XII. The Milky Way

Up to here we have discussed the evolution of individual stars from their birth to their death. To learn about the structure of our universe we have to expand our knowledge to the distribution of the billions of stars that fill the space of the universe, i.e. we need to determine their distribution over the sky along with their distance distribution.

We have already seen that stars like to start their life in bunches. We see a number of obvious groupings of this kind in the sky, **open star clusters** such as the **Pleiades** or the Hyades. Slide XII.1

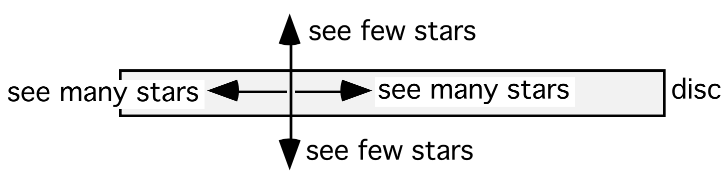
All stars in such groups are at approximately the same distance from us. Thus they really belong to the same group of stars, and all stars are of the same age. Such a group of stars is tied together by gravity, as we would immediately expect. How are all these smaller groups and other more lonely stars distributed on a larger scale?

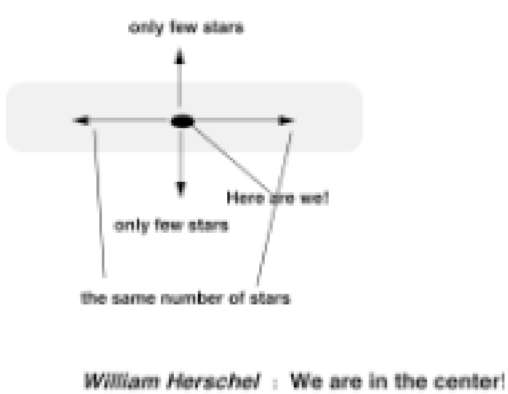
1. Size and General Structure of the Milky Way

a) The Disc of the Milky Way

From looking into the sky you must have noticed during a beautiful clear dark night that there is a faintly glowing band across the sky, which we call the Milky Way, just from its look like spilled milk. When resolving the band with a telescope it turns out to be a **band of stars.** This is what *Galileo* found out when employing his telescope the first time to the Milky Way. Slide XII.2

What can we conclude from this? Obviously we are in a disc full of stars. If we were in a sphere of stars, we should see them evenly distributed over the entire sky. This is true for individual stars and for clusters. View XII.1



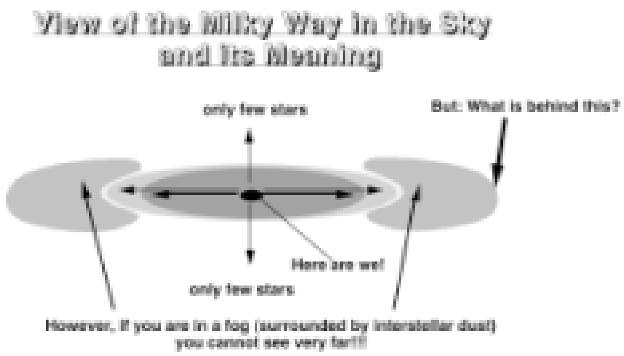


View XII.2: Herschel's view

Herschel was the first to count the stars in different directions, and he concluded that our sun was at the center of a huge disc of stars. After the Earth had been thrown out of the center of the solar system, the sun seemed to be still in the center of the milky way. As we will see, also this was a wrong perception, and thus raised suspicion. View XII.2

b) Distance Determination

Early in this century a Dutch astronomer, *Jacobus Kapteyn*, added the determination of the distances to his statistics. He used the methods of **geometric parallax** and **spectroscopic parallax,** View XII.3
which we discussed already earlier in connection with the individual stars. Again he found an equal distribution of stars in all directions of the disc and a fall-off of the density of stars to all sides at about the same distance. Therefore, he concluded: we are in the center of the Milky Way.



View XII.3: *Kapteyn* measured star distances and concluded: we are in the center, but was fooled by dust.

What prevented him from finding the true distribution was the interstellar dust, which as wee discussed earlier makes the distant stars dimmer. Taking this observation one step further it is easily concluded that the most distant stars in the disc cannot be seen at all any more. This is as if you were in a street with street lamps on a foggy night. What you will probably are a few lamps (the same number of lamps) on either side of you. You would not notice that there are more beyond those lamps, since in the fog you don't see anything beyond the closest lamps. View XII.3a
In the same way the dust blocks our sight in various places in the sky, in particular, in the galactic plane. Slide XII.3
If we look at our Milky Way in the infrared regime, we see the distribution of this dust very clearly. Dust is cold and thus radiates in infrared. Slide XII.4

c) Determination of the Center from Globular Clusters in the Galactic Halo

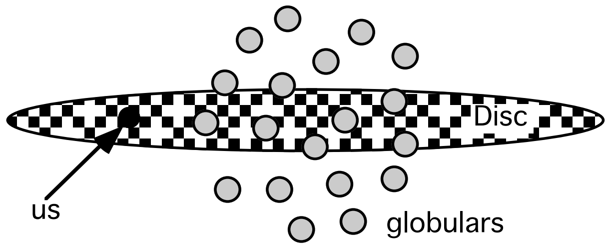
Instead of using individual stars and open clusters *Shapley* used the **Globular clusters,** Slide XII.5, 6
which appear as dense star spheres all over the sky. He argued that these must be part of our Milky Way galaxy and thus their distribution would reveal its true center. He used the **Cepheid variables** as distance indicators, because the globulars are so far away that the other methods were not sufficient. Brighter Cepheids have a longer variation period. Remember:

Cepheid variables show a clear **Period - Luminosity relation**.

Measure period ⇒ luminosity.

Luminosity & apparent brightness ⇒ distance.

He calibrated the Cepheids within the Milky Way with the other methods and then produced a 3 dimensional map of the globular clusters using the distance of the Cepheids in these clusters (1917). View XII.4



We are not central

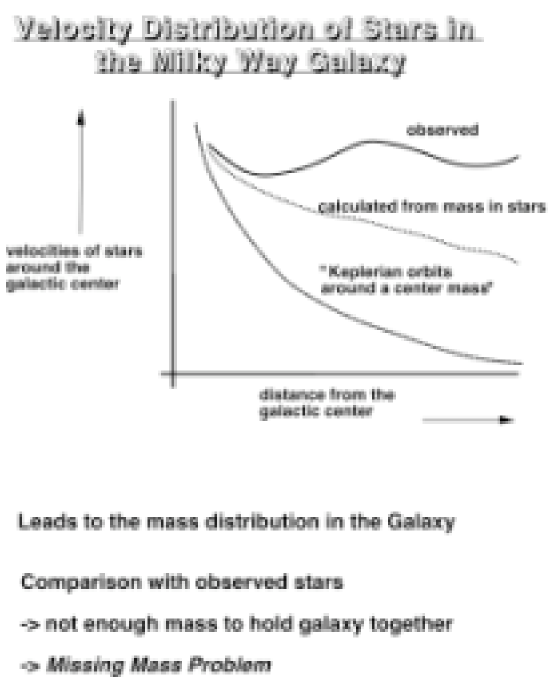
These globular clusters have to orbit around a center mass. **Slide XII.7**
Thus the center of their motion must be the mass center or in other words the center of our Milky Way. *Shapley* found that the globular clusters were centered around a point about 30,000 Parsec away into the direction of the constellation **Sagittarius**.

Slide XII.8

These are the dense star clouds in this direction. Since all stars in our Milky Way have to orbit around the center of mass in order not to fall into one another, he concluded that the center of the Milky Way had to be in these clouds in Sagittarius.
In conclusion our galaxy is a disc shaped object similar to **Slide XII.9**
the neighboring Andromeda galaxy, and we live in the outskirts of our galaxy rather than in the center. The radius of the disc is 50,0000 LY and the radius of the inner bulge only 15,000 LY. The sun is 30,000 LY from the center and orbits around in 250 million years. The galaxy is embedded in a spherical halo of globular clusters and some lonely stars.

2. Mass of the galaxy and motion

a) Mass Determination from Motion



View XII.5: Velocity curves and mass

We have noted above that the globular clusters have to be in constant motion in order not to fall into the galaxy center. Every star in the galaxy has to be in motion as well. As we have done with planets and stars in binary star systems, we can now employ the motion of the stars in the milky way disc and of the globular clusters to determine its mass. In this way always the mass of the material inside the orbit of the stars or the clusters under observation is determined. To measure the motion we use again the Doppler shift of spectral lines of stars in **open clusters**, in **globular clusters** and, in addition, the shift of the **21 cm line** of hydrogen gas to construct the "galactic motion curve". The 21 cm line of H is very important, because via radio waves (21 cm is 1420 MHz, the dial setting of the “radio station hydrogen”) information can be gleaned from regions that are blocked by dust. View XII.5

The velocity does not fall off with distance from the center, i.e. it is not a Keplerian orbit around a massive center. As a consequence most of the mass must be outside in the disc or in the halo. Compared with the mass that is computed adding up only the number of stars as derived from their light, we find that **most of the mass does not seem to be visible**. At least it is not visible in the form of stars or gas. This is known as the *missing mass problem*.

b) Galactic Corona

For this reason it has been speculated that there is a galactic corona of hot gas that spreads throughout the halo. There is indeed some gas, which can be seen in X-rays and UV, but it is by far not enough. Most of the mass seems to be dark in some yet uncovered form. Brown dwarfs, black holes, strange unknown form of matter??? Recently, the discovery of a few potential objects that have masses of a brown dwarf have been reported. The "gravitational lensing" of such an object made a star behind it flash up very brightly for a moment. From the discovery of the few objects it is still not clear how many of these objects are in orbit around the galaxy. However, many more such objects need to be found, to make a substantial contribution to the missing mass. The common conclusion is currently that there is not enough.

c) Spiral structure

Let us go back to the disc. We can learn more about the detailed structure of the galaxy disc from the motion of the stars and the gas. The stars and the gas are even not equally distributed here. They come in individual bands. In addition, they are embedded in interstellar gas. Most of the interstellar gas is hydrogen, which emits a very prominent line in the radio regime. Its wavelength is 21 cm. This line has been used to map the gas in the entire galaxy. Slide XII.10

Again the banded structure is revealed. Because this is a line radiation, like the visible spectral lines from atoms, it can be used to measure velocities with the Doppler effect. The disc of the galaxy is in **constant rotation**, but not like a rigid disc. Thus we see a relative motion of various different gas clouds. If everything would rotate rigidly, the radiation would not be Doppler shifted at all. Instead we can think of the disc as being split into separately rotating discs. If the outer disc moves at the same speed as the inner one, the inner disc will overtake it, since it has to go a shorter way. It seems to approach the material of the outer disc. What we see in fact is a collection of three separate spectral lines with two of them shifted towards the blue. View XII.6

Therefore, the material must be distributed in distinct bands around the galaxy. In fact, a mapping throughout the galaxy shows that the Milky Way has several **spiral arms** like the M51 galaxy. Slide XII.11

The bright young and hot (blue) stars are concentrated in the spiral arms and make them stand out of the rest of the disc.

One might think that such spiral arms are quite natural for a galaxy, which rotates in the way shown. It looks similar to the spraying with a rotating garden hose. However, the Milky Way has rotated already 20 times since the sun was formed, and thus all the arms would have wrapped around the disc several times already. It is impossible that the same stars would have remained in such a spiral structure as we observe today. In addition, the bright stars would not have lasted nearly as long. We need a model that produces the stars always anew within a spiral structure.

A model that explains these features is a **density wave**. It maintains a compression of the material in a certain location leading to more self-gravity. As a result it can also trigger star formation. An every day analogy for such a density wave is, for example, a police car that slows down the following traffic and thus piles up the cars which otherwise would go faster. View XII.7

In this picture, stars are formed in that density wave. Once it travels further into fresh interstellar gas, this is compressed, and more stars are formed. In this way we may fill up the entire disc, but the bright blue stars only live for 10 to 20 million years. Therefore, they have died when new stars in the neighboring region light up. The spiral arms still stand out from the rest of the disc. In this picture even supernovae have their place. When the massive stars are burnt out, they explode, and with their shock wave compress the material in the density wave even more.

3. Galactic center:

Yet there is one larger concentration of matter in the galactic center. It is somewhat obvious in the molecular clouds Slide XII.12

and in gamma ray emission Slide XII.13

SgrA* - is a small intense radio source. The material rotates in a disc around the center so fast that more than 3 x 10^6 M_{sun} is needed in the radio source SgrA* to keep stars from flying away. In addition, expanding and rotating rings of hydrogen have been found in the 21 cm radiation, which seem to hint at explosions in the center.

A suggestion is that SgrA* is a **supermassive black hole**? More recent observations of material ever closer to the center support this view. There is practically no other explanation left than a black hole. The radiation source does not change position. Thus it is very massive. Matter falling into a black hole may produce the energy to power all the bizarre features. Other galaxies seem to have the same rapid central rotation.

As an indication of extremely violent processes, very recently Gammas from electron-positron annihilation have been found in the galactic center: View XII.8

It is referred to as the "Great Annihilator". The scenario is as follows: Mass falls into a black hole. Since the matter reaches the speed of light, the material surrounding the black hole is heated to billions of degrees. This leads to an environment of very dense gamma radiation. In particular, in a strong gravity field these Gammas produce an enormous amount of pairs of electrons and positrons, i.e. matter is produced out of radiation here. At larger distances positrons and electrons merge again and thus emit **Gammas from pair annihilation**. Sketch