Chapter 17: **The Milky Way**

- history
- the H-R diagram
- star clusters & galactic archaeology
- structure & components of the galaxy (including H II regions and neutral H clouds)
- more on synchrotron emission
- sample problems

History

With a clear dark sky it's obvious that things are not uniformly distributed around the sky: there's this fuzzy band of the Milky Way, roughly 10° thick, running all the way around the sky tilted at an odd angle to the celestial equator or to the plane of the solar system. For pre-telescopic observers, though, it was not obvious that this fuzzy band contains stars, dust, and gas, or that it is not centered on us. And it was only in the 1920s that we were able to recognize the existence of other galaxies and started to need the term "Milky Way" to mean our galaxy as well as that fuzzy band of light around the sky. Determining the size and shape of our galaxy is an on-going process.

When Galileo turned his telescope on the Milky Way in 1609 he wrote that it was "in fact nothing but congeries of innumerable stars" (The Starry Messenger). Stars are not distributed uniformly around the bright band of the Milky Way, although that isn't quite as obvious without a telescope. For quite some time, though, no one, Galileo included, seems to have bothered to use new telescope to pursue further the question of how these "innumerable stars" actually were distributed.

William Herschel, who discovered Uranus in 1781, made some of the largest and best telescopes of his day and, among other things, chose to turn his mind and his telescopes to the question of the shape of the Milky Way. Consider what it might be possible to learn by counting stars in various directions: If stars were uniformly distributed, if they were equally luminous, if there were no extinction, and if your telescope were large enough to see far enough, then you might be able to determine the shape of the galaxy by looking at the faint stars. Suppose that the galaxy were shaped roughly like a grindstone, with the Sun roughly on the midplane and at or near the center of the disc. Suppose further that all stars are about like the Sun, i.e., 5th (absolute) magnitude. Herschel understood the concept of parallax, but no one had yet successfully measured the parallax, and thus the actual distance, for any star; many astronomers, including Herschel, were trying. In the absence of evidence to the contrary, it made sense to assume that stars were uniformly luminous and that, therefore, fainter = farther. Many stars are located in clusters, rather than being uniformly spread around the galaxy, and Herschel knew this, but the clusters themselves are spread relatively uniformly around the plan of the galaxy.

Historical note: in 1784 Herschel reported to the Royal Society (in Britain) about observations made with a telescope he had constructed having an aperture of "$18\frac{7}{16}$ inches":

> On applying the telescope to a part of the *via lactea*, I found that it completely resolved the whole whitish appearance into small stars, which my former telescopes had not light enough to effect. The portion of this extensive tract, which it has hitherto been convenient for me to observe, is that immediately about the hand and club of Orion. The glorious multitude of stars of all possible sizes that presented themselves here to my view was truly astonishing; but, as the dazzling brightness of glittering stars may easily mislead us so far as to estimate their number greater than it really is, I endeavored to ascertain this point by counting many fields, and computing from a mean of them, what a certain given portion of the milky way might contain. . .
> (. . .*to Investigate The Construction of the Heavens*, 1784)

Herschel clearly understood that telescopes of different sizes would make it possible to see to different distances and that the distribution of visible stars might appear differently:

> . . .suppose the small circle *g h l k* to represent the space into which, by the light and power of a given telescope, we may penetrate; and let GHLK be the extent of another portion, which we are

> enabled to visit by means of a larger aperture and power; it is evident that the gages [star counts] with the latter instrument will differ very much in their account of stars. . .
> (. . .*to Investigate The Construction of the Heavens*, 1784)

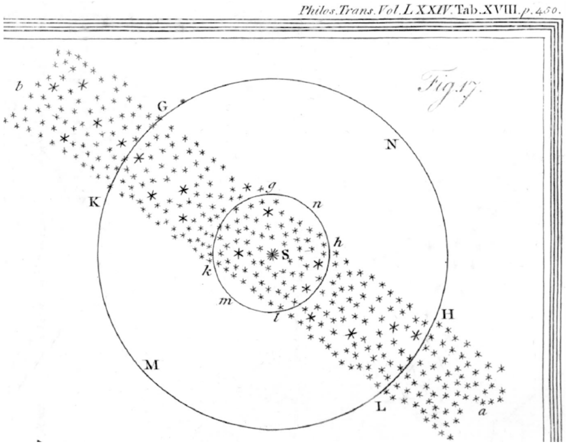


Figure 17.1:
William Herschel's sketch illustrating the geometry of counting stars

Philosophical Transactions of the Royal Society of London, 1785.

In other words, suppose, for instance, you have a telescope capable of seeing stars down to 14th apparent magnitude but there are no stars fainter than 13th; then you must be looking at the edge of the distribution of stars. By eye, it might be tough to distinguish 12th magnitude from 13th magnitude stars. But it is not a hard integration problem to determine, at least relatively, how many stars brighter than a given limiting magnitude should be visible in a given field of view. It's relative; remember that you don't yet know actual distances to stars and thus don't have a good estimate for the number density of stars. In principle, though, you should be able to estimate how many times farther the stars extend in one direction than in another direction. Herschel counted stars – he called it "star gaging" – in an arc around the sky and got a result that suggested that the Milky Way was shaped somewhat like a slightly flattened amoeba with the Sun near the center. The following is from Herschel's 1785 paper to the Royal Society, *On the Construction of the Heavens*:

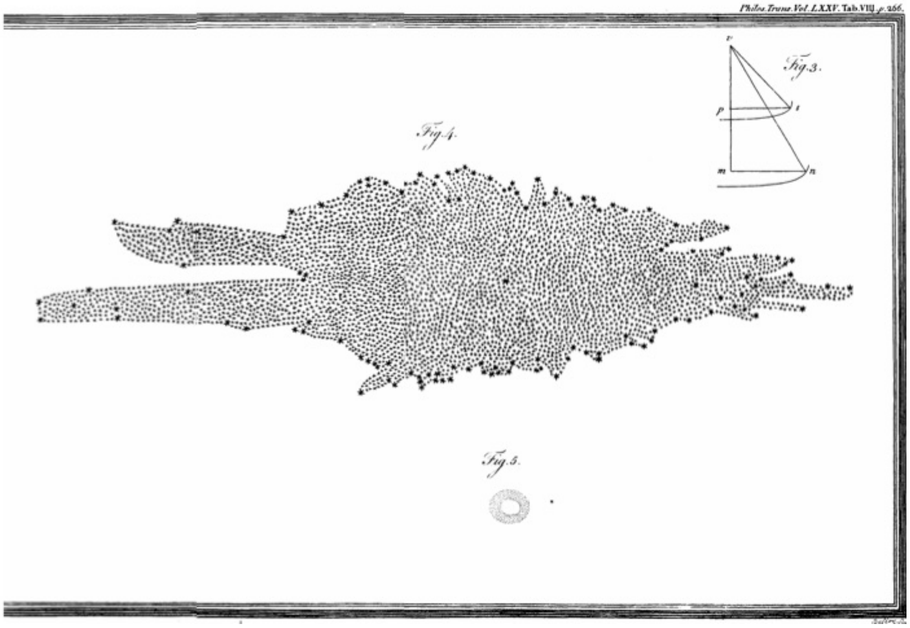


Figure 17.2:
One slice of Herschel's star counts.
Philosophical Transactions of the Royal Society of London, 1785.

No wasting space on the page: Herschel's *Fig. 3*, in the upper right corner, is related to his description of how he observed various regions of the sky; *Fig. 5* is a drawing of M57, the Ring Nebula.

Math excursion, for those of you inclined toward considering how the number of stars might vary with magnitude should they happen to be uniformly distributed, i.e., having a uniform number density in space: First, assume that stars all have the same absolute magnitude, perhaps ~5 (i.e., like the Sun), and that there is no extinction. Using the distance modulus equation, we can establish a relationship between apparent magnitude and distance:

$$m - M = 5\log r - 5$$

which becomes

$$m = 5\log r \rightarrow r = 10^{m/5}.$$

Over the entire sky, number of stars of a given apparent magnitude should thus be

$$N(m) = \tfrac{4}{3}\pi[r(m)]^3 \cdot n,$$

where n is the number density and $r(m)$ is the distance to the shell containing stars of magnitude m. This implies that

$$\log N(m) \propto 3 \log (r(m)) \propto 0.6\, m.$$

If this were true, then counting stars at magnitude $m+1$ in a given region of the sky should produce $10^{0.6}$, i.e., ~4, times more stars than counting stars at magnitude m. It doesn't. Nice idea, though, in principle.

"In principle" means, given all of those caveats we set out initially: if there's no extinction, if stars are all the same luminosity, if your telescope is big enough, if stars are uniformly distributed. Herschel came, later in life, to suspect that these assumptions were possibly not all valid. Where he, for instance, drew a lack of stars, we are more likely today to say, dust happens.

In addition to counting stars, Herschel observed that there were quite a few (over 2,000) "nebulae", both bright and dark, objects that steadfastly refused to resolve themselves into stars. Today we tend to associate nebulae with one of Herschel's contemporaries, Charles Messier. Messier published a classic catalogue of objects that were not comets. Seriously. Recall that Edmond Halley, who died in 1742, famously predicted the return of the comet that now bears his name, using that new-fangled understanding of gravity and orbits published by Newton in 1687. It was totally reasonable for 18th-century astronomers to be interested in comets, orbits, and the structure of the solar system (Herschel, Uranus, 1781; calculations of the orbit of Uranus played a role in the 1846 discovery of Neptune). In modest telescopes, comets, particularly those that have yet to pass close enough to the Sun to develop distinguished tails, look a lot like other fuzzy celestial objects. A little more than one-third of the Messier objects turned out, in the 20th century, to be other galaxies (e.g., the Andromeda galaxy is M 31); the rest are stars clusters and nebulae of gas &/or dust within our Milky Way. The 110 objects in the catalog include almost all of the bright fuzzy objects in the northern sky. Messier lived and worked in France, so none of the Messier objects is farther south than about –36° declination.

The H-R diagram

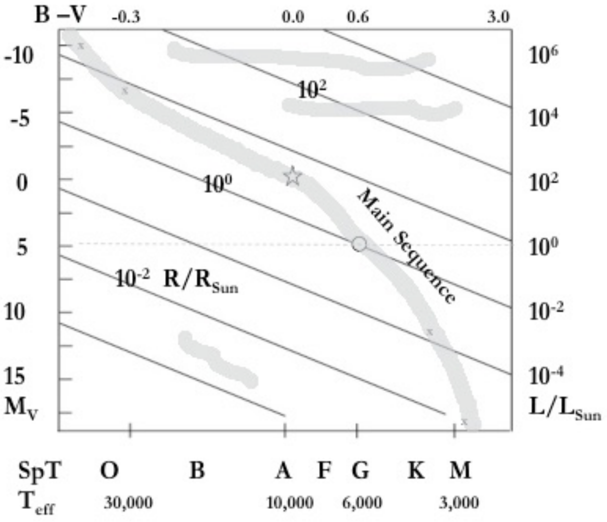
If you've studied the sections on stars you are probably already familiar with this tool for organizing stars by temperature and luminosity (or color and magnitude) and might want to skip ahead to star clusters. If you aren't familiar, you'll need this background to make sense of the following section.

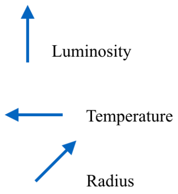
The H-R diagram is named for Ejnar Hertzsprung and Henry Norris Russell. By the early 1900s, particularly as a result of many of the women who worked for the Harvard College Observatory, star catalogs had begun to move into the modern age: positions, distances, magnitudes, colors, spectral types.

Spectral types: Stellar spectra show absorption lines, where atoms in the cooler outer layers of a star (its "atmosphere") absorb specific colors that correspond to the possible transitions between the energy levels of the atoms' outer electrons. In the 1800s, as astronomers accumulated spectra of enough different stars, it rapidly became apparent that stellar spectra are not all alike. For one thing, lines of an element differ by ionization stage; e.g., the energy transitions of calcium are different than the energy transitions of singly ionized calcium. The hottest stars show very little hydrogen in their spectra, not because they aren't made of hydrogen but because it's so hot that the hydrogen is mostly ionized. Ionized hydrogen means just bare protons, with no electrons around to absorb the energies that would show up as absorption lines in the spectrum. Stars with surface temperatures of about 10,000 K show strong hydrogen absorption lines; stars like the Sun show many lines of heavy elements such as iron, calcium, sodium. Initially it made sense to sort stars based on the strengths of the lines of hydrogen. Those classifications stuck once people realized that it made more sense to sort stars based on their temperatures. That led to the following somewhat confusing order for spectral types, from hottest to coolest: O B A F G K M. The Sun is a G star.

Back to the H-R diagram. On the vertical axis plot a measure of the stars' luminosities, usually either absolute magnitude (M_V) or luminosity normalized to solar ($L / L_{\odot}$) or, for stars in a cluster where the distance is the same for all stars, we could plot apparent magnitude (m_V). On the horizontal axis, plot a measure of the stars' surface temperatures, e.g., T_{eff} or B – V color or spectral type. Stars that, like the Sun, are producing their energy by hydrogen fusion, follow a relatively well-defined distribution called the Main Sequence. Evolved stars (older, past their hydrogen-fusing days) will have relatively larger radii and cooler surface temperatures. White dwarfs, which are the remnant cores of stars that started out like the Sun, are small and hot.

Figure 7.3: H-R diagram





The arrows indicate the direction these quantities increase.

The Sun is shown on the plot, as is a star symbol representing the location of stars such as Sirius or Vega. Stars at the top of the Main Sequence are the most massive, on the order of 10^2 solar masses; at the bottom end of the Main Sequence, the smallest M stars have masses of about 0.08 solar masses. High-mass stars evolve faster than low-mass stars. Even though, being more massive, they have more mass to fuse, they also have hotter cores, their fusion reactions proceed at a faster pace, and they run through their nuclear fuel faster than low-mass stars.

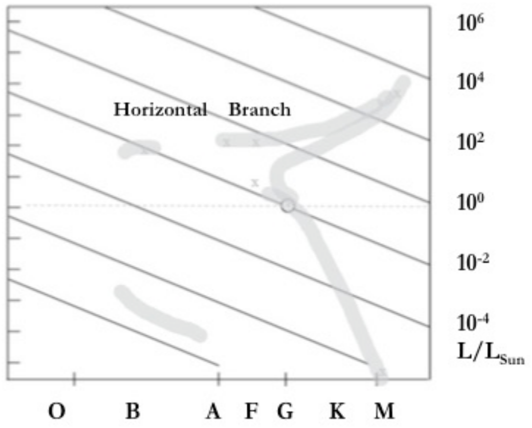


Figure 17.4: A cluster of older stars.

Here, there are no longer any stars on the upper main sequence because those more massive stars have already exhausted their hydrogen and evolved into Red Giants (or exhausted all of their fuel and become stellar remnants). Many of the giants lie on a Horizontal Branch, where they are producing energy by helium fusion.

Star clusters & galactic archaeology

Let's look at the two main types of star clusters and then at some of the roles they've played in determining the structure of the Milky Way.

The older, more massive type are the *globular clusters*, roughly spherical balls of several hundred thousand stars. We know ~157 of them in the Milky Way, although there may be more that we can't see well enough to have detected yet. One of the brightest is M13, which is visible to the naked eye, on a clear dark night, in the constellation Hercules. If you've spent some time in the southern hemisphere, you may also have seen Omega Centauri. Here is a Hubble Space Telescope image of M80 (or, NGC 6093, where NGC stands for New General Catalog):

PRC99-26 • Space Telescope Science Institute • Hubble Heritage Team (AURA/STScI/NASA)

Figure 17.5:

M80 / NGC 6093

http://heritage.stsci.edu/1999/26/big.html

Other galaxies have clusters like this as well; some of the largest galaxies appear to have thousands of similar clusters. Our globular clusters are themselves distributed roughly spherically around the Milky Way. They tend to have radii of ~10 pc (defined as the distance at which the amount of light have fallen to half its value at the core of the cluster). They mostly tend to be old, on the order of 11-13 billion years. The stars in globular clusters are low in heavy elements (often less than 1% the solar metallicity) because they formed before there was much enrichment of the heavy element content of the universe by stellar nucleosynthesis and recycling. These clusters are going to consist of low-mass stars and stellar remnants; anything more than about the mass of the Sun would evolve too fast to survive for that long. Some slightly more massive stars ("blue stragglers") may be binary stars where one star gained extra mass from its companion or the two stars were actually close enough to have merged to form a newly more massive star. There are some observations that suggest, not yet definitively, that at least some globular clusters may have intermediate-mass black holes, i.e., on the order of thousands of solar masses, in their centers. One of the most convincing is a 2023 analysis of HST and Gaia data of star motions near the center of M4 which support the existence of a central black hole of ~800 solar masses. Gravitational interactions among the stars in a cluster have long-term effects on the locations of stars in a cluster. Over time, higher-mass stars are likely to sink to the center of a cluster; conversely, some of the lowest-mass stars may "evaporate" from the cluster. Clusters whose stars experienced more interactions are likely to have relatively denser cores than clusters with fewer stellar interactions.

Many of our Galaxy's globular clusters formed as part of the Milky Way, but not all of them. One clue that some globulars may have an odd history is if their stars are not all uniform in age but rather show an age range or perhaps two distinct ages. Large-ish galaxies such as the Milky Way grow, at least in part, by tidally disrupting smaller galaxies that happen to pass too close; many of the stars from the disrupted galaxy become part of the larger galaxy. Omega Centauri, the largest of the Milky Way's globulars, appears to be the remnant core of a disrupted galaxy. The Gaia spacecraft (launched in 2013) is providing very precise position and motion data for billions of objects, including many of the Milky Way's globular clusters. Several groups of astronomers analyzing Gaia data have identified streams of stars and/or groups of globular clusters whose coherent motions, ages, and metallicities suggest that they have been grabbed from one or another small galaxy. A stream of ~ 300 stars leading back to Omega Centauri strengthens the argument that this cluster is the remnant core of a dwarf galaxy.

The Gaia data, in combination with other observations of globular clusters, suggest that many of the older and/or more metal-poor of the Milky Way's globulars are in orbits around the galaxy that are less tightly bound, more inclined and more eccentric, than many of the younger and/or less metal-poor globulars. The conclusion is that the less tightly bound globulars formed in dwarf galaxies that were then accreted onto the Milky Way. A half dozen potential merger events have been identified, ranging from 7 - 11 billion years ago. One of the largest streams of globulars and stars has been dubbed Gaia Enceladus, or, by others, the Gaia Sausage. The stellar remnants of the Gaia-Enceladus event have highly eccentric orbits around the Milky Way ($e \sim 0.9$). The progenitor dwarf galaxy merged with the Milky Way roughly 10 billion years ago, bringing with it at least eight globular clusters, and possibly more than twice that many. NGC 2808, a globular with multiple episodes of star formation, has been suggested as a strong candidate for being the remnant core of the Gaia-Enceladus dwarf galaxy. Probing our galaxy's past, we now have the tools to do galactic archaeology.

It's also not necessarily the case that mergers are a process relegated to the distant past: There are suggestions that we have some stars whose original home was the Large Magellanic Cloud, a companion galaxy a bit larger and a bit farther away (~10% the mass of the MW, ~50 kpc distance), perhaps explosively ejected from the LMC, e.g., by the supernovae of more massive companion stars, with large enough velocities to carry them far enough toward us for the Milky Way to capture them.

For purposes of determining the shape and size of the Milky Way, let's return to the idea that the globulars are roughly spherically symmetrically distributed around the galaxy. In other words, they are not confined to the disk of the galaxy. This means that they don't suffer as much extinction from the interstellar dust, which happens to be mostly confined to the plane of the galaxy. They are also all roughly the same size and roughly the same age. None of them happens to be close enough for us to determine a distance by trigonometric parallax. On the other hand, if we could determine the distance to one of them (or to one of the stars in one of them) we could estimate the distances to all of them. A three-dimensional map of the distribution of the globular clusters should give us an idea our location relative to the center of the galaxy. Let's see how this works.

Look at the Horizontal Branch (HB) in the H-R diagram for a cluster of old stars. There's a gap, called the RR Lyrae gap. RR Lyrae stars are variable stars whose properties change noticeably on time scales of a few hours to about a day. Because of the fact that they vary, these stars are often simply not plotted on the cluster H-R diagram. The distribution of stars on the HB across the "gap" really is very close to horizontal and stars on the gap edges have just about the same absolute magnitude in all globular clusters, $M_V \sim 0.75$. That makes them very very useful for finding the distances to globular clusters. Recall the distance modulus equation:

$$m_V - M_V = 5\log d - 5 + A_V.$$

If we consider a globular cluster that lies well out of the plane of the galaxy, so that there is minimal extinction along the line of sight, and if we consider the stable stars on the sides of the RR Lyr gap, for whom we know the absolute magnitudes, we can determine the distance to that cluster. We can in fact use this to determine the distances to several globular clusters and plot their locations in three dimensions. The center of that distribution of clusters should be a good first estimate of the location of the center of the Galaxy.

One of the first astronomers to try this was Harlow Shapley (1885 – 1972). Shapley worked for a time at Mount Wilson Observatory and then for many years as director of the Harvard College Observatory. Initially Shapley overestimated the distances to the globular clusters. For one thing, RR Lyrae stars are low-metallicity stars; Shapley was comparing them to solar-metallicity Cepheid variables (more on Cepheids below) without knowing that the metallicity difference was going to make the RR Lyr stars less luminous than their solar-metallicity cousins. For another, there really is some dust, even along the lines of sight to globulars, and that will make them look fainter and more distant than they really are. Still, Shapley was instrumental in developing our understanding of the size of the Milky Way and the fact that the Sun is most definitely not at the center of the Galaxy.

Robert Trumpler (1886 – 1956), at Lick Observatory, got a handle on the extinction problem during the 1920s. Trumpler observed *open clusters*, also called galactic clusters because they tend to lie more in the plane of the galaxy. Open clusters tend to contain a few hundred stars (although some have thousands) and may include hot O and B stars as well as cooler redder stars. An example with which you may be familiar is the Pleiades, or the Seven Sisters, in the constellation Taurus. Here is another, NGC 602, in the Small Magellanic Cloud (SMC):

Figure 17.6: NGC 602. At the distance of the SMC, this image spans ~200 light years.

Credit: NASA, ESA, and the Hubble Heritage Team

http://www.nasa.gov/multimedia/imagegallery/image_feature_740.html

By 1930 Trumpler had data for ~100 clusters. For any given cluster, we can assume that the cluster stars are roughly all at the same distance from us, meaning that we can produce a color-magnitude diagram for that cluster by plotting (B – V) color (i.e., blue magnitude minus visual magnitude) vs. apparent magnitude (this CM diagram is the observational equivalent of the H-R diagram). The distribution of stars will be shifted, vertically, from the distribution in a plot of color vs. *absolute* magnitude, by an amount that is related to the distance to the cluster. If there were no extinction, then the amount of shift is simply given the distance modulus, i.e., every star plotted is shifted by an amount $m - M = 5\log d - 5$; shifting the cluster plot vertically until the cluster stars overlay the expected locations in the absolute magnitude diagram gives us the distance to the cluster.

The problem that Trumpler ran into was that he logically expected that open clusters should all be roughly the same linear size, or at least a subset of open clusters that had the same stellar population should have the same size. It isn't a trivial problem determining where the stars in a cluster stop and the star count fades to the general background level, but an individual observer, with practice, is likely to over- or under-estimate cluster angular diameters in a consistent fashion. Angular diameter should be inversely related to distance. But for Trumpler's clusters, this was not the case: "distant" clusters consistently appeared to be larger. Trumpler was forced to accept that the distances determined from the cluster CM diagrams were off because of the existence of an interstellar medium that interfered with the star light, making our observations of the cluster magnitudes too faint and hence our estimations of the cluster distances, based on those magnitudes, too large. Trumpler was also able to show that the absorption was color-dependent, making distant stars look redder than they would look in the absence of the absorption.

The stellar *population* in globular clusters is distinctly different from that in open clusters. The terminology that we use is to say that star with roughly solar metallicities are Population I; this will include almost all open clusters. Stars that formed when there was much less enrichment of heavy elements in the galaxy are called Population II; globular cluster stars are Pop. II. If we could find any stars uncontaminated by any heavy elements, i.e., composed only of hydrogen and helium, we would call those stars Population III. Globular clusters are distributed roughly spherically symmetrically around the Galaxy, so we could say that most Population II stars are found in the galaxy's halo. Stars that formed more recently live in the galaxy's plane, where the majority of the gas and dust, i.e., the raw materials for star formation, are found. While some clusters have metallicities higher than the Sun's, most don't, meaning there hasn't been a huge change in the proportion of heavy elements available for star formation over the past five billion years. One main reason is that although star deaths have continued to contribute heavy elements our galaxy is also still accreting hydrogen gas; the balance of these two processes means that stars today form with roughly solar metallicity.

The Structure & Components of the Milky Way

Let's look at some of the major regions of the Galaxy and a useful coordinate system for referring to directions around the Galaxy. Here are two sketches of the Milky Way, one edge-on and one face-on view:

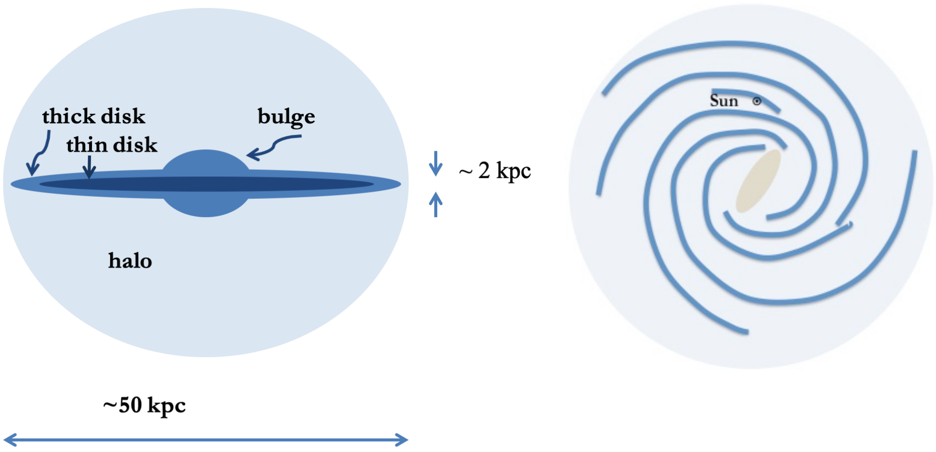


Figure 17.7: Milky Way — a) side view; b) top view

Based on its stellar content, the thick disk is old, perhaps as much as 13 billion years old, i.e., dating from when the universe was only about 800 million years old. Near the Sun the thick disk is roughly 2 kpc thick, although there's not a hard and fast edge to the distribution of stars. The Milky Way grew and added material as it merged with other, usually smaller, galaxies and formed thick disk stars for several billion years. As the thick disk ran out of star-forming material and the number of mergers bringing fresh gas dropped off, the star-forming material settled into a thinner disk. The thin disk includes the Sun and new young stars and the dust and gas out of which they form. It is a few hundred pc thick. Stars in the thin disk are more enriched in heavy elements than are the older thick disk stars.

For comparison, here are images of two spiral galaxies, roughly similar to the Milky Way:

Figure 17.8: NGC 4302 (edge-on) and NGC 4298 (nearly face-on).

Credit: NASA, ESA, and M. Mutchler (STScI).

http://hubblesite.org/image/4019/news_release/2017-14

It will often make sense to use a coordinate system that is based on our location relative to the plane of the Galaxy (rather than on our horizon or our celestial equator). (The tricky part here is that it is not easy to determine precisely where the center of the Galaxy is or the plane of the Galaxy, or how far off the plane the solar system is. We'll look in a bit more detail at these complications, below.) Galactic latitude (*b*) is measured in degrees north or south of the plane of the Galaxy. By convention, the north galactic pole is the pole that is in the same half of the sky as the north celestial pole; the NGP is in the constellation Coma Bernices. Galactic longitude (*l*) is measured in degrees eastward from the direction toward the galactic center, which is in the direction of the constellation Sagittarius.

Note that this coordinate system is centered on the location of the Sun; it is *not* centered on the core of the Galaxy. The Sun's distance from the center will usually be given as 8.5 kpc from the center because for many years that was the best value available. Today 8 kpc is a bit more realistic. The solar system is not quite in the plane of the galaxy. We are about 8 pc above it; over long periods of time, as we orbit the galaxy, we oscillate up and down through the plane. The solar system is on the inner edge of a spiral arm called the Local Arm or the Orion Arm (for the constellation). Around us the interstellar medium is relatively low density. In this Local Bubble, ~ 90 pc across, the ISM is ~ 10% the density outside. The Local Bubble is thought to be the result of one or more supernova that would have exploded over the past 2 - 20 million years, pushing away much of the nearby material in the ISM. The ISM within the Local Bubble is not entirely uniform, though. The solar system lies in the Local Interstellar Cloud (sometimes called the Local Fluff), ~9 pc across, where the ISM density is less depleted than in the rest of the Local Bubble. Over time our orbit will likely take us out of these for-the-moment local features.

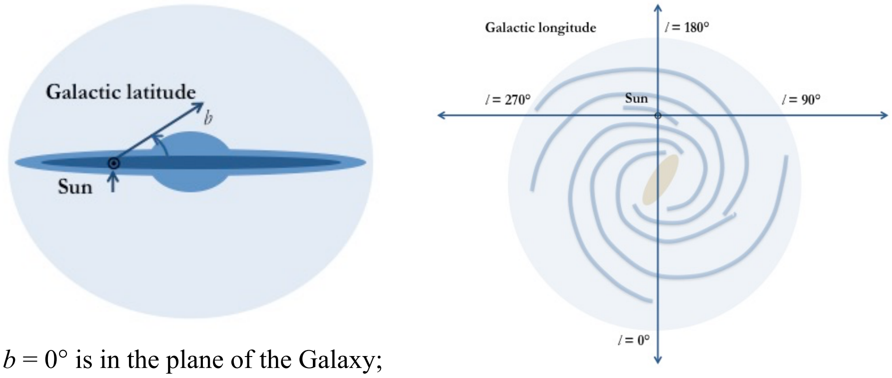


Figure 17.9: galactic coordinates; a) side view, b) top view.

b = 0° is in the plane of the Galaxy; +90° is straight north.

The Milky Way's disk of stars is ~50 kpc diameter; the halo, containing dark matter and globular clusters, has a diameter on the order of 200 kpc (only the inner part is shown in the sketch, above). The mass of the Galaxy is on the order of 10^{12} solar masses. Of that total, about $8\cdot10^{9}$ solar masses is gas. (And by mass, interstellar gas is ~100 times more abundant than dust particles.) Interior to the orbit of the Sun, the mass is on the order of 10^{11} solar masses.

The Milky Way is a barred spiral galaxy, meaning that it has spiral arms in the disk and has an elongated ("barred") nucleus. Halo stars and stars in the nuclear bulge are older; the dust, gas, and younger stars are found in the disk; the disk rotates, and spiral arms form in the disk (the halo rotates, too, but not as rapidly as the disk). These pieces of evidence suggest that, much earlier, the galaxy was shaped more spherically, and that the relatively rapidly rotating, flattened, disk formed more recently.

Any given star, such as the Sun, will orbit the galaxy under the gravitational influence of the material that is closer to the center of mass. As long as the mass distribution is symmetric, i.e., as long as the density of mass in the disk is the same for a given galactocentric distance regardless of where you are around the center, then it will be the case that orbits are not (much) influenced by mass that's farther out from the center. Here's a sketch to show why that works

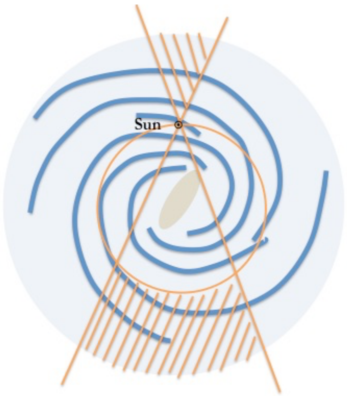


Figure 17. 10:
The stars in the wedge above the Sun are closer and thus you might expect them to exert more gravitational force on the Sun than the stars in the wedge on the far side of the galaxy. But the area of that latter wedge is larger, and thus there are more stars there. The two effects cancel. The gravity that controls the orbit of the Sun is only due to the mass interior to the orbit of the Sun.

The orbit of the Sun around the galaxy is nearly circular, meaning that the circular velocity equation is appropriate for expressing the relationship between speed and mass:

$$v_{circ}^2 = {}^{GM}\!/\!{}_{R},$$

where M is the mass of the galaxy interior to the orbit of the Sun and R is the distance between the Sun and the center of mass of the galaxy (~8.5 kpc).

Examples:

1. Assume that we've measured the speed of the solar system and know it to be ~220 km/sec. How much mass are we going around?

$$M_{\text{MW, interior to Sun}} = \frac{v^2 R}{G} = \left(\frac{220\ \text{km/s}}{4.74\,{}^{\text{km/s}}\!/\!{}_{\text{AU/yr}}}\right)^2 \cdot \frac{8500\ \text{pc}\cdot 206{,}265\ \text{AU/pc}}{4\pi^2\ \text{AU}^3/M_\odot \text{yr}^2} \approx 10^{11} M_\odot .$$

Here, we've converted km/sec into AU/yr and done the calculation in solar system units.

2. Assume instead that we were given as data that there are ~10^{11} solar masses of material interior to the orbit of the Sun and were asked how fast we are going in km/sec. Let's do this one in mks units.

$$v_{circ}^2 = \frac{GM}{R} = \frac{6.67\cdot10^{-11}\ \mathrm{m}^3/(\mathrm{kg\ s}^2)\cdot10^{11}M_\odot\cdot2\cdot10^{30}\mathrm{kg}/M_\odot}{8500\ \mathrm{pc}\cdot3.09\cdot10^{16}\ \mathrm{m/pc}}$$
$$\rightarrow v = \sqrt{5.08\cdot10^{10}\ \mathrm{m}^2/\mathrm{s}^2} = 2.25\cdot10^5\,\mathrm{m/s} = 225\ \mathrm{km/s}.$$

Physics note: in this context it is not too hard to see that the circular velocity equation arises from the balance of gravitational and centripetal accelerations. The former is given by GM/r^2 and the latter by v^2/r. Set these two terms equal and solve for the velocity.

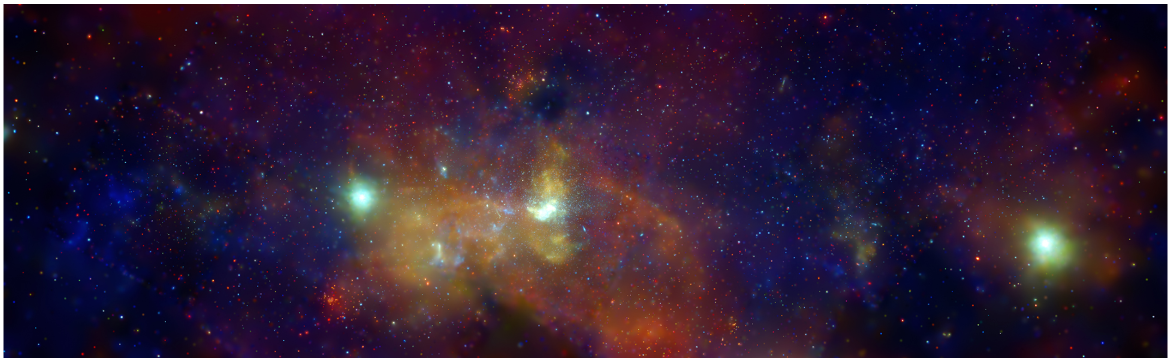
In a system such as the solar system, where the overwhelming majority of the mass is in the Sun in the center of the system, we expect the speeds of objects in roughly circular orbits to follow this circular velocity equation, meaning that the velocity will fall off as the square root of the distance. In equation form, $v \propto \sqrt{(1/r)}$. This kind of motion is called Keplerian (although presumably we could just as logically have called it "Newtonian"). Note here that spiral galaxies exhibit some motions that are distinctly *not* Keplerian:

First, spiral arms don't wind up. You might expect them to, given that the far ends of the spiral arms are a lot farther from the center of the galaxy than the inner ends. But they don't. Spiral arms are what's called a density wave. A decent analogy is a traffic jam: cars arrive at the traffic jam, slow down, the density of the cars increases, cars move through, and out the other side of the traffic jam, where they can speed up again. The traffic jam itself may or may not move along the highway, but if it does, the speed with which it moves will be unrelated to the speed of the cars. Stars and dust arrive at a spiral arm, pile up, slow down a bit, and move on through. The density perturbation moves around the galaxy at its own rate as if it were rigid. Because they are density enhancements, and because the dust and gas lie in the plane of the galaxy, spiral arms tend to be locations for star formation.

Second, stars farther out in the disk in spiral galaxies don't tend to slow down. You might expect the speeds to drop off as we get farther away from the center of mass. That works in the solar system, where the mass in concentrated in the center. It doesn't hold for galaxies; as we move farther out in the disk we orbit more mass. In fact we orbit more mass than we can account for based on the mass of the material – stars, dust, gas – that we can see. We need *dark matter* to account for the high speeds of stars well out in the galactic suburbs.

Now let's look in a bit more detail at the various components of the Galaxy. We'll start in the center, where there is a supermassive black hole and a lot of energetic activity. We can't see to the center of our galaxy in visible wavelengths because there is just too much dust. Radio, yes, or infrared, at wavelengths of a few microns, are good for penetrating the dust. At the high-energy end of the spectrum, x-rays will also penetrate the dust and reach us from the core of the Galaxy. The center of the Milky Way is in the direction of the constellation Sagittarius. The radio source Sagittarius A* (Sgr "A star"), identified in 1974, is thought to mark the location of the actual center of the Milky Way. By the early 1990s infrared observations had achieved enough sensitivity and angular resolution that several teams of astronomers (in particular, teams at UCLA and at the Max Planck Institute for Extraterrestrial Physics) have been able to identify individual stars and clouds of gas in very tight orbits – many within ~1,000 AU – around a very massive central object. One star, known as "S02", has an orbit period of ~15.5 years and a pericenter distance of ~120 AU. Based on observations of these objects, the mass of the central object is now estimated to be 4.3 million solar masses. That much mass in a space smaller than our solar system pretty much has to be a supermassive black hole. The radio emission from Sgr A* may arise from an energetic accretion disk and/or a jet of material being ejected from the disk. There are also occasional x-ray flares, possibly from material falling onto the accretion disk, on its way to being eaten by the black hole, or perhaps magnetic reconnection events such as power the flares on the Sun. We'll look at the activity of galactic black holes in more detail later, when we discuss active galaxies and quasars.

Figure 17.11: Here is a relatively wide view of the center of the galaxy in x-rays:



Credit: NASA/CXC/UMass/D. Wang et al.
http://chandra.harvard.edu/photo/2009/gcenter/

This image is 117 by 36 arcmin, which, at the distance to the center of the galaxy, corresponds to about 900 by 400 light years. We see an x-ray haze from the whole region, light emitted by gas that's been superheated by supernova explosions, by winds of particles from massive young stars, by emission from gas being pulled off a companion star by one of the thousands of stellar-mass black holes near the galactic center, as well as by the energetics of Sgr A* (at the center of the image). In the following image, almost exactly the same width, the three colors represent x-rays (blue; 1 – 8 keV), mid-IR (green) and radio (red; 90 cm).

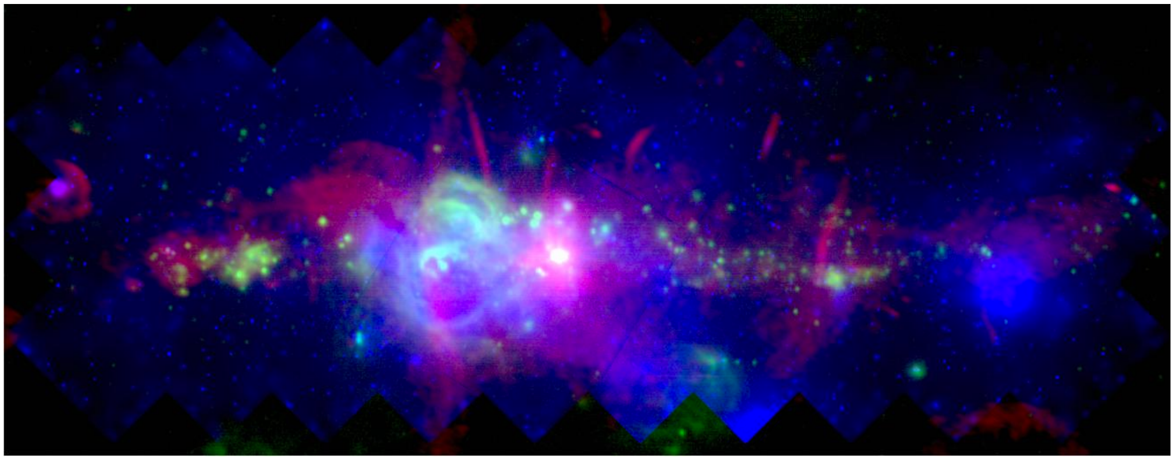


Figure 17.12: Multi-wavelength galactic center

Credit: X-ray: NASA/UMass/ D.Wang et al., Radio: NRAO/AUI/NSF/NRL/ N.Kassim, Mid-Infrared: MSX
http://www.chandra.harvard.edu/photo/2002/gcenter/gcenter_xray_ir_r.jpg

In the radio we see filaments, stretching several 10s of light years in length, probably associated in some way with regions of active star formation, possibly influenced by the alignment of the galaxy's magnetic field near the center.

In 2009 NASA released an intermediate scale, reasonably high-resolution image including both x-rays and infrared; Sgr A* is the bright region just to the right of center in the following image.

Figure 17.13 - caption below.

http://www.spitzer.caltech.edu/images/2795-ssc2009-20a-Great-Observatories-Unique-Views-of-the-Milky-Way

Figure 17.13: Caption:
In celebration of the International Year of Astronomy 2009, NASA's Great Observatories -- the Hubble Space Telescope, the Spitzer Space Telescope, and the Chandra X-ray Observatory -- have produced a matched trio of images of the central region of our Milky Way galaxy. Each image shows the telescope's different wavelength view of the galactic center region, illustrating the unique science each observatory conducts.

Bottom Left - Spitzer's infrared-light observations provide a detailed and spectacular view of the galactic center region. The swirling core of our galaxy harbors hundreds of thousands of stars that cannot be seen in visible light. These stars heat the nearby gas and dust. These dusty clouds glow in infrared light and reveal their often dramatic shapes. Some of these clouds harbor stellar nurseries that are forming new generations of stars. Like the downtown of a large city, the center of our galaxy is a crowded, active, and vibrant place.

Bottom Middle - Although best known for its visible-light images, Hubble also observes over a limited range of infrared light. The galactic center is marked by the bright patch in the lower right. Along the left side are large arcs of warm gas that have been heated by clusters of bright massive stars. In addition, Hubble uncovered many more massive stars across the region. Winds and radiation from these stars create the complex structures seen in the gas throughout the image. This sweeping panorama is one of the sharpest infrared pictures ever made of the galactic center region.

Bottom Right - X-rays detected by Chandra expose a wealth of exotic objects and high-energy features. In this image, pink represents lower energy X-rays and blue indicates higher energy. Hundreds of small dots show emission from material around black holes and other dense stellar objects. A supermassive black hole -- some four million times more massive than the Sun -- resides within the bright region in the lower right. The diffuse X-ray light comes from gas heated to millions of degrees by outflows from the supermassive black hole, winds from giant stars, and stellar explosions. This central region is the most energetic place in our galaxy.

Zooming in still further, here is a Chandra X-ray Observatory image of the region near Sgr A* and, in the insets, evidence of an x-ray flare.

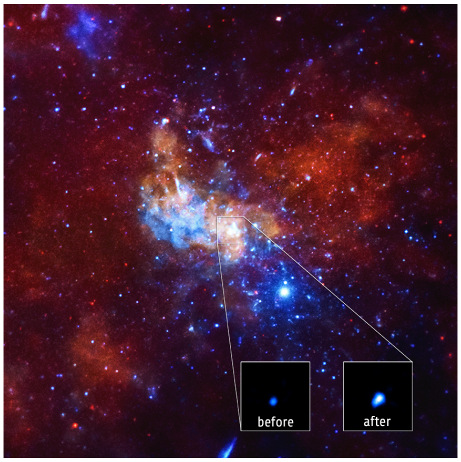


Figure 17.14: Sagittarius A*

The main image is ~8 arcmin (~18.7 pc) across; the insets are ~1 arcmin (~2.3 pc) across.

The colors in the image correspond to three different x-ray energy bands:
red: 2.0 – 3.3 keV;
green: 3.3 – 4.7 keV;
blue: 4.7 – 8.0 keV.

Credit: NASA/CXC/Amherst College/D.Haggard et al.
http://chandra.harvard.edu/photo/2015/sgra/

We now have images of the silhouettes of two supermassive black holes. The Event Horizon Telescope is a current collaborative project combining radio telescopes all around the world into one huge array (using very-long baseline interferometry, VLBI) to observe Sgr A* and the supermassive black hole at the center of M87, at a resolution equivalent to the event horizon size. Teams made observations of M87 in April 2017; in April 2019, after considerable effort and time to ensure that the data were appropriately calibrated and instrumental effects appropriately taken into account, the team released an image of the core of M87 (see image in Ch 18). In May 2022, they were able to add their first image of Sgr A*.

It is possible, at these non-visible wavelengths, to see some evidence of the activity of the galactic core well outside the nucleus of the Galaxy. Huge bubbles of hot gas, visible in gamma rays, extend above and below the nucleus of the galaxy. These bubbles were detected by the Fermi Gamma-Ray Space Telescope, observing at energies of 1 – 10 GeV. The Fermi bubbles are a bit hard to detect because high-energy cosmic rays interacting with gas and photons in the Milky Way create a "fog" of gamma ray emission around the sky. Below is an artist's conception of what those bubbles might look like if we had gamma-ray vision and could step outside the Milky Way. The "why" is still being debated. Measurements of the expansion rate of the northern bubble suggest the Fermi Bubbles were formed approximately 6 million years ago. It's possible that a jet, or a long-ago jet, fired off as the black hole in the galactic core destroyed a huge clump of gas, created the bubbles. In 2020 the European eRosita team reported detecting similar structures in the x-ray.

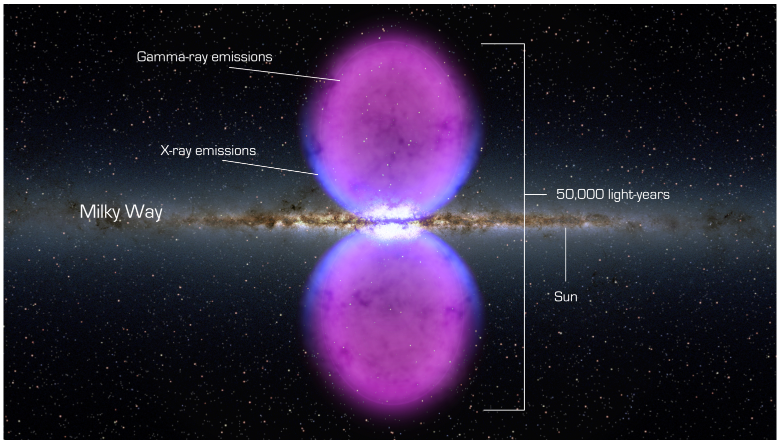


Figure 17.15: Edge-on Milky Way. Credit: NASA / Goddard Space Flight Center artist's illustration.
http://www.nasa.gov/mission_pages/GLAST/news/new-structure.html

The central bar. Here, annotated (and "upside down") is an artist's sketch of the Milky Way, showing the barred nucleus. It's based in large part of observations by the Spitzer IR Space Telescope. The bar is about 8 kpc long. We'll look at images of other barred spirals when we discuss other galaxies. The majority of nearby spiral galaxies seem to have bars, but Spitzer studies of distant (and thus younger) spirals show many fewer having bars. We don't have entirely satisfactory answers for why some spirals have bars, how bars form, how long they last, or how they are related to the dark matter content of a galaxy. Stars in the bars do seem, often, to have elongated orbits that keep them trapped in the bar (unlike spiral arms, where stars move through the density enhancement). Some material flowing inward along the bar funnels into the central regions, where it may participate in formation of new stars.

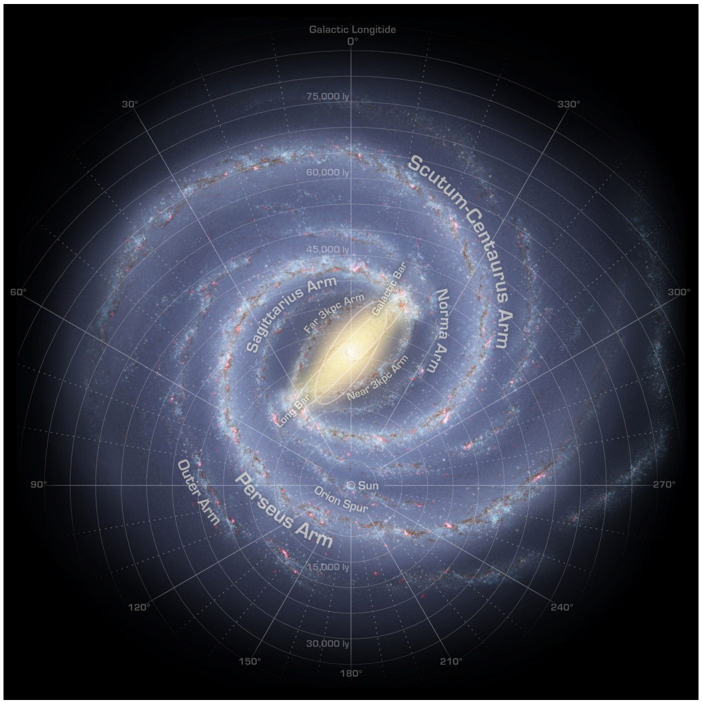


Figure 17.16: Top view of Milky Way.

Credit: R. Hurt (SSC), JPL-Caltech, NASA.

https://www.nasa.gov/mission_pages/spitzer/multimedia/20080603a.html

If we look out of the plane of the Galaxy, the core is surrounded by a relatively spherical bulge of older stars, which shows up quite nicely in wavelengths such as 2 microns.

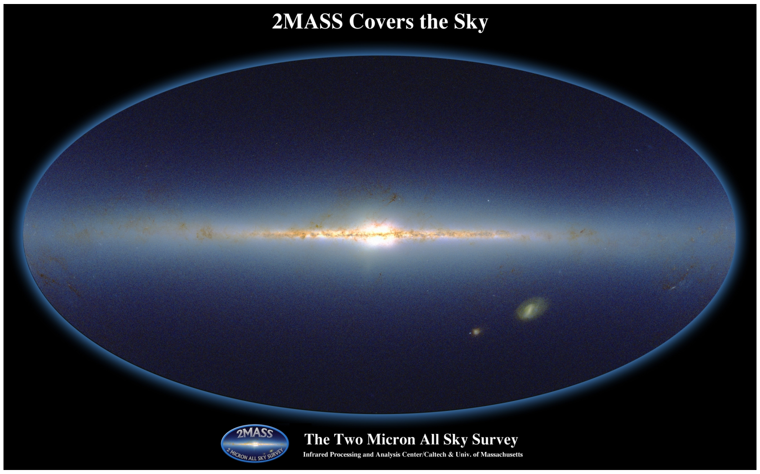


Figure 17.17: 2-micron all-sky image.

Credit: Atlas Image courtesy of 2MASS/UMass/IPAC-Caltech/NASA/NSF.

http://www.ipac.caltech.edu/2mass/gallery/2mass_allskyatlas.jpg

Let’s back away from the center and start to consider the distribution of stars, gas, dust, and dark matter in the disk and halo. It should be apparent from these images of the central region of the galaxy that observations in different wavelength regimes provide information on different sources of emission. NASA has compiled a series of 360° panorama views around the plane of the Milky Way in a range of different wavelengths. These strips are (almost) all ~10° above and below the plane of the Galaxy; all are centered on Sgr A* (or, equivalently, 0° galactic longitude). Below the image are a few comments about the sources of emission at these various wavelengths.

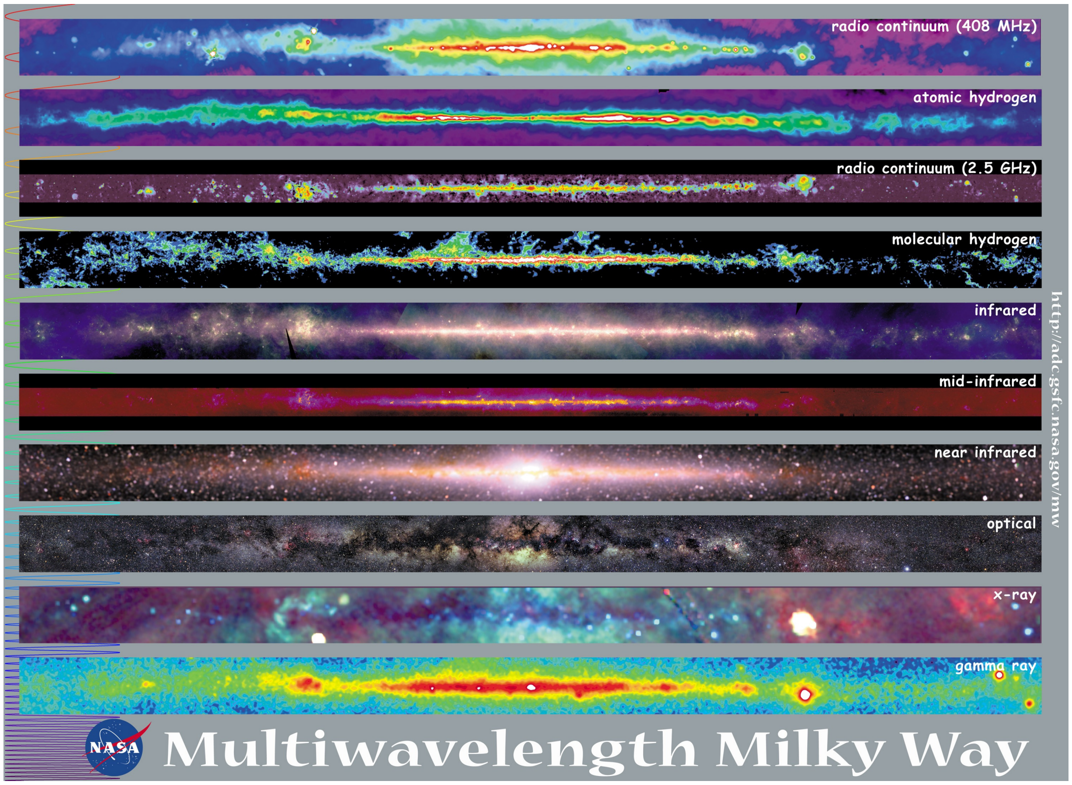


Figure 17.18; http://mwmw.gsfc.nasa.gov/mwpics/mwmw_8x10.jpg

The 408 MHz radio continuum. The term “continuum” means that this is radio emission that is broad-band, not confined to a narrow wavelength range or single monochromatic energy transition. If the observations had been made in a nearby frequency the image would look pretty much the same. This region of the electromagnetic spectrum is good for observing the emission from very fast-moving charged particles (mostly electrons) interacting with the interstellar magnetic field. We would likely call this synchrotron emission, which was described earlier in the section on light and emission processes. To get fast-moving electrons, we need a source capable of accelerating them. Often that is the shock wave from a supernova explosion, which is why we observe synchrotron emission from supernova remnants. For instance, the bright source at ~110° longitude (the left-most yellow dot, with an associated x-shaped diffraction pattern, in blue) is the supernova remnant Cassiopeia A. The “A” means that Cas A was the first, brightest radio source detected in the constellation Cassiopeia. The supernova was a type IIb, meaning it was the collapse and subsequent explosion of a single massive star.

The atomic hydrogen. This is 21-cm emission from cold, neutral hydrogen gas in the interstellar medium. The 21-cm emission is an important tool for mapping the locations of hydrogen gas in the Galaxy and we’ll consider it in much more detail, below.

The 2.4 – 2.7 GHz radio continuum. This strip only goes to ± 5° around the galactic plane. The angular resolution in this image is considerably better than the 408 MHz image. The sources for the emission at these frequencies include electrons interacting with magnetic fields (synchrotron emission) and also with electric fields of ions (called free-free emission, or bremsstrahlung) in regions where the interstellar gas is hot and has a high degree of ionization.

The molecular hydrogen. Actually, it's molecular CO. Molecules have energy transitions as they change the rates at which they vibrate or rotate. Symmetric molecules such as H_2 (or N_2, etc.) are hard to detect. We are fairly confident that CO tracks with H_2, although the expectation is that the hydrogen is a lot more abundant. Here what we are seeing is emission from cold molecular clouds, which are often the precursors to star formation regions.

The mid- and far-IR composite. This is based on data from the IRAS satellite, which, in 1983, was one of the first infrared space telescopes. There are three bands in this image, at 12, 60, and 100 µm, displayed as blue, green, and red, respectively. At these wavelengths interstellar dust is emitting, pretty much as we would expect a not-very-warm black body to emit. One source of emission that has been subtracted from this image is the zodiacal light, emission from dust along the plane of our solar system.

The mid-IR. This is another image that only extends ± 5° above and below the plane. It covers 6.8 – 10.8 µm emission, as observed by MSX, the Midcourse Space eXperiment satellite, 1996-7. The diffuse emission is molecular, including light from polycyclic aromatic hydrocarbons (PAHs), which are among the more complex interstellar molecules. This wavelength range is getting short enough that there are some bright spots where very cool stars, or stars that are very embedded in dust clouds, show up.

The near-IR. The three bands in this image are at 1.25, 2.2, and 3.5 µm, shown in blue, green, and red respectively. At these wavelengths we see many individual red stars. Note that in this image you can see the stars in the bulge of the galaxy.

Optical. This slice is from a classic set of photographs made by Dr. Axel Mellinger in the late 1990s. The wavelength range covers 400 – 600 nm. Obscuring dust is very apparent, as are several red H II regions, about which we'll say more below.

There doesn't seem to have been a set of UV images available when this poster was created, so the next shortest bandpass is in the x-ray. The three bands used here have energies of 1.5 keV, 0.75 keV, and 0.25 keV, coded blue, green, and red, respectively. These are considered relatively low-energy, or "soft", x-ray bands. As with some of the x-ray emission for the core of the Galaxy, we're seeing emission from gas that's been shock heated. These aren't wildly high energies, so some of this emission still gets absorbed by interstellar dust. These images were obtained with ROSAT (Röntgen Satellite), a German – U.S. – British x-ray space telescope that operated for most of the 1990s. (It was finally "de-orbited", meaning brought into a low enough orbit that it would experience atmospheric drag and burn up, in 2011. It came down over the water east of India; no pieces seem to have survived to hit the ground.)

The gamma rays. This image represents photons with energies greater than 300 MeV, observed with the Compton Gamma Ray Observatory, a space telescope that operated from 1991 to 2000 (de-orbited over the Pacific Ocean in June, 2000.) Gamma rays often result from very energetic collisions, e.g., of galactic cosmic rays with hydrogen nuclei in the interstellar medium or of high-energy electrons scattering (boosting) otherwise modest photons to gamma ray energies. Pulsars (neutron stars, remnants from supernovae) are also sources of gamma ray emission; the three round sources on the right side of the image, so bright that they are white, are associated with known pulsars.

Bright stars are an obvious aid in figuring out the structure of the Galaxy. Bright *hot* stars, in particular, are found in the spiral arms near the dust and gas out of which they formed. Even with dust, a star with an absolute magnitude of, say, −5, is going to be visible for a long ways. But there are some other tools we can use to determine how material is distributed in the Galaxy. In particular, let's look in more detail at a couple of ways that emission from hydrogen can help us map more of the structure of the Galaxy.

Those red blobs on the optical images of spiral galaxies are an indication of star formation and excited hydrogen gas. In a young cluster of stars, recently formed from a cloud of dust and hydrogen gas, we expect to find a few hot, massive, UV-emitting stars. They won't live very long, but while they do, they will provide a source of ultraviolet light that will excite the surrounding hydrogen. You may recall that it takes 13.6 eV to ionize a hydrogen atom; that corresponds to a wavelength of 91.2 nm, so we are interested here in the light that these hot stars are emitting at wavelengths of 91.2 nm and shorter. Suppose that one of these UV photons hits a hydrogen and ionizes it. Protons and electrons are likely to recombine; in one possible scenario, the electron drops immediately back to the ground state and re-emits a photon of 91.2 nm. That's kind of a wash if we're tracking UV photons to see what happens to them. A second scenario is that the electron drops back down to the ground state by way of one or more intermediate energy levels. In this case, what started as a 13.6 (or 13.6+) eV packet of energy gets broken up into two or more smaller packets of energy as the atom emits the lower-energy photons that correspond to the transitions between energy levels. In particular, the electron may go down by way of the transition from the 3rd to the 2nd energy levels, which, you may recall, will give us the red 656 nm H-alpha line. Lots of the hydrogen atoms near our high-temperature star(s) will emit Hα; at some distance away, though, we will have used up our supply of UV photons. We'll see a roughly spherical glowing red ball with a size that corresponds to the number of available UV photons and the density of the surrounding hydrogen. Because the hydrogens are emitting a visible wavelength, we call this an emission nebula. Because the hydrogens are spending some fraction of their time being ionized, we also call this an H II region – recall that the designation "II" means singly ionized. Further, because astronomer Bengt Strömgren was one of the first to describe this process, H II regions are also called Strömgren spheres. The confusing part of all this nomenclature is that ionized hydrogen is *not* what is emitting Hα; Hα gets emitted by the recombined, now neutral, hydrogen atom.

Even if we had only one O or B-type star, we'd get a bright red ball about a pc across, which is possibly noticeable enough to help us determine distances to the star and, if it's in another galaxy, to the star's host galaxy. That would work better if all Strömgren spheres were the same size, but at least it is a start for estimating distances. Let's see how that math would work. We will start with a few simplifying assumptions, namely that the hydrogen gas is uniformly distributed, that we have a single star and we know the rate at which that star emits photons capable of ionizing hydrogen, and that we are in equilibrium, meaning that the number of ionizations per second will be balanced by the number of recombinations per second. We further assume that we are going to use up all of those ionizing photons. That means

$$N_{\text{ionizing}} = \frac{4\pi}{3} R^3_{\text{Strömgren}} \cdot n_{e^-} \cdot n_{H^+} \cdot \alpha(2),$$

where we assume that the number of ionizing photons (which implicitly = number of ionizations) equals the number of recombinations. The number of recombinations depends on the number density of electrons and protons (which should be the same, assuming that hydrogen ionization is our only source of electrons). The factor $\alpha(2)$ is a coefficient that describes the probability of all recombinations that *don't* involve dropping immediately back down to the $n = 1$ level (i.e., don't result in immediately re-emitting another ionizing photon). It should make a bit of sense that the higher the number density, the faster they recombine, and the smaller the H II region will be.

If we want to put some numbers in this, we need to estimate the number of ionizing photons. For simplicity, let's assume that we have a very hot star, perhaps O5 or O6 spectral type, a star with a surface temperature of ~ 50,000 K, emitting on the order of $2 \cdot 10^5$ solar luminosities. In this case it is not unreasonable to make the approximation that *all* of the photons emitted by the star are shorter than 91.2 nm wavelength. Recall Wien's law for the most probable wavelength of a blackbody spectrum:

$$\lambda_{\text{peak}} = \frac{2.898 \cdot 10^{-3}}{T} \text{m} \rightarrow \lambda_{\text{peak}} = \frac{2.898 \cdot 10^{-3}}{50{,}000} \text{m} \cdot \frac{10^9 \text{ nm}}{\text{m}} = 58 \text{ nm},$$

which is shorter than the 91.2 nm it takes to ionize hydrogen, so our assumption that we can use all the photons is not going to be too wildly wrong. Convert that 58 nm to energy per photon:

$$E = \frac{hc}{\lambda} \rightarrow E = \frac{(6.623 \cdot 10^{-34} \text{J} \cdot \text{s}) \cdot (3.0 \cdot 10^{8} \text{m/s})}{58 \cdot 10^{-9} \text{m}} = 3.43 \cdot 10^{-18} \text{J / photon}$$

(or 21.4 eV). If our star has a luminosity of ~$2\cdot10^5$ solar luminosities, we have

$$\frac{(2\cdot10^5)\cdot(3.85\cdot10^{26}\,\text{J/s})}{3.43\cdot10^{-18}\,\text{J / photon}} \approx 2\cdot10^{49}\,\text{photons / sec.}$$

That recombination coefficient $\alpha(2)$ is temperature dependent; for H II regions, with temperatures on the order of 8,000 K, it's about $3\cdot10^{-19}$ m^3/s. The relevant densities are about 10^9 electrons / m^3 (and we assume that the number of electrons = number of protons). That all means we have

$$R_{\text{Strömgren}} = \sqrt[3]{\frac{3N_{\text{ionizing}}}{4\pi(n_{e^-})^2\alpha(2)}} \approx \sqrt[3]{\frac{3\cdot2\cdot10^{49}\,\gamma\,/\,\text{s}}{4\pi(10^9\,e^-\,/\,\text{m}^3)^2\cdot(3\cdot10^{-19}\,\text{m}^3\,/\,\text{s})}} = 2.5\cdot10^{16}\,\text{m}$$

or ~0.8 pc or $1.7\cdot10^5$ AU.

Now, suppose we wanted to use that estimate to find a distance to an H II region in the Large Magellanic Cloud (LMC). We observe the angular size of the H II region. Suppose we measure that size to be 3.4 arcsec. That's not a very large angle; pc = AU / ″ gives us

d = $1.7\cdot10^5$ AU / 3.4 ″ ~ 50,000 pc.

That tells us that, roughly speaking, the LMC is about 50 kpc away.

So, what do these H II regions look like and how do they show up in other galaxies? Below is a Hubble Space Telescope image of the central regions of two colliding galaxies, known as "the Antennae" because, outside this field of view, are long tails of stars. In the central region, shown here, the dust and gas from the two galaxies are colliding like crazy, making new stars, and lighting up the star-forming regions with bright pinkish-red hydrogen emission characteristic of H II regions.

Figure 17.19

http://hubblesite.org/newscenter/archive/releases/2006/46/image/a/format/web_print/

That's the excited hydrogen. Now let's look at the neutral atomic hydrogen and the 21-cm emission. Radio astronomers are more likely to use frequency units, and this corresponds to 1420.406 MHz. The energy of this transition is tiny, only 5.9 μeV. This is a transition *within* the ground electron energy level. What? Electrons and protons have a quantum property called spin, associated with what's called spin angular momentum; it's related to the fact that they have a magnetic moment, meaning they act as if they are little tiny bar magnets. Spin can either be up or down. The energy of the hydrogen atom is a tiny bit higher if the electron and proton spins are parallel than it is if they are antiparallel. The fact that there are really two energy levels very close together within the ground state is called hyperfine splitting. Well, ok, if we've got two energy levels, we should be able to make a transition between them. Except that certain energy transitions are quantum mechanically "forbidden", not supposed to happen (although this doesn't exactly mean *forbidden!,* but more like "highly discouraged"). Electrons also have a quantity called orbital angular momentum and the "selection rule" says that in permitted transitions this orbital angular momentum has to change by one unit. If the electron just flips over, within the ground state, it hasn't changed its orbital angular momentum. That makes just flipping over a forbidden transition. In practice what this means is that a hydrogen atom in the slightly higher level, left alone with nothing to excite it, is likely to sit around for something on the order of 10^6 years before it will spontaneously de-excite and emit that 21-cm photon. The only reason this is even remotely useful is that there's an awful lot of cold, bored, hydrogen sitting around in the plane of the Galaxy, enough to give us a detectable signal.

That cold neutral hydrogen often resides in discrete clumps. Those clumps are not all moving around the Galaxy in synch with us, which means that we will observe the 21-cm emission Doppler shifted by any radial velocity component in the motion of the hydrogen cloud relative to us. *That* is exciting. It means that 21-cm observations are one of the most important means of determining the locations of the spiral arms in the Galaxy (remember that gas and dust pile up in spiral arms) and that is exciting enough to warrant a side trip into some calculus and trigonometry for a few pages. The basic idea is this: objects that are not too far away from us in the plane of the Galaxy will be orbiting around almost exactly the same mass we are orbiting, only moving slightly faster or slower than we are, depending on whether they are slightly closer or slightly farther away from the galactic center. We are observing those objects from a moving platform; we may observe radial and tangential velocities, but those are relative to us, and we are moving, too. If we could disentangle our motion from the motion of these other objects, if we could establish a rule of thumb for how the motion of objects at other locations in the galaxy changes as you get farther away from us, then we could use those observed velocities to figure out objects' distances and their actual velocities around the center of the Galaxy. Jan Oort (1990 – 1992) was a Dutch astronomer who made significant contributions to our understanding of the question of how the Milky Way rotates and the following analysis originates with his work. (He also thought about comets, and the Oort cloud of distant comet nuclei, well out in the solar system, is named for him.)

Before we launch into the math, let's review what we know about the motion of the Sun. Stars relatively near to us make up what is called the Local Standard of Rest (LSR), meaning that on average, we have a sphere of stars that are all moving around the center of the Galaxy together. On average, with respect to the LSR, the motions of the nearby stars should average to zero. (There is no fixed set of stars that constitute the LSR; galactic astronomers today use some tens of thousands of stars within a few hundred parsecs of the Sun.) Anything that's not zero should be due to the motion of the Sun with respect to the LSR. The Sun is moving toward a point called the solar apex. What we find is that stars in the direction of the solar apex show radial velocities that are negative, i.e., they have slightly blue-shifted spectra, because we are moving toward them, and stars in the direction of the antapex have positive radial velocities. Stars at the apex or antapex have low proper motions. On the sides, we don't see radial velocities but we do see proper motions. Recall that we can break stars' proper motions into two components, an υ (upsilon) component parallel to the solar motion, and a τ component perpendicular to the solar motion. The τ components of the proper motions of the LSR stars are random, but their υ components, on average, point backward toward the solar antapex. The figure on the left shows the LSR centered around the Sun. the solar apex is roughly in the direction of the star Vega. On the right is a slice through the LSR in the plane of the Sun's orbit around the Galaxy.

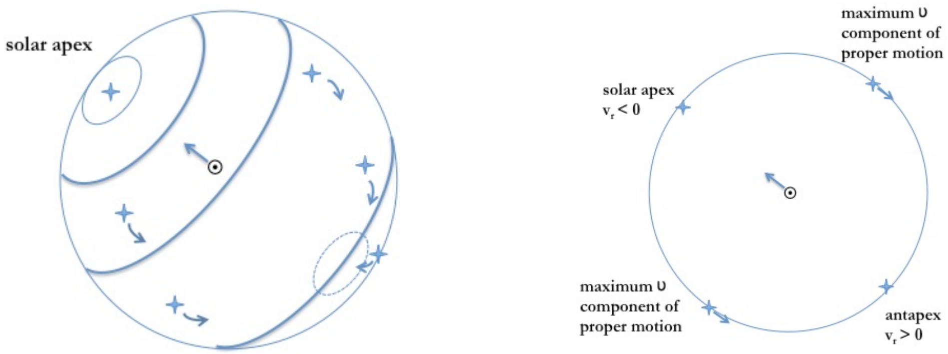


Figure 17.20: The solar motion with respect to the LSR is ~20 km/s; the LSR moves at ~220 km/s around the galaxy.

Now for the differential rotation math. In the following diagrams we have the Sun and a star or gas cloud, some object seen at a distance *d* in the direction of galactic longitude *l*. The direction to the galactic center is down, with R_0 being the distance between the Sun and the galactic center. The instantaneous velocity of the Sun is V_0, assumed to be toward *l* = 90°. R and V, without the subscripts, indicate the location and velocity of the object being observed. (Some texts will use θs for the velocities, trying to make it clear that these are the actual orbital velocities, not the relative-to-us velocities that we observe.) Let α be the angle, indicated, between the line of sight and the object's velocity vector; similar to the Sun, we assume that the instantaneous velocity of the object is perpendicular to the direction to the galactic center. Given *l*, α, and the right angles, satisfy yourself that the other angles indicated are labeled correctly.

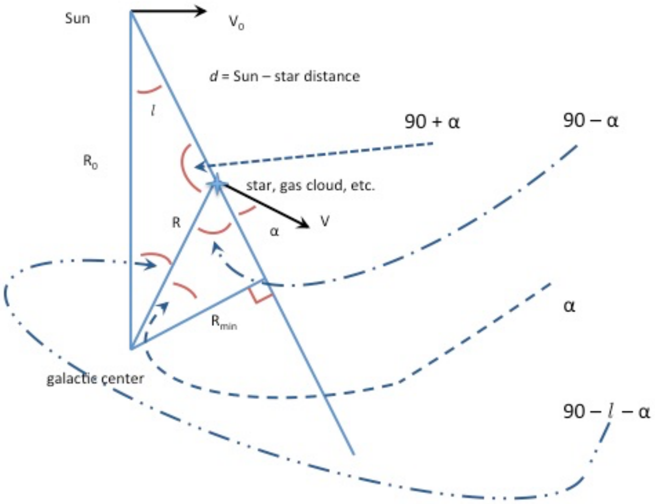


Figure 17.21

Next. Both the Sun and the star are moving, so the v_{tan} and v_{rad} that we observe are the *differences* between the Sun's motion and the star's motion.

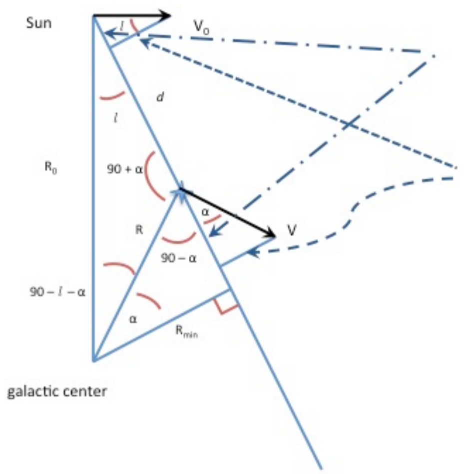


Figure 17.22
The dash-dot lines point to the two components of motion along the line of sight.
The observed radial velocity, $v_{rad} = V \cos \alpha - V_0 \sin l$.

The dashed lines point to the two components of motion perpendicular to the line of sight. The observed tangential velocity, $v_{tan} = V \sin \alpha - V_0 \cos l$.

At this point we are going to need some trig identities:

$$\frac{\sin A}{a} = \frac{\sin B}{b} = \frac{\sin C}{c}$$
$$a^2 = b^2 + c^2 - 2bc\cos A$$
$$\cos(A + B) = \cos A \cos B - \sin A \sin B$$
$$\cos^2 \ell = \tfrac{1}{2}(1 + \cos 2\ell)$$
$$\sin 2\ell = 2\sin \ell \cos \ell$$

We are also going to need the relationship between linear and angular velocity:

$$\omega = {}^{\mathrm{V}}\!/_{r}\,.$$

Use the law of sines to eliminate cos α from the radial velocity:

$\sin(l) / R = \sin(90 + \alpha) / R_0 = \cos(\alpha) / R_0$; therefore

$$v_{rad} = V \cos \alpha - V_0 \sin l \rightarrow V[R_0/R] \sin l - V_0 \sin l.$$

Next, substitute in the angular velocities for the V/ R combinations:

$$v_{rad} = R_0\,(\omega - \omega_0) \sin l.$$

Use the law of sines and the formula for the cos (A + B) to simplify the tangential velocity:

$\sin(l) / R = \sin(90 - l - \alpha) / d = [\cos(l + \alpha)] / d = [\cos \alpha \cos l - \sin \alpha \sin l] / d$; therefore

$$v_{tan} = R_0\,(\omega - \omega_0) \cos l - d \cdot \omega.$$

Now we need a bit of calculus. The Taylor series expansion is a way to approximate the value of a function based on its value at a nearby point and some estimation of the rate at which the function is changing. The math looks like this:

$$f(x) = f(x_0) + (x - x_0) \cdot \left(\frac{df}{dx}\right)\Bigg|_{x_0} + (x - x_0)^2 \cdot \frac{1}{2}\left(\frac{d^2 f}{dx^2}\right)\Bigg|_{x_0} + \ldots$$

In this case, our function *f(x)* is the angular velocity as a function of *R*. We approximate

$$\omega - \omega_0 \approx (R - R_0) \cdot \left(\frac{d\omega}{dR}\right)\Bigg|_{R_0} .$$

In words, we are assuming that the angular velocities of stars, gas clouds, etc., with galactocentric distances that aren't too different from the Sun's galactocentric distance, are not too different from the Sun's angular velocity *and* that the rate of change in the angular velocity doesn't change too fast near us. The rate of change of the orbital angular velocity is the $\left(\frac{d\omega}{dR}\right)$ term; we assume that we can evaluate that rate of change at the location of the Sun (R_0) and use it to calculate angular velocities at some other *R*.

Define the Oort coefficients as follows:

$$A \equiv -\frac{R_0}{2}\left(\frac{d\omega}{dR}\right)\Bigg|_{R_0} \approx 14.8 \text{ km}/(\text{s}\cdot\text{kpc})$$

$$B \equiv A - \omega_0 \approx -12.4 \text{ km}/(\text{s}\cdot\text{kpc}).$$

Note also that

$$R_0 - R \approx d\cos l$$

and that

$$\sin 2l = 2\sin l \cos l.$$

Using these quantities, our velocity equations become

$$\text{v}_{\text{rad}} = A\cdot d \sin(2l)$$

$$\text{v}_{\text{tan}} = d\,(A\cos(2l) + B).$$

(Yes, if you are really looking carefully you'll notice that we made a sneaky assumption that ω and ω_0 are not too different, in the tangential equation.) Once we've measured the Oort coefficients for objects whose distances we know, we can use these equations to determine distances to other objects.

If we wanted, we could step back and express the Oort coefficients in terms of the velocities, rather than the angular velocities. That takes another bit of calculus:

$$\left.\frac{d\omega}{dr}\right|_{R_0} = \left.\frac{d\,{}^{\text{v}}\!/\!_r}{dr}\right|_{R_0} = -\frac{\text{V}_0}{R_0^2} + \frac{1}{R_0}\left.\frac{d\text{v}}{dr}\right|_{R_0} \rightarrow$$

$$A = \frac{1}{2}\left(\frac{\text{V}_0}{R_0} - \left.\frac{d\text{v}}{dr}\right|_{R_0}\right)$$

$$B = -\frac{1}{2}\left(\frac{\text{V}_0}{R_0} + \left.\frac{d\text{v}}{dr}\right|_{R_0}\right).$$

The Oort *A* describes the shear, or the deviation from rigid rotation; *B* can be interpreted as an angular momentum gradient. It makes sense that they are about the same magnitude.

Ok, why did we do this math?! Remember that we started by asserting that we would like to be able to use the observed radial (and possibly tangential) velocities of objects such as clouds of neutral hydrogen gas to estimate the distances to those objects and their velocities and thus to map the galaxy. To accomplish this, radio astronomers observe at frequencies near 1420 MHz along many lines of sight, i.e., along many different galactic longitudes *l*. A given line of sight may intersect clouds of gas in two or three different spiral arms. The emission from each cloud will be Doppler shifted a bit from the 1420 MHz because each cloud has its own orbit around the Galaxy and some component of its velocity will be along the line of sight and thus we will observe a radial velocity relative to the Sun. The measured Doppler shifts give us those radial velocities and, once we have established values for *A* and *B*, we can use the above equations to get the distances to the clouds from the radial velocities. In practice, we aren't restricted to just the 21-cm emission from clouds of neutral hydrogen, but could use other wavelengths as well. Long wavelengths, that get through the dust, are likely to be most useful. As mentioned above, regarding the figure of multi-wavelength images of the Milky Way, emission from CO molecules is also important for determining the structure of the Galaxy, particularly farther out in the disk of the Galaxy.

If the Sun's velocity vector points toward 90° galactic longitude, and by and large everything in the disk of the galaxy is rotating the same direction that we are, we would expect the following distribution of radial velocities:
Objects with orbits interior to ours, and thus having larger velocities around the galactic center:
270 – 360° longitude, $v_r < 0$ (objects catching up to us);
0 – 90° longitude, $v_r > 0$ (those objects are pulling away from us).
Objects with orbits exterior to ours, having lower velocities around the center:
90 – 180° longitude, $v_r < 0$ (we are catching up to them);
180 – 270° longitude, $v_r > 0$ (we are pulling away from them).

One major result from this sort of analysis is the determination of the rotation curve for the Milky Way. There is, actually, a fair bit of scatter to the data points, but roughly speaking it looks like this:

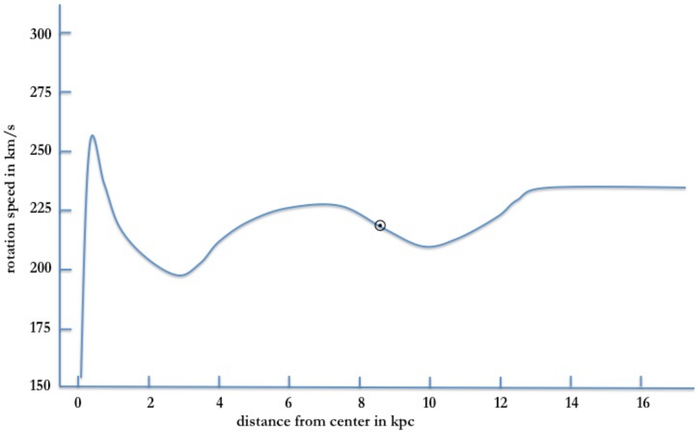


Figure 17.23
Milky Way rotation curve

Here we are using the canonical 8.5 kpc and 220 km/sec for placing the Sun on the diagram. Note that in close to the core, where there really is a large chunk of mass, centrally located, the speeds fall off with distance the way you would expect for Keplerian motion. That holds out to almost 3 kpc but beyond that the speeds go up again. Beyond about 13 kpc from the center, the speeds flatten out. As noted above, this result implies that the amount of mass in the disk of the Galaxy is not dropping off, even as we near the edge of the disk of visible stars. There must be dark matter, something that does not interact with electromagnetic radiation but does interact gravitationally, to account for the high speeds at large distances.

Looking ahead a bit, this rotation curve is consistent with what we observe in other galaxies, as well. Astronomer Vera Rubin did substantial research on the rotation rates of galaxies beginning in the 1960s. Rubin found that, like the Milky Way, most galaxies rotate too fast for the amount of mass we can infer from their electromagnetic radiation, so fast that they should fly apart if not for the gravitational attraction of some even larger mass of dark matter. The term "dark matter" had actually come onto the scene several decades earlier; in the early

1930s Fritz Zwicky used the term in reference to extra unseen matter whose gravitational presence he inferred based on motions of galaxies in the Coma cluster.

The neutral hydrogen in the plane of the Galaxy is confined to a fairly thin disk; significantly closer to the center than the orbit of the Sun it's about 100 – 120 pc, getting generally thicker as we move out in the disk beyond the Sun until it's about 3 kpc thick by the time we are out near the edge of the disk, about 30 kpc from the center. In this case, "how thick" means twice the scale height, where the scale height is the distance over which the density falls by a factor of *e*. In other words, if, near the Sun, the density of the gas has dropped by a factor of *e* relative to the density in the plane by the time we are ~150-180 pc above (or below) the plane, then we would say that the scale height is ~150-180 pc and the disk thickness is twice that, or 300-360 pc. (Hydrostatic equilibrium and the math for the scale height are described in more detail in Chapter one.)

Interior to the orbit of the Sun that disk of gas if fairly flat, but it is distinctly warped farther out in the disk. Warped disks are not weird. Material in the disk may oscillate; a more obvious cause of a warp is a gravitational interaction with another galaxy. Here is a Hubble Space Telescope image of an edge-on spiral galaxy, ESO-510-G13, where the whole disk, dust, stars, all of it, is clearly warped. This galaxy is in the constellation Hydra, ~150 million light years away. The warp in the disk of the Milky Way may not be quite as extreme as this.

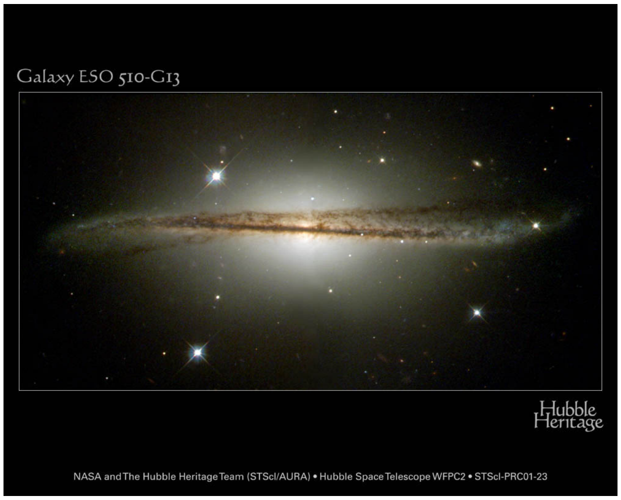


Figure 17.24

http://heritage.stsci.edu/2001/23/big.html

We have looked at H II regions and at neutral hydrogen; there's another possible condition for the gas in the interstellar medium, though, briefly mentioned above, and that is that it could be very hot, shocked and superheated bubbles of gas around the locations of supernova explosions. To a lesser extent, there are bubbles of gas around all stars, due to the wind of particles they emit, but in the case of supernovae, "super bubbles" of gas can be so large and energetic that they burst out of the disk of the galaxy. These bubbles are not as large as the gamma-ray bubbles shooting out of the galactic core, but still, they are impressive. Fountains of highly ionized gas, containing heavy elements ejected in the supernova, shoot out of the plane of the galaxy and expand rapidly in the lower-density intergalactic medium (IGM). Some of the material falls back down toward the plane as a high-velocity cloud of gas; some contributes to the IGM, the million-ish K diffuse plasma between the galaxies.

The Milky Way isn't alone, and we've briefly mentioned already our major companion galaxies, the Large and Small Magellanic Clouds, visible in the southern hemisphere sky. In the context of gas and high-velocity clouds, it's worth noting that there is a ribbon of gas, called the Magellanic Stream, between us and the Magellanic Clouds. It stretches nearly halfway around the Milky Way. Based on its heavy element content, it seems to be gas that was pulled principally out of the Small Magellanic cloud (with some contributions from the LMC) about 2 billion years ago when the SMC plowed a bit too close through the halo of the Milky Way. Here's an image of radio observations of the Magellanic Stream, overlain on an Axel Mellinger visible-light montage of the Milky Way:

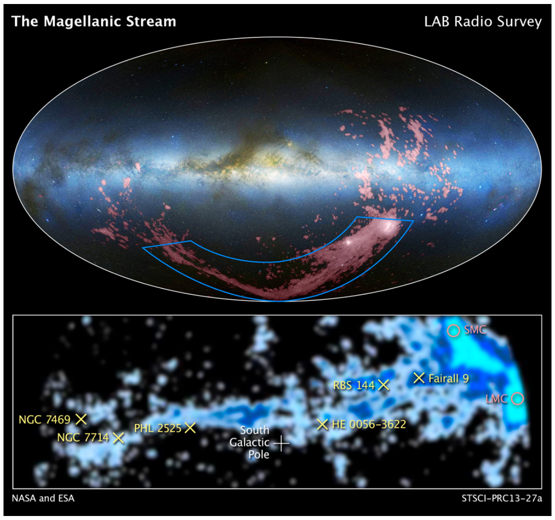


Figure 17.25

http://hubblesite.org/newscenter/archive/releases/2013/27/image/a/

The image at the bottom is an expanded, and straightened out, view of the boxed region from the top image. The locations marked with the Xs are where HST made observations that led to the conclusion that the gas composition indicated that the gas in the Stream arose, mostly, from the SMC. These locations were chosen because there are distant quasars in those positions, the light from which passes through the Magellanic Stream, where atoms in the Stream absorb particular UV wavelengths from the light of the background quasar. The quasar serves as a flashlight, shining through the Magellanic Stream. The oxygen and sulfur content of the Stream, in particular, is distinctly different than we find in gas in the Milky Way.

The other 1%: dust happens. Dust particles only account for about 1% of the mass of the interstellar medium but they have an outsized effect on the light passing through the ISM. You already know, from reading about magnitudes, that dust both dims and reddens the visible wavelengths of light. Just as a reminder, though, let's review:

$$m_V - M_V = 5\log d - 5 + A_V$$
$$E_{(B-V)} = (B-V)_{\text{obs}} - (B-V)_0$$
$$A_V \approx 3.1 \cdot E_{(B-V)} \approx 1 \text{ mag / kpc}.$$

In the distance modulus we added the A_V term to represent the number of magnitudes of extinction caused by the dust. The $E_{(B-V)}$ is the color excess, which is a measure of the reddening in the $(B - V)$ color index of a star due to the dust. The 3rd line gives two ways of estimating the amount of the extinction, either from knowledge of the color excess or based on the average of 1 magnitude per kpc.

Dust in the Milky Way is not uniformly distributed, as anyone who is fortunate enough to have seen the Milky Way high in a dark night sky can readily attest. Even if we don't have enough spectral information to use the color excess to estimate extinction, we can do better than simply using that average 1 magnitude per kpc if we know where we are looking with respect to the plane of the galaxy. If we are very near the plane of the Milky Way, roughly less than about 2° galactic latitude, a better estimate would be $A_V \sim 1.8$ magnitudes per kiloparsec. At higher galactic latitudes, $b >$ about 10°, we can make use of the fact that the thin disk component of the galaxy, within which the dust lies, has a scale height of only ~ 125 pc to argue that the distance to our object isn't all that important and the extinction can be estimated by 0.18 / sin *b*. Thus we could add to the above set of equations:

$$A_V \approx 1.8 \text{ mag / kpc for } b < 2^\circ;$$
$$A_V \approx 0.18 / \sin b \text{ for } b > 20^\circ.$$

Because the dust is not totally cold, particles will emit, roughly as black bodies, with spectra that peak in the infrared. See that infrared strip in the multi-wavelength set of images of the Milky Way, above.

In addition to the extinction and the reddening, interstellar dust also has the effect of imparting ~10% polarization to the starlight passing through it. Recall that polarization is a measure of the extent to which the planes of the electric fields of the incident radiation are aligned. The fields are what's doing the "waving" in our electromagnetic wave; if all the electric fields are waving up-down and none are waving right-left, then our light is linearly polarized. If it's 50/50 up-down vs right-left, then our light is unpolarized. Polarizing filters, which pass one orientation and (almost) completely block fields waving in the perpendicular direction, allow us to measure the percentage of polarization in the starlight we are observing. If our dust grains are slightly nonspherical and slightly aligned with the magnetic field of the Galaxy, they can impose this slight polarization on what was initially unpolarized starlight. Basically if the waving electric field see the long axis of the dust grains it will suffer more extinction than if it sees the short axis.

The light from a reflection nebula is even more highly polarized, ~25%. A reflection nebula occurs when a dust cloud is behind a star, preferably a bright blue-ish star. The red light gets through the dust cloud; the blue, being scattered, will bounce back in our direction. Because the dust grains it bounced off of were slightly elongated and slightly aligned, the reflected light will be polarized. NGC 7023 is a classic reflection nebula:

Figure 17.26: NGC 7023
NASA, ESA and Digitized Sky Survey 2. Acknowledgment: Davide De Martin (ESA/Hubble)

http://www.spacetelescope.org/images/heic0915b/

We also get some clues about the nature of the dust from the shape of the extinction curve. There's more extinction along some line of sight than others, but in the Milky Way the extinction as a function of wavelength in the visible to near UV has this shape:

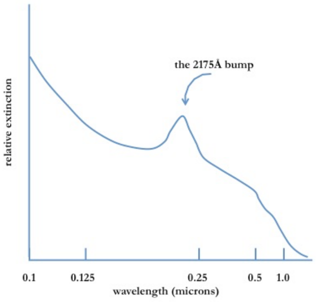


Figure 17.27
The 0.2 μm bump seems to be due to carbon grains. Farther out in the infrared we find spectral features due to absorption by water ice (at ~3 μm) and silicates (at ~9-10 μm). Some distinct emission features in the IR can be identified with PAHs, large hydrocarbon molecules containing several 10s of carbon atoms.

To summarize the observations: polarization happens; extinction and absorption of starlight happen, especially in the near IR – visible – UV, with spectral signatures that can be identified with carbon, water ice, silicates; there are spectral features due to complex molecules such as PAHs; there's thermal emission characteristic of cold black body particles particularly along the plane of the Galaxy.

What we think this means for the nature of the dust particles: they likely have a range of (small) sizes, at least most of which must be in the nanometer – micron scale; they likely are often somewhat elongated; they likely are composed of some mix of dust, ices, and metals. The prime suspects are:

slightly elongated dirty ice grains;
more complex silicate grains with icy mantles, ~100 nm in diameter
grains of graphite, ~40 nm diameter
grains of metal (including Fe) oxides
tiny silicate grains, ~10-20 nm diameter;
large molecules such as PAHs

At this point, with the complex molecules, we have to acknowledge that there's not a neat distinction between a big molecule of gas and the tiniest grain of dust!

Dust grains probably form in more than one environment because some are distinctly more volatile (ices, for example) and some are distinctly more refractory (metals and silicates can solidify at much higher temperatures than ices). The more refractory grains seem to be made in the outer layers of cool giant stars, where the temperatures are only on the order of 2 - 3,000 K and we know there to be substantial outflows of particles from the underlying stars. The icy components, which aren't going to solidify at temperatures above a few hundred K, probably condense in the interiors of molecular clouds, which protect the fragile ices from heat and UV.

Given the dust grains and the polarization, we can work backward a bit to determine what the orientation of the galactic magnetic field must be, at least relatively near us. In June, 2014, the European Space Agency released an all-sky map of the orientation of the galactic magnetic field, based on observations by the Planck satellite. Darker regions indicate regions of stronger polarization; it should make sense that those are mostly along the plane of the Galaxy, since that's where most of the dust lies.

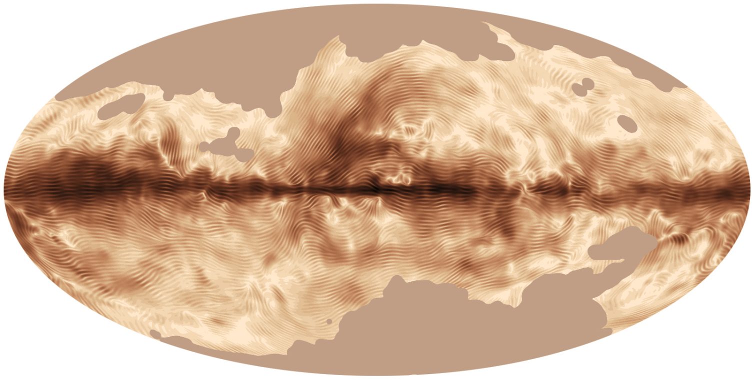


Figure 17.28: Milky Way magnetic field. Credit: ESA and the Planck Collaboration
http://www.esa.int/spaceinimages/Images/2014/05/Milky_Way_s_magnetic_fingerprint

The component of the Galaxy that we don't understand quite so well is the dark matter. We are confident that it exists and, based on the motions of visible components of the Galaxy, we find that it is spherically symmetrically distributed around the Galaxy. In other words, it is not in a flattened distribution, like the disk, but roughly spherical, like the halo. A quantity that is often used to characterize the amount of dark matter is the mass-to-light ratio. If we were using unit of solar masses and solar luminosities, then $(M/L)_\odot = 1$. Most stars are less massive than the Sun. They are also less luminous, and the luminosity drops faster than the mass. (The smallest M-type stars are ~1/10 the mass of the Sun but they are only 1/10,000 the luminosity of the Sun.) On average, for the stars within the LSR, $(M/L)_{\text{ave over all stars}}$ is ~ 4 $(M/L)_{\odot}$. But our galaxy isn't just stars. There is quite a bit of normal matter in the interstellar gas and dust, in planets, in brown dwarfs (intermediate-sized objects with masses between the largest planets and the smallest stars, objects that form by collapse the way stars do but have masses that are too low for sustained hydrogen fusion). We will therefore not be surprised, at least initially, to find that the (M/L) ratio for the galaxy is larger than 4 $(M/L)_{\odot}$. But what we find is that it is a lot larger. In the Milky Way it's ~25 $(M/L)_{\odot}$, although that doesn't get much beyond the distribution of stars. If we include the entire halo, it's probably higher.

What is dark matter? We aren't sure, although there are several possibilities that are being investigated. One possible culprit could be low-luminosity objects made of normal (baryonic) matter such as rogue planets or remnants of normal matter such as black holes. Collectively these are known as MAssive Compact Halo Objects (MACHOs). Some of these objects would occasionally pass in front of more distant stars, e.g., stars in the Magellanic Clouds. If the foreground object and the background star are well enough lined up during such a transit then we could observe a microlensing event. The foreground object warps the fabric of spacetime enough to act as a lens, the light from the background star follows the curvature of spacetime, and we receive more light than usual from the background star over the period of days that the alignment lasts. Such events have been observed, but not frequently enough for MACHOs to account for the necessary amount of dark matter. Another possibility are primordial black holes, i.e., black holes formed from the collapse of small regions of overly dense fluctuations in the density of the early universe rather than end points in the lives of massive stars. If they exist, primordial black holes could be anywhere from asteroid-sized up to one or two solar masses, i.e., any black hole too small to be the end point in the life of a massive star.

At the other end of the size scale, various types of hypothetical particles have been suggested, particles that would interact by the force of gravity but either not or not much by the other forces. A leading contender are particles dubbed WIMPs, for Weakly Interacting Massive Particles, meaning particles with mass that interact by the weak nuclear force. A possible extension to the standard model of particle physics, called supersymmetry, proposes that the known elementary particles would have partner particles differing by half-integer spin. In other words, all the elementary bosons would have supersymmetric fermion partners, and all the elementary fermions would be paired with bosons. Some of these supersymmetric partners could qualify as WIMPs. Various experiments have been designed to look for WIMPs (and for supersymmetry) but so far without any detections.

Another possibility, also hypothetical, are particles called axions. (Named for a dishwashing liquid, and/or characters from ancient Greek mythology.) Like the Higgs, the axion would be a neutral spin-zero boson, although one with a very low mass. Axions were originally proposed as part of a solution to a particle physics problem: violation of charge conjugation - parity (CP) symmetry. Charge conjugation symmetry says that the basic physical processes should not care if a particle's electric charge flips (e.g., the particle might go the other direction under the influence of an electric field, but the magnitude of its acceleration wouldn't change). Parity symmetry says that physical processes shouldn't care if spatial coordinates are flipped (e.g., gravity doesn't care whether a particle is moving to the left or to the right). Taken together, CP symmetry says that matter and anti-matter should behave similarly. But they don't always. The Peccei-Quinn mechanism is a proposed solution to this problem, which, importantly for dark matter, involves the existence of the hypothetical axions. Once they'd been proposed as a solution to the particle physics problem, people noticed that axions might also be the dark matter particles we are looking for. Like WIMPs, though, axions have not been detected.

We will have more to say about constraining the nature of dark matter when we talk about the large-scale structure of the universe and the formation and evolution of galaxies. Briefly, we find that the first galaxies form very early given that the early universe was expanding. We think that dark matter helped the normal matter to clump enough for the first stars and galaxies to form. More on that in the next chapters.

More on synchrotron emission

As a moving electron spirals around a magnetic field line it is being continually accelerated; it radiates at a range of frequencies with a peak frequency, f_0, that decreases with time as the electron loses energy. A region that has one high-energy electron likely has a whole ensemble of electrons and the emission we see is a combination of all of their emissions. The total flux will be dominated by the fluxes of the electrons at their peak frequencies. Here is a sketch of the emission from one electron and from an ensemble of electrons:

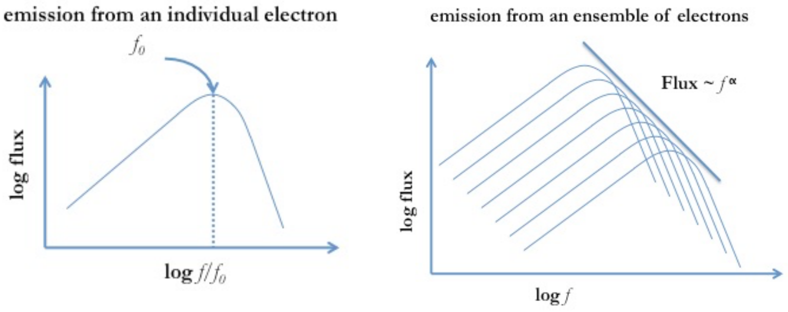


Figure 17.29: synchrotron emission

The flux of the whole ensemble is proportional to f^{α}. This falls off more slowly with wavelength than a blackbody spectrum, meaning that we can distinguish synchrotron emission from the emission of stars. The following sketch illustrates this shape difference:

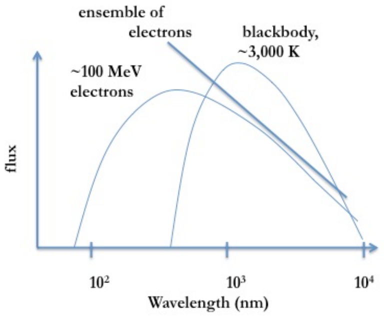


Figure 17.30: Synchrotron emission vs. blackbody emission

The spectrum of the flux from free-free emission from electrons interacting with the electric fields as the electrons pass by has a different shape as well, one that is nearly flat at radio wavelengths and then drops steeply at higher frequencies (where the free-free flux is likely to be swamped by other sources of emission anyway).

Sample problems.

1. Sketch the Milky Way, both side and face-on views, labelling where the Sun would be and any relevant distances or specific regions.

2. Sketch the rotation curve for the Milky Way and explain why the shape of the curve suggests the presence of dark matter.

3. Use Kepler's third law to estimate the orbit period of the solar system around the Milky Way. Assume that we are 8.5 kpc from the galactic center, that the mass of the galaxy interior to our orbit is ~ 10^{11} solar masses, and that our orbital eccentricity is very low. Express your answer in years.

4. At what frequency will we observe the neutral hydrogen spectral line, rest frequency = 1420.406 MHz, when we observe a cloud of gas moving away from us at 200 km/sec?

5. Consider a star observed to have an apparent V magnitude = 12.5 and an apparent B magnitude = 12.9. This star has a spectral type = A0, so we know that its intrinsic $(B - V) \approx -0.02$ and its $M_V \approx 0.65$. Determine the distance to the star. Hint: account for extinction.

6. Consider a cloud of neutral hydrogen gas in our Galaxy, with a radius of 10 pc and a density of 10^5 atoms / m^3. Assume we are looking along the line of sight at galactic latitude $b = 0°$, longitude $l = 15°$. (That's on the eastern edge of Sagittarius.) The rest frequency for 21-cm radiation is 1420.406 MHz. The lifetime for this transition is roughly 11 million years.

a) Estimate the number of 21-cm photons this cloud emits every second.

b) If the observed frequency of the 21-cm emission is 1420.376 MHz, determine a possible distance for this cloud using the expression for relating the Oort A coefficient to distance and radial velocity:

$$v_r = A \cdot d \cdot \sin 2\ell, \quad \text{where } A = 15 \text{ km/s/kpc}.$$

c) Given the distance that you determine in part b), what is the energy flux of this radiation in W / m^2 that we receive from the cloud?

7. Suppose we have an H II region, with a number density of $3 \cdot 10^8$ atoms / m^3. Our hydrogen is surrounding two late O-type stars, which are quite hot and together generate $1.8 \cdot 10^{49}$ photons / sec that have wavelengths shorter than 91.2 nm. Recall that we can assume that there is a balance between ionizations (per second) and recombinations (per second) and (with a bit more uncertainty!) that none of those UV photons escape without hitting a hydrogen. That gave us the following equation:

$$N_{UV} = \frac{4\pi}{3} R^3_{Strömgren} n_{e^-} n_{H^+} \alpha(2).$$

A typical value for $\alpha(2)$ is $3 \cdot 10^{-19}$ m^3/s. The hydrogens might spend about 90% of their time ionized and 10% neutral. What is the radius of the Strömgren sphere in parsecs?

8. Reading carefully? Explain / define / sketch

a) H II region
b) ISM
c) accretion disk
d) open cluster vs. globular cluster
e) Sgr A*
f) Fermi bubbles
g) Local Standard of Rest
h) solar apex
i) reflection nebula
j) the 0.2 micron bump

Answers to selected problems are on the next page:

3. ~230 million years

4. ~ 1419.5 MHz

5. ~ 1,312 pc

6. 11 million years implies a transition rate of $2.9 \cdot 10^{-15}$ per second for any given atom.
    a) $\sim 3.6 \cdot 10^{43}$
    b) 0.85 kpc
    c) $\sim 4 \cdot 10^{-21}$ W/m^2

7. ~ 1.9 pc