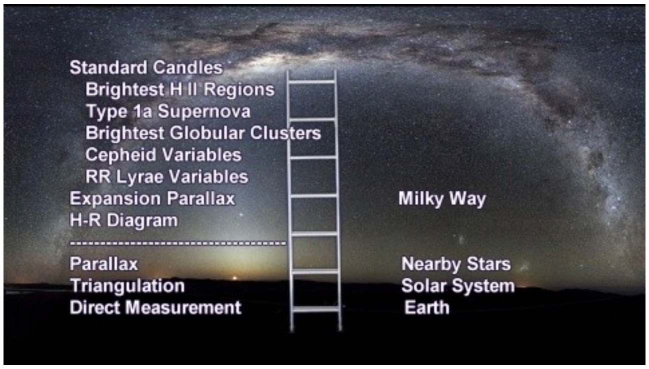
For the most part, they also thought that this galaxy was the entire Univers and that the sun and our solar system were at the center.

In this segment we took a look at how this picture changed during the 20th century.**]**

Chapter Conclusion

In our chapter on the Milky Way:

- We studied the nearby stars were parallax told us how far away they were.
- We developed the H-R diagram as a way to calculate luminosity based on temperature and spectral analysis.
- We covered key standard candles such as Cepheid and RR Lyrae Variables as well as Type 1a Supernovae
- And we examined star clusters; planetary nebula; and emission nebula for their beauty and value as standard candles.



This distance ladder took us all the way across the galaxy. In our next chapter, we'll use all these techniques to move out into intergalactic space.