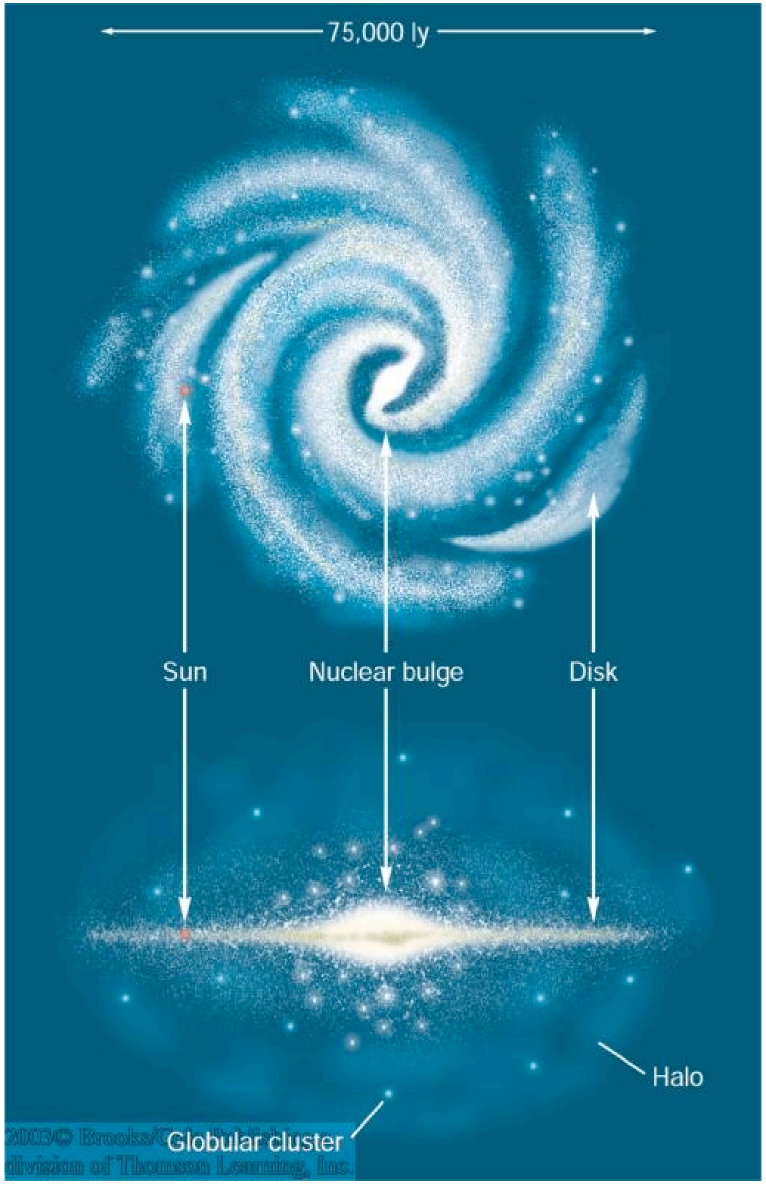
The Milky Way

Almost every star we can see in the night sky belongs to our galaxy, the Milky Way. The Galaxy acquired this unusual name from the Romans who referred to the hazy band that stretches across the sky as the via lactia, or "milky road". This name has stuck across many languages, such as French (voie lactee) and spanish (via lactea).

Note that we use a capital G for Galaxy if we are talking about the Milky Way

The Structure of the Milky Way

The Milky Way appears as a light fuzzy band across the night sky, but we also see individual stars scattered in all directions. This gives us a clue to the shape of the galaxy.



The Milky Way is a typical spiral or disk galaxy. It consists of a flattened disk, a central bulge and a diffuse halo. The disk consists of spiral arms in which most of the stars are located. Our sun is located in one of the spiral arms approximately two-thirds from the centre of the galaxy (8kpc). There are also globular clusters distributed around the Galaxy.

In addition to the stars, the spiral arms contain dust, so that certain directions that we looked are blocked due to high interstellar extinction.

This dust means we can only see about 1kpc in the visible.

Components in the Milky Way

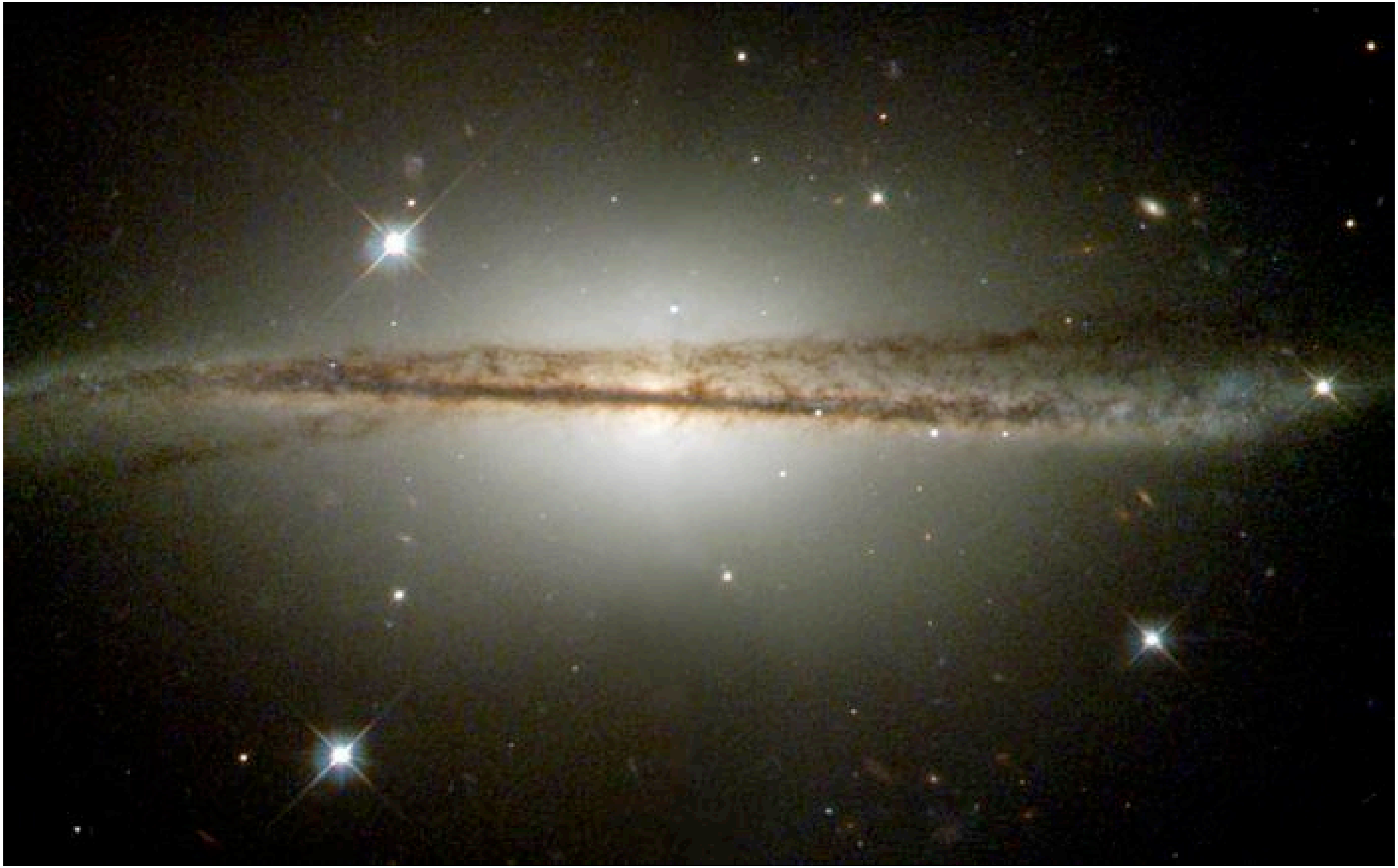
The disk: contains most of the stars (in open clusters and associations) and is formed into spiral arms. The stars in the disk are mostly young. Whilst the majority of these stars are a few solar masses, the hot, young O and B type stars contribute most of the light. There is also dust in the disk which can be seen as dark lanes across the milky way in dark skies. The disk is about 100 pc thick and 25 kpc in diameter.

The bulge: also referred to as the spherical component, the bulge is the thickened central region of the galaxy. The bulge contains older stars, but is hard to observe because of the large extinction due to dust that observations towards the Galactic centre suffer. It is about 1.5 kpc in radius and 0.7 kpc in height.

The halo: contains a very old population of stars sparsely scattered out of the plane of the disk. There is almost no gas and dust and no new star formation is ongoing. The halo extends out to about 5 kpc.

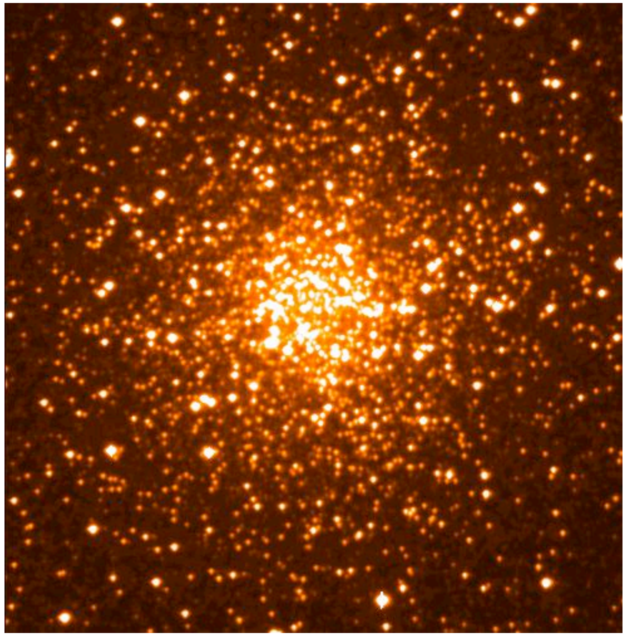
Globular clusters: scattered throughout the halo, these are bound clusters that contain thousands or millions of stars and are about 20 to 30 pc in diameter. Globular clusters are old – about 11 billion years.

There is also evidence that the disk of the Milky Way is warped. We see this in (some) other spiral galaxies as well.



Open clusters, associations, HII regions and molecular clouds (i.e. all the flags of star formation) occur in the Galactic disk.

Our view of the Galactic centre (bulge) is highly obscured by dust in the disk. You can look towards the Galactic centre by looking towards the constellation of Sagittarius and noticing the dark dust clouds.



Globular clusters contain thousands of old (red) stars that are some of the oldest in the Galaxy. They are tightly bound by gravity, unlike the open clusters.

The Rotation of the Galaxy

We have seen (e.g. in stellar evolution) that in order for any object to be in equilibrium, the various internal forces must be balanced. Since all the stars and clusters in the MW have their own gravity, there must be a force to counteract this. Indeed, it is by rotating that the Galaxy sets up an opposing force.

At the position of the sun (at a Galactocentric radius of about 8.5kpc), the rotation speed is about 220 km/s. We call a cosmic year the time taken for the sun to rotate once around the Galaxy. How long is a cosmic year (given that the orbit is almost circular)?

First we need to convert all our units to the same thing, let's choose km. So 8.5 kpc is 8500 pc and we know that 1pc=3.1×10^{16}m. Therefore 1 pc in km is 1000 times less than this (1000 m in a km), so 1 pc=3.1×10^{13}km.

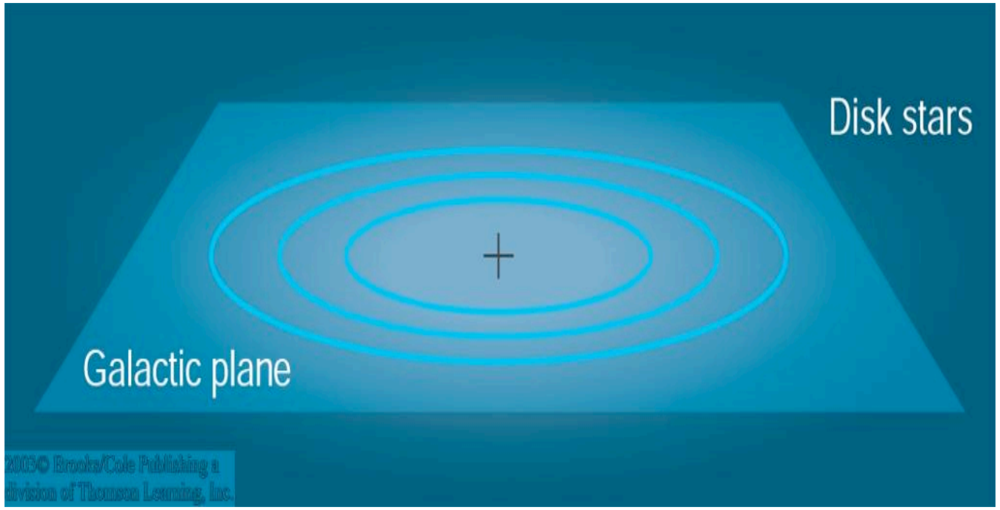
So now we know that the radius of the sun's orbit is 8500 x 3.1×10^{13}km = 2.64×10^{17} km.

The circumference of a circle is $2\pi r$, i.e. the circumference of the sun's orbit is 2 x 3.142 x 2.64×10^{17} = 1.66×10^{18} km.

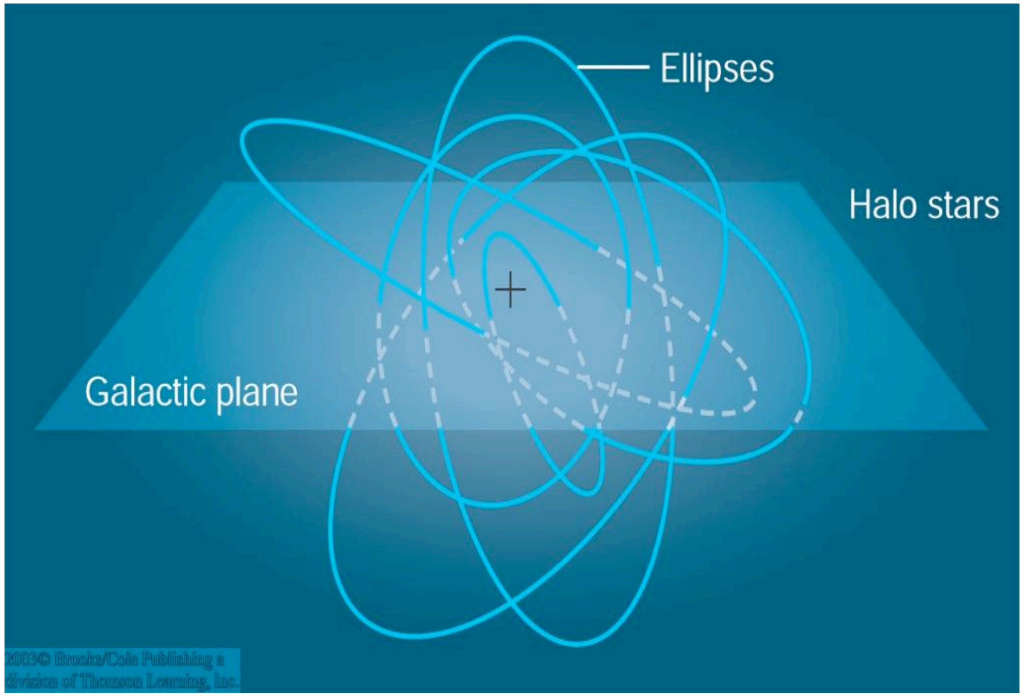
Finally, the time taken to travel this distance is 1.66×10^{18} / 220 = 7.5×10^{15}s. I leave it for you to show that this is about 240 million years.

The Rotation of Other Stars

Stars in the Galactic disk all rotate in approximately circular orbits, but stars in the halo (and globular clusters) have highly elliptical orbits. Some halo stars move very fast and it seems that these high velocity stars are receiving an extra “kick” as the travel across the disk.



Stars in the very centre of the MW also move very fast, this is because there is a black hole at the centre of our galaxy and its large gravitational effect causes stars to swing by very fast. Stars farther from the centre don't feel the pull of the black hole so strongly. Only very recently, astronomers have been able to look into the centre of the Galaxy and trace the orbits of these stars.



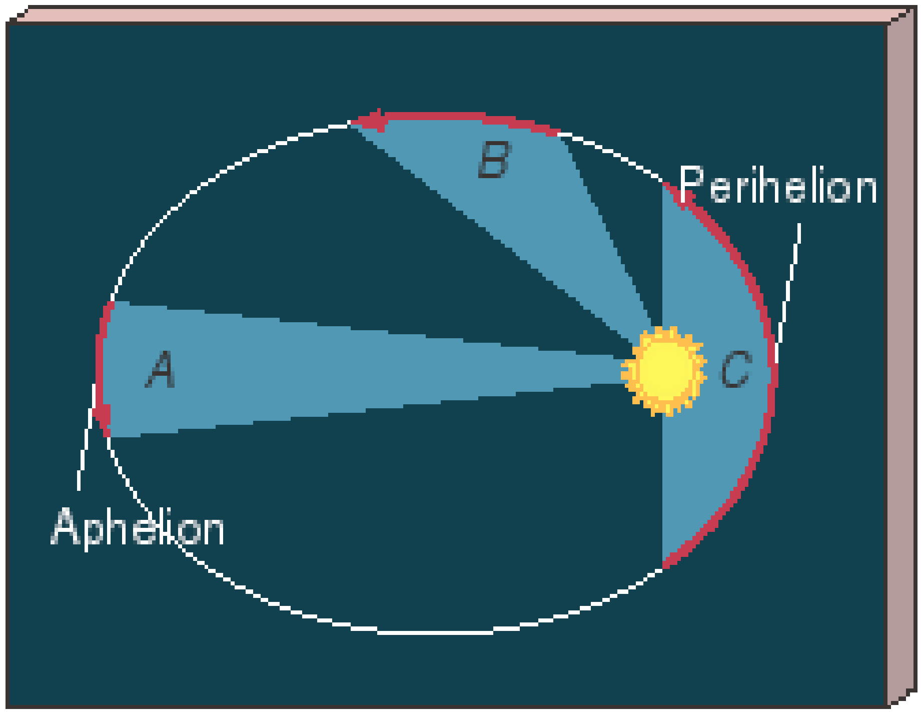
Kepler's Laws

Johannes Kepler was a German astronomer born in 1571 and, like Tycho Brahe (who he worked with for many years), studied the motions of celestial objects, in particular the planets.

Kepler came to understand the motions of the planets around the sun, but his conclusions are applicable for any 2 bodies (planets and the sun, binary stars, or stars moving around the centre of a galaxy).

Kepler came up with 3 fundamental laws for 2-body motion:

1. The orbits of a 2 body system are not circular, but elliptical.
2. Equal areas are swept out in equal times.
3. The orbital period squared is equal to the average separation cubed divided by the total mass of the system: $P^2 = a^3 / M$. This equation uses the P in years and a in AU to give mass in terms of solar masses.



Weighing the Galaxy

Using Kepler's laws we can weigh the galaxy, because all we have to know is the rotation period (e.g. the cosmic year for the sun) and the radius of rotation. Note that Kepler's laws only tell us about the mass that is contained within a given orbit.

Example: What mass is contained in the Galaxy within the radius of the sun's orbit?

We previously found that a cosmic year (the sun's period) is 240 million years. We also know the sun's radius is 8500 pc which is 1.75×10^9 AU.

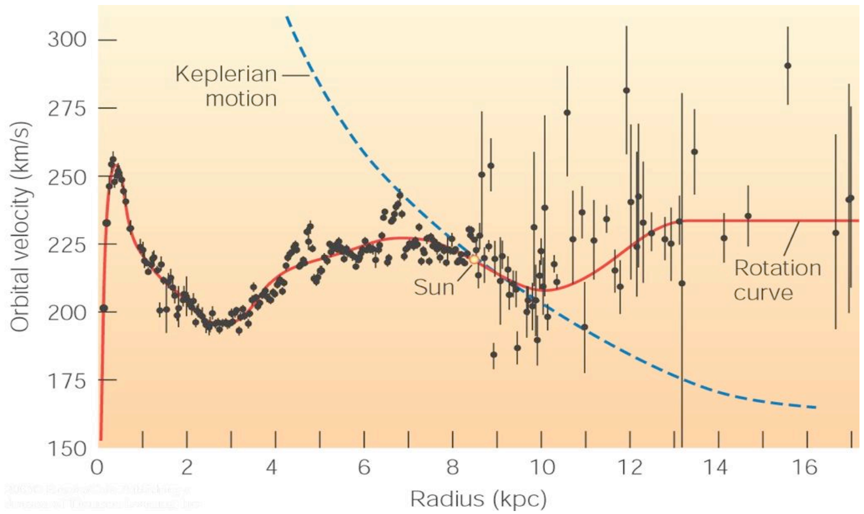
$$M = a^3/ P^2 = (1.75 \times 10^9)^3 / (240 \times 10^6)^2$$

$$= 0.9 \times 10^{11} \text{ solar masses}$$

If we take into account the mass outside the sun's orbit, we would find a mass of at least 2×10^{11} solar masses, i.e. 200 billion solar masses.

The Galaxy's Rotation Curve

A rotation curve is a plot that shows the velocity of stars as a function of radius. If Kepler's laws were a complete description of the MW (and all the mass were concentrated more or less at the centre), we would expect a clean fall-off of orbital velocity at larger Galactocentric radius.



However, the Galaxy's rotation is much more erratic than that, and we see that stars orbit differentially (remember differential rotation from the sun where the photosphere rotates faster at the centre). So structures in the MW get drawn out with time (unless they are strongly bound by gravity).

By studying the orbits of stars very far out in the Galaxy, we find that rather than falling off, the orbital velocities stay constant, or even increase. This tells us that there must be a lot of mass sitting in the outer part of the Galaxy, and this is mass that we can't see!

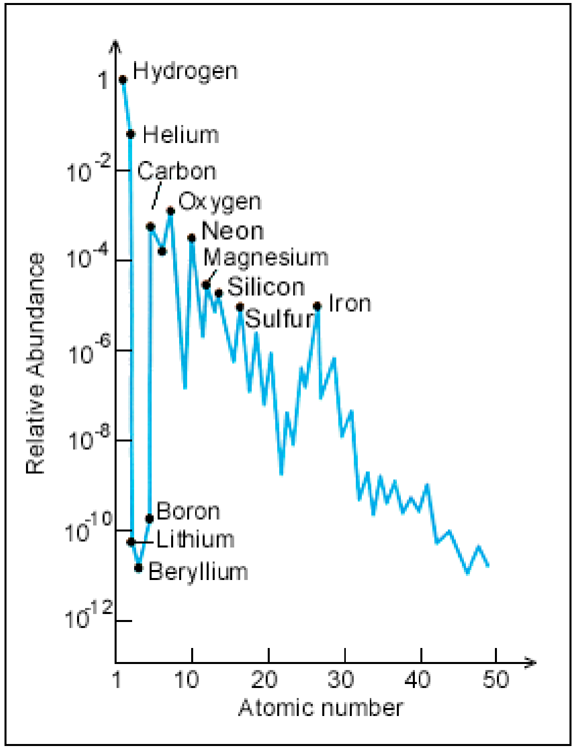
This outer part of the galaxy, sometimes called the Galactic Corona may extend out to 10 times the visible disk. Some of the “dark matter” will be dead or failed stars (white or brown dwarfs), but there is evidence for other types of exotic dark matter that we'll come back to later.

The Chemistry of the Milky Way

The initial composition of the universe (as we'll see in future lectures on the Big Bang) is 75% hydrogen and 25% helium, with effectively no heavier elements. So all the "metals" in the universe are processed through stars.

We saw in the lectures on stellar evolution that more massive stars can process their nuclear fuel to form heavier nuclei and that supernovae are responsible for forming the heaviest elements like uranium and gold.

Looking at the *abundances* of elements in stars can therefore paint a picture which tells us about how star formation has proceeded up until now, i.e. how much of each element is present tells us how many of what type of star has come before.



Stellar Populations

Stars can roughly be divided into 2 categories, imaginatively called population I and II

Population I:

Pop I stars are young stars found in the disk. Because they are young, they are formed out of an interstellar medium that has been pre-enriched by the heavy elements from previous generations of stars. They may be up to 2 or 3% metals. The sun is a Pop I star.

Population II:

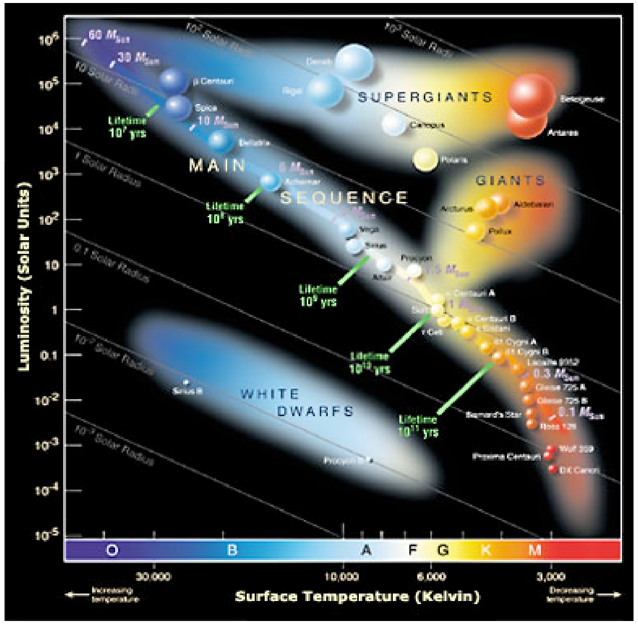
Pop II are old (2 to 12 billion years old) stars found in the halo. They are metal poor (only about 0.1% of metals) because they were among the first generation of stars to form. Globular clusters are also made up of Pop II stars.

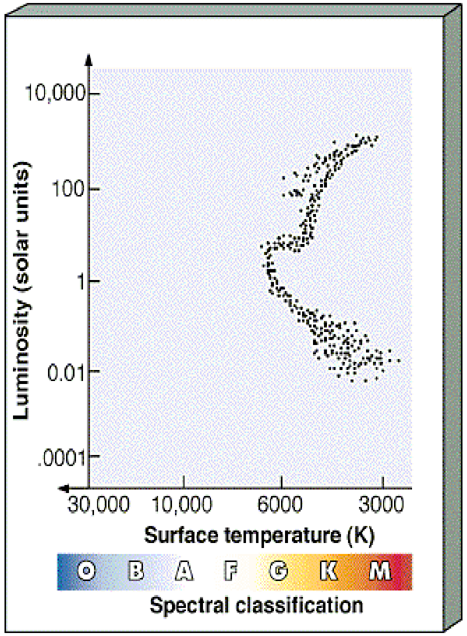
There is also a hypothetical Population III: stars with zero heavy elements, so they would represent the *very first generation of stars.* The search for Pop III stars is a holy grail for stellar astronomers because we could study how the very first elements are synthesized in stars. So far, the most metal poor star found in the Galactic halo has 1/100,000 the metallicity of the sun and astronomers are still looking....

The Age of The Milky Way

Because we know about stellar evolution and tracks on the HR diagram (i.e. how stars change their position on the HR diagram as a function of age) we can look at the HR diagram for the old stellar population and estimate the age of the Galaxy.

Globular clusters are useful for this because they are old and all the stars in a given globular cluster formed more or less at the same time, so they paint a coherent picture of ages.



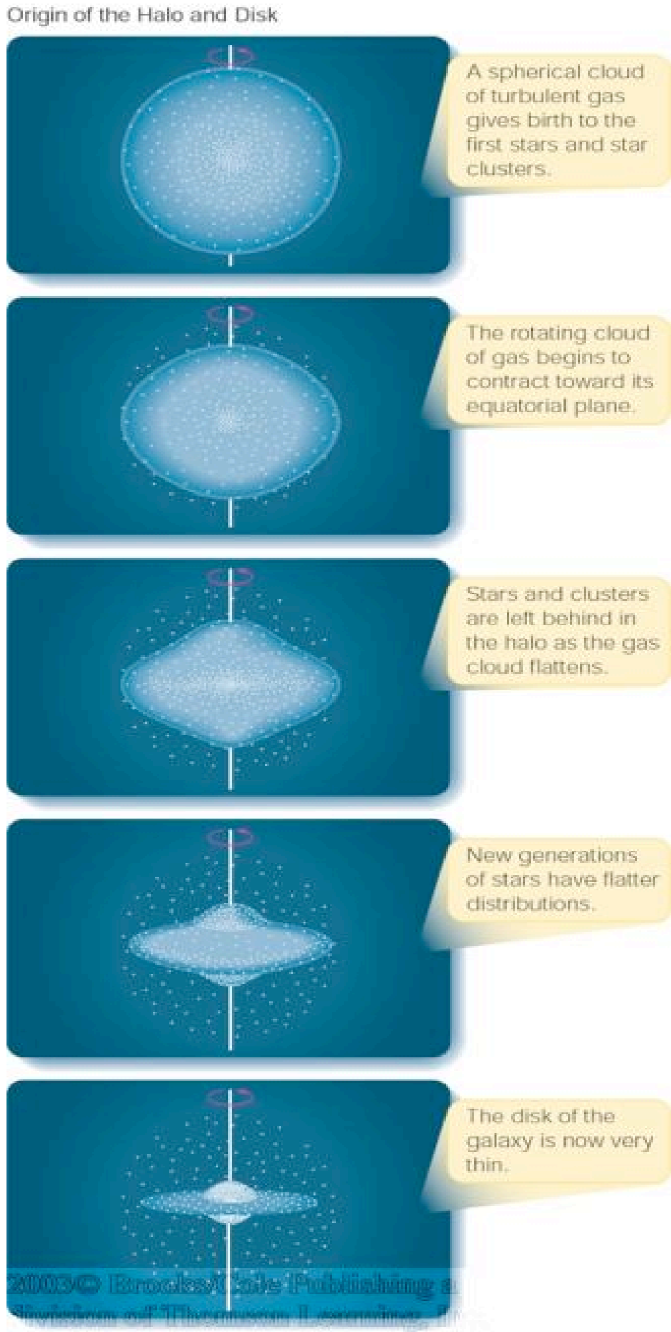


Remember, by measuring what mass of stars are still on the HR diagram we can figure out how old the cluster is. Studies find that most GCs are about 11 billion years old, but some are as old as 13 billion years.

The Formation of The Milky Way: Monolithic Collapse?

In the 1950s and 60s, the popular theory of how the Galaxy (and other galaxies) formed, was one of monolithic collapse. This theory stated that the MW formed from a single giant gas cloud that fragmented to form smaller clouds and star clusters. The first stars formed with no metals and random orbits (which accounts for the Pop II halo stars). From this ball of collapsing gas, the disk formed, orbits settled into circular shapes and subsequent generations of disk stars were more metal rich.

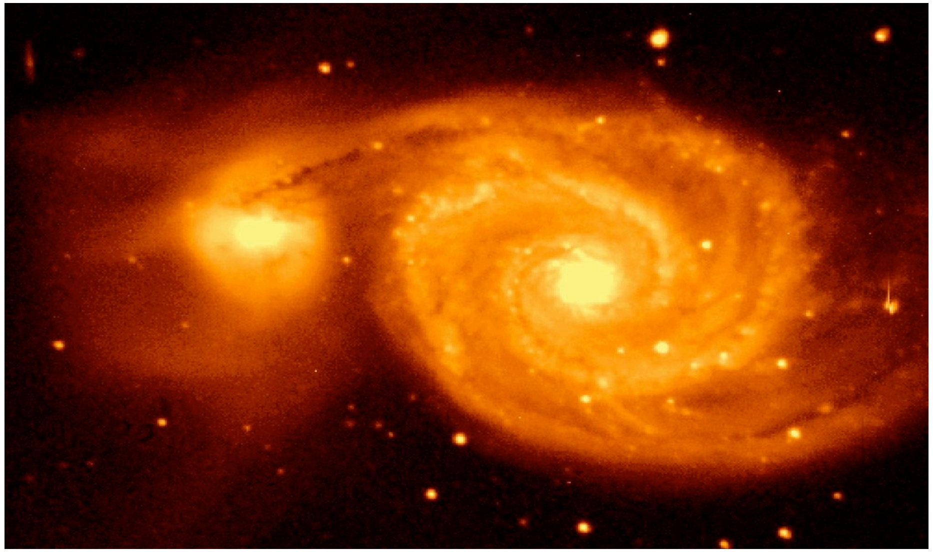
However, there are aspects of this scenario that don't fit our observations. For example, some of the oldest stars in the MW are not in the halo, but in the bulge. Also, monolithic collapse predicts that globular clusters are the first component to form, along with the halo, and at that they should have the same ages. This is not what we observe, and some halo stars are more metal poor (i.e. older) than globular clusters.

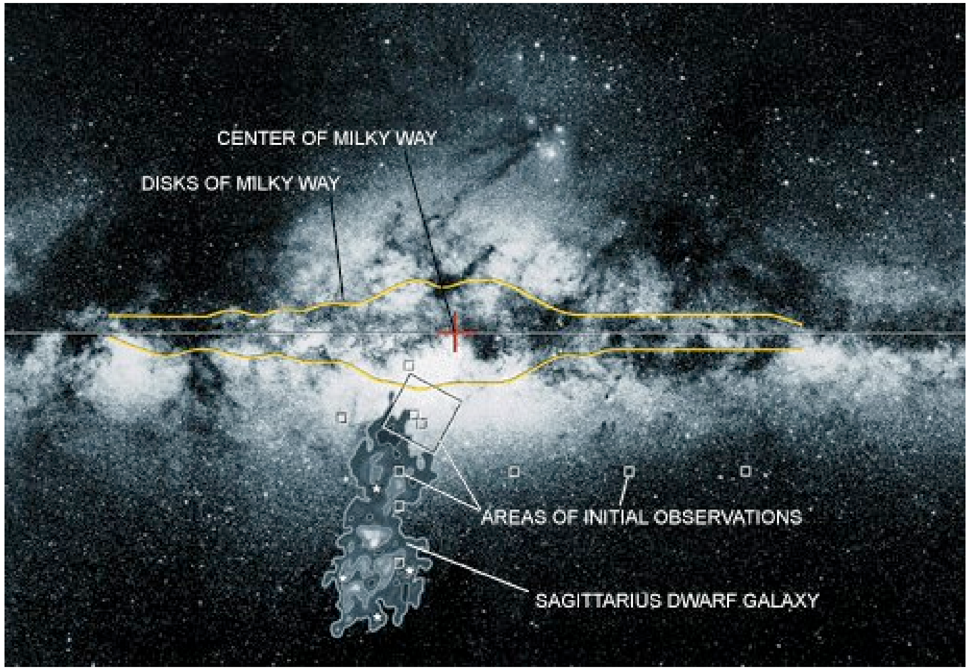


The Formation of The Milky Way: Growth by Merging

Rather than monolithic collapse, most astronomers now favour a picture in which galaxies grow by merging smaller clumps over an extended time. The halo is the galaxy's nascent cloud and the disk grows as gas is added over time.

In this picture, the Milky Way would grow by consuming smaller galaxies and re-distributing their stars and gas into the disk. We see evidence for this merging going on in other galaxies today, and such interaction seems to trigger new bursts of star formation.





We also have evidence that a galaxy is merging with the MW right now! Although we can't see the galaxy that is merging, astronomers have detected a group of stars with strange velocities that indicate the merger of a dwarf galaxy with the Milky Way

Galactic Spiral Arms

A significant fraction of galaxies are spirals (we'll be looking more at the morphologies of galaxies in future lectures) with arms of bright stars cartwheeling from their centres.

We say that the Milky Way is a spiral, but how do we know since we can't actually see their structure through the disk?

Also, how are these spiral arms formed, given that we believe galaxies grow as they consume smaller galaxies?

And if galaxies rotate differentially, why aren't the spiral arms destroyed within a few Galactic rotations?

Grand design spirals have 2 main spiral arms that are clearly outlined in hot young stars.

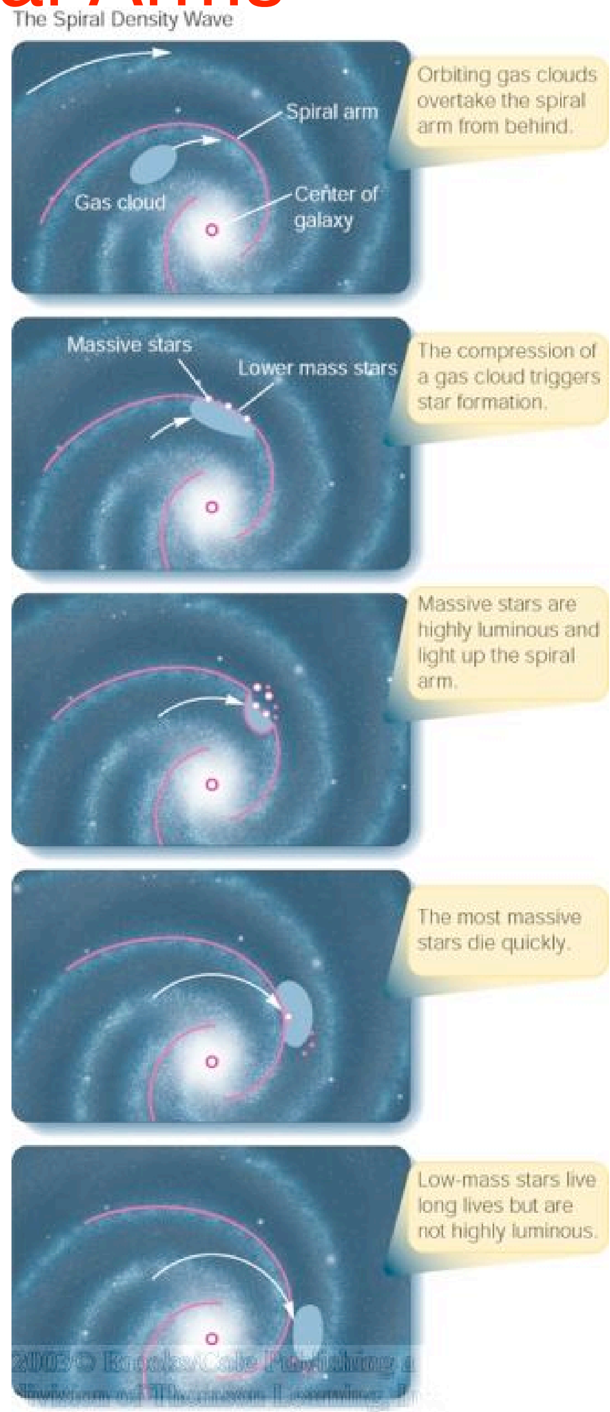
The Formation of Spiral Arms

We know that the spiral arms are not solid structures (because they would get torn apart by differential rotation). Even though their internal structure changes (e.g. stars migrate in an out of them), we believe that they are stable.

The currently favoured models have spiral arms as density waves, that is they are regions where the gas is compressed. The regions between the arms are therefore not empty, they just contain gas at lower pressure.

The arms themselves don't rotate, matter just moves through them. A gas cloud moving through a spiral arm gets compressed and can trigger star formation. There is evidence for this picture from the fact that most young stars do appear in spiral arms.

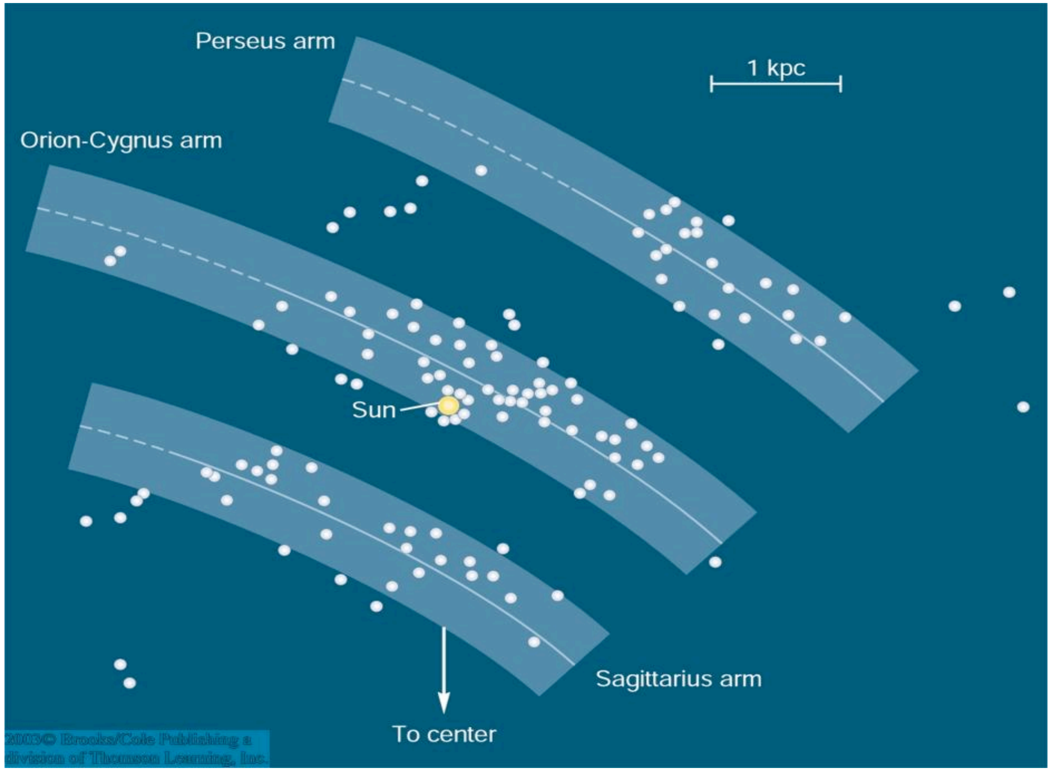
Older stars live long enough to migrate from the spiral arms. the fact that the sun is in a spiral arm is circumstantial: the sun has done about 20 orbits in the 5 billion years of its life.



Tracing Galactic Spiral Arms: O and B Stars

We have already seen that the disk of the MW is mostly Pop I young stars. It is therefore a good idea to use the brightest of these, the O and B stars, to trace the spiral arms because they will be the easiest to find over large distances.

We can use O and B stars (and associations) to trace the spiral arms near us, although we can't trace the whole galaxy this way because dust gets in the way and hides even bright stars. However, these stars are good enough for the solar neighbourhood within a few kpc.

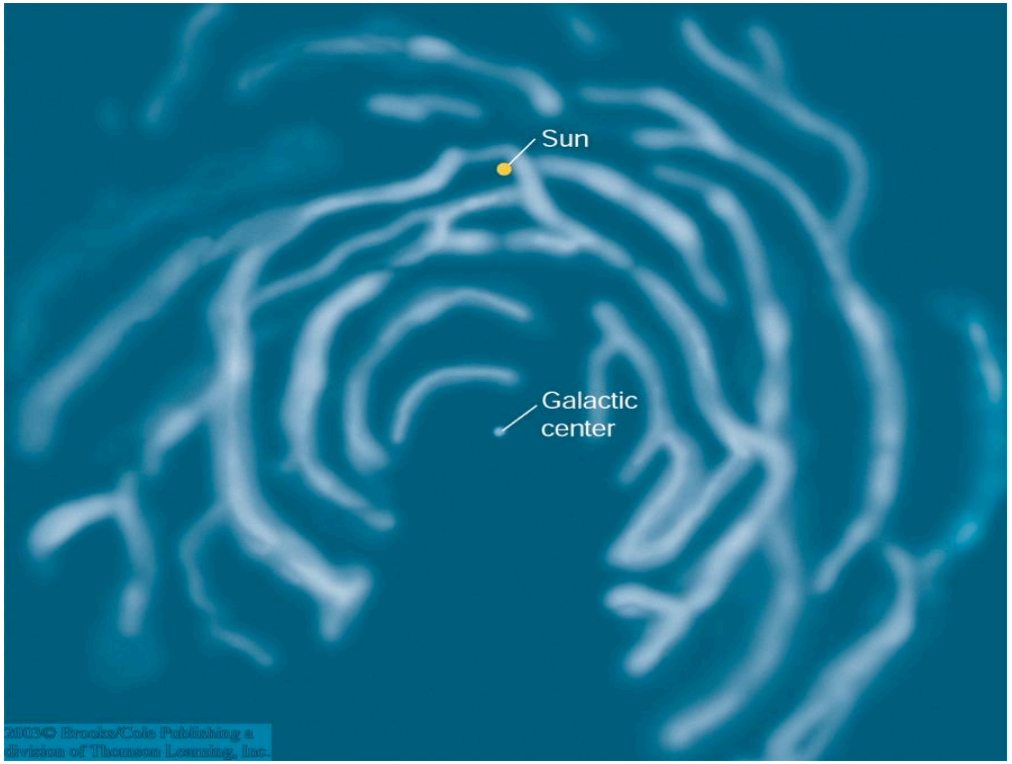


It is important to use young stars for tracing spiral arms, not only because they are bright, but because they won't have moved very far during their short lives. Because of differential rotation, and other random motions, long lived stars can travel out of the spiral arms (or even between arms).

Tracing Spiral Arms: Radio Maps at 21cm

In the section on the ISM, we saw that hydrogen emits at radio wavelengths because of the orientation of electrons in the atom. A very important property of radio waves is that (unlike optical light) it is not affected by dust. This is why radio telescopes are able to make maps of the gas throughout the Galaxy.

In order to reconstruct the picture of the Galaxy's spiral arms using 21cm radiation from hydrogen, we map the velocities of the gas across the sky. We measure the Doppler velocities, which tells us about the kinematic structure. Although we can't use this technique to map gas moving across our line of sight, because this does not cause a Doppler shift.

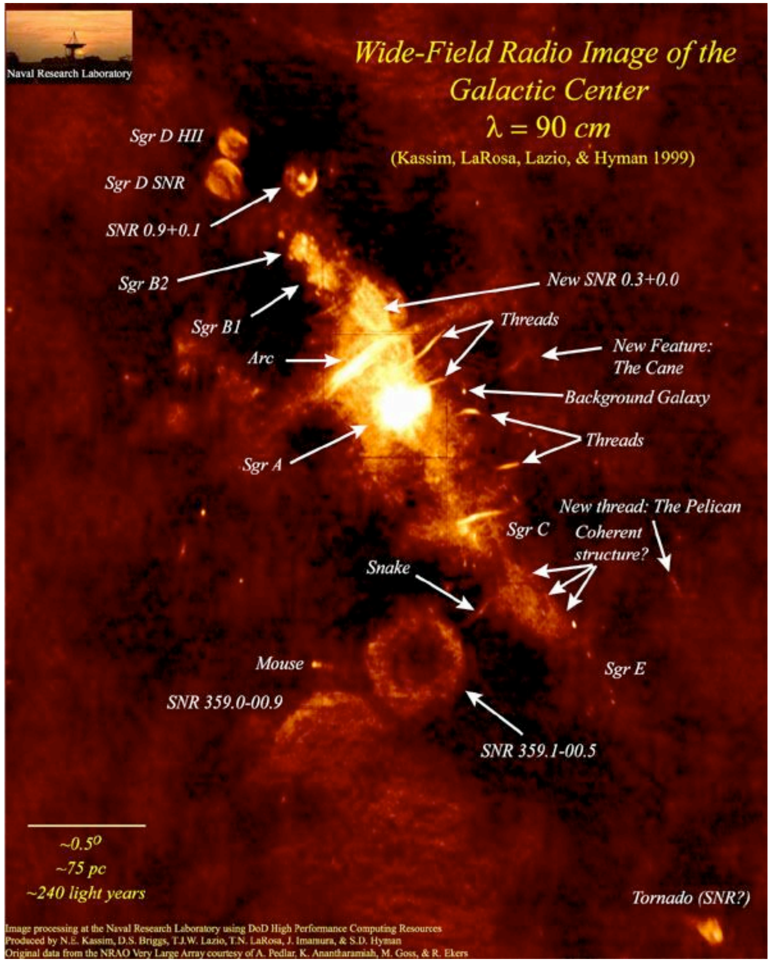


The maps made of the Milky Way indicate our galaxy has 4 main spiral arms, with a few irregular spurs and branches. The central bulge appears to be elongated into a bar, again this is not uncommon amongst galaxies.

The Galactic Nucleus

The centre of the Galaxy is a mysterious place; it is extremely difficult to observe because of a very large amount of dust that hides the central regions. This dust makes stars look 30 magnitudes fainter, i.e. a star looks 1000 billion times fainter!

However, when radio telescopes are pointed in the rough direction of the centre of the galaxy, a powerful radio source called Sagittarius A*. Size estimates of Sgr A* show that it is very small (a few AU).



In addition to this strong radio source, the Galactic centre also produces a lot of IR energy, probably due to dust that is heated by young stars.

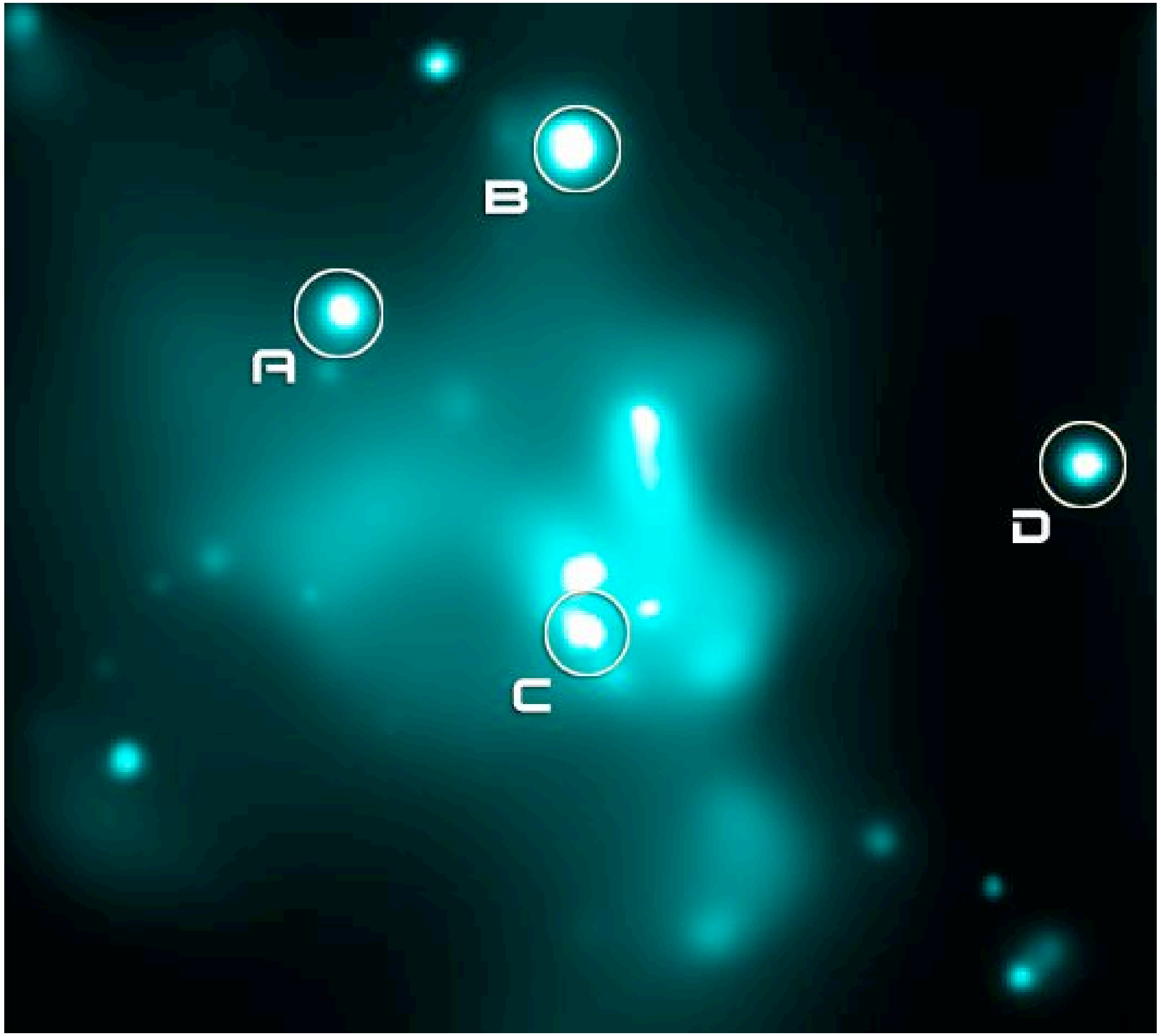
The morphology of the Galactic centre is strange: we can see several SN remnants, regions of star formation and arcs of gas caught in magnetic fields.

A Black Hole At The Centre Of The Galaxy?

Astronomers have postulated for many years that there is a black hole at the centre of our Galaxy based on:

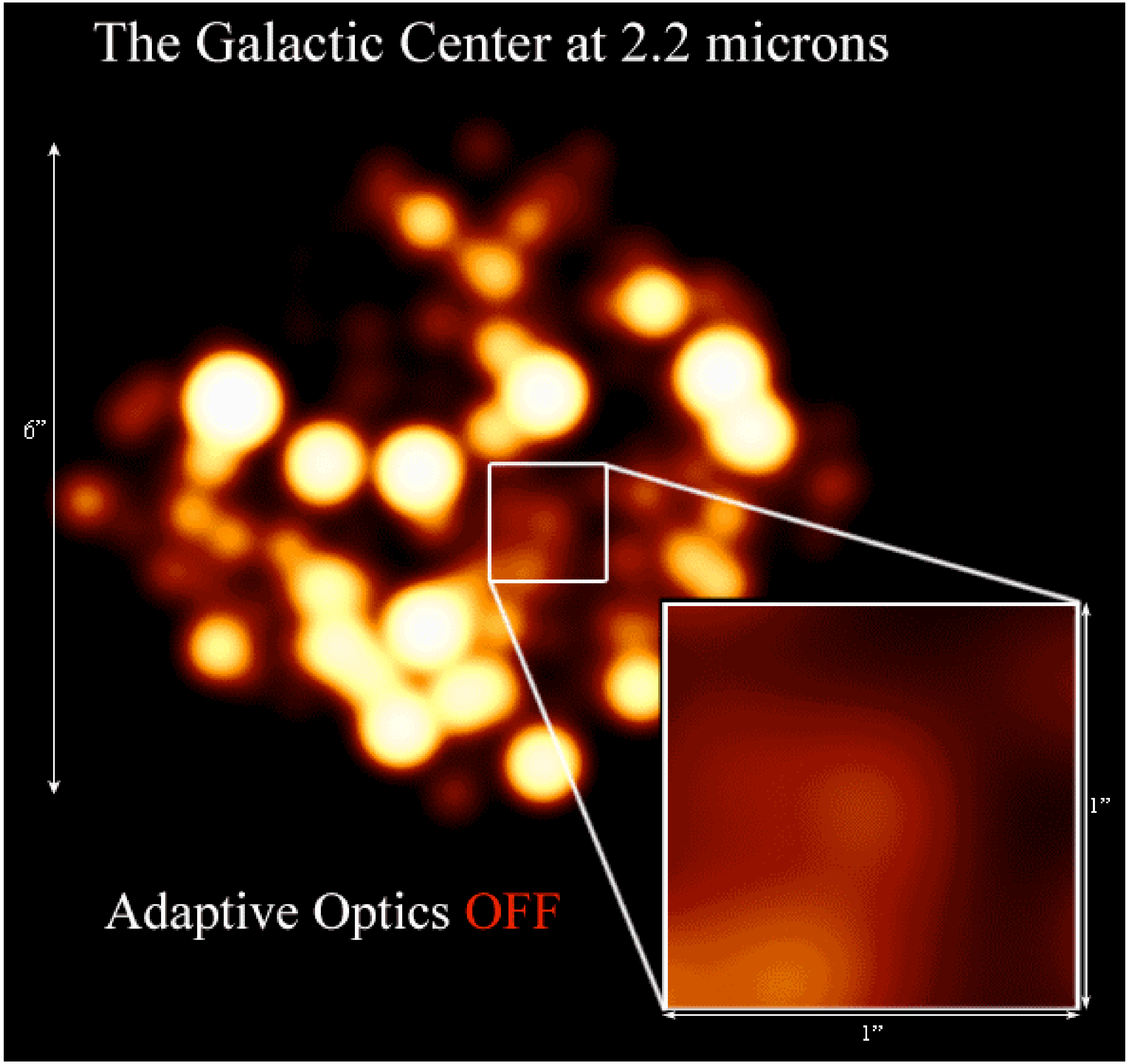
- The powerful radio radiation coming from the Galactic centre
- High resolution radio imaging of Sgr A* which gives a size of 4 AU
- IR observations of stars show them to be moving *around* Sgr A*
- By tracing the velocities of stars near Sgr A* and using Kepler's law we can determine its approximate mass, about 2.6 million solar masses

Alternative, exotic theories that attempt to explain these observations (such as quark stars) have been put forward. However, very recent observations using the Very Large Telescope in Chile, with their new adaptive optics camera has been able to trace the fine scale motions of stars very close to Sgr A*. These measurements provide very strong evidence that there is a supermassive black hole at the centre of the Milky Way.



Recently, the Chandra X-ray telescope has seen that there may be a whole swarm of black holes in the centre of the Galaxy. The source marked ‘C’ is Sag A*.

Adaptive optics, allows us to correct for the distortions in the Earth's atmosphere and obtain images as good as Hubble.



Advances in adaptive optics have allowed us to peer into the Galactic centre and see how stars move around the central black holes. We do these observations in the IR so we can 'see' through the dust to the Galactic centre.