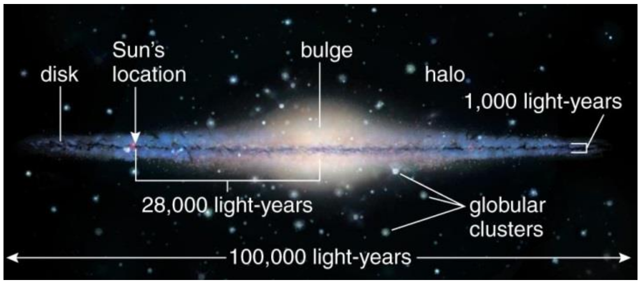
Chapter 14
The Milky Way Galaxy
A Spiral in Space

14.1 Our Parent Galaxy



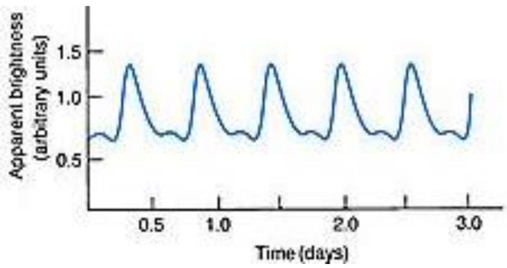
Edge-On View of Milky Way Galaxy

- A Galaxy is a giant collection of stellar and interstellar matter isolated in space by its own gravity
  - Contains stars, gas, dust, neutron stars, black holes, etc…
- The Milky Way Galaxy is the galaxy we live in (also known as "The Galaxy")
  - The Galactic Disk is an immense, circular, flattened region containing most of the Galaxy's luminous stars and interstellar matter
  - At the center of the disk, it fattens into what is known as the Galactic Bulge
  - The disk and bulge are surrounded by a faint ball of faint old stars called the Galactic Halo

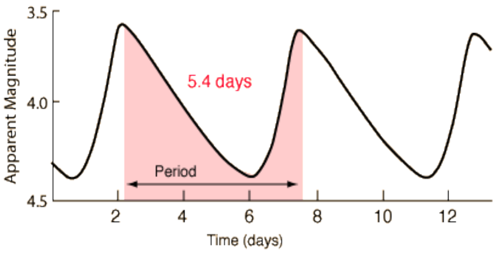
14.2 Measuring the Milky Way


William Hershel's Diagram of the Milky Way Galaxy

- Star Counts
  - In the 18th century, William Herschel tried to estimate the size and shape of our galaxy by counting how many stars he could see in different directions in the sky
    - He assumed that all stars were about equal brightness and concluded the galaxy was somewhat flattened, roughly disk-shaped and had the Sun at the center
- Observations of Visible Stars
  - Variable Stars are stars that have their luminosities change significantly over a relatively short period of time
    - Very few starts are variable stars, but they are very important
  - Pulsating Variable Stars vary their luminosity in a cyclical manner and in a very characteristic way
    - The curves allow us to use the brightness of the known variable star and compare it to a star of unknown distance in order to determine the distance to the unknown star
      - RR Lyrae Stars are stars with a characteristic light curve containing a large increase in apparent brightness over a short time period with a very small increase in luminosity between each large increase
      - Cepheid Variable Stars are stars with a characteristic light curve containing a "saw-tooth" increase in apparent brightness, but over longer periods of time

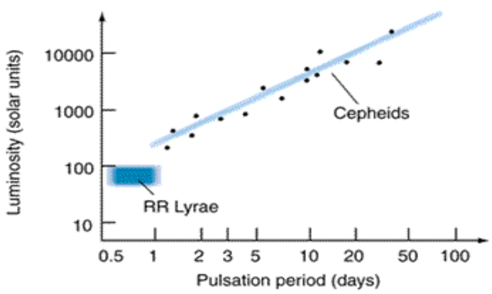


Light Curve for RR Lyrae Star



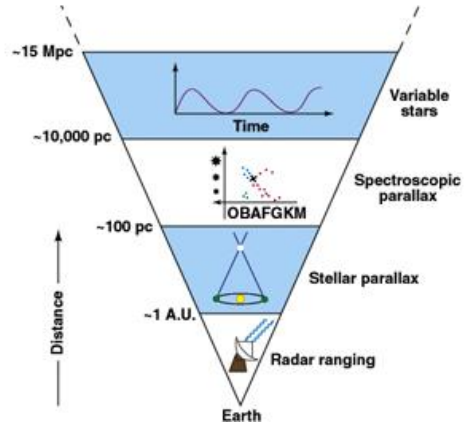
Light Curve for Cepheid Variable Star

- A New Yardstick
  - In 1908 Henrietta Leavitt (1868-1921) discovered that Cepheids that the length of the period of a variable star is related to the luminosity
  - The Period-Luminosity Relationship is the relationship between the period of a Cepheid Variable Star and its luminosity
    - Long periods mean high luminosity
    - Short periods mean low luminosity

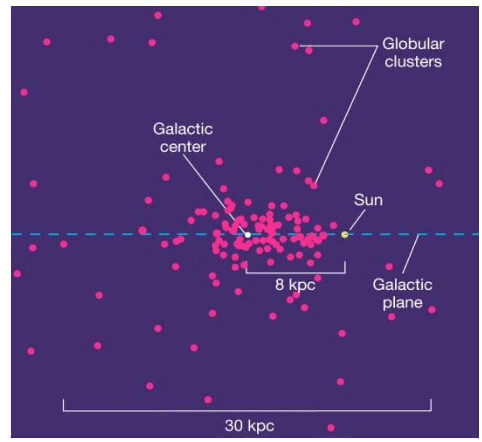


Period-Luminosity Relationship of Variable Stars

- Using the known luminosities from the variable stars, distances can be measured to globular clusters by comparing the apparent brightness of a variable star to its known luminosity from the period-luminosity relationship
  - Globular clusters all formed at the same time from the same cloud of dust and gas, so if a variable star is a certain distance away from earth, the rest of the stars in the cluster must be relatively close to that distance away as well.

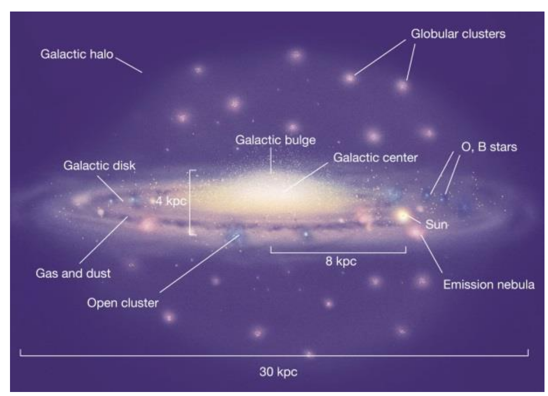


- The Size and Shape of Our Galaxy
  - Harrow Shapley (1885-1972) used RR Lyrae stars to make two discoveries about the Galactic globular cluster system
    - Most globular clusters reside at great distances from the Sun
      - This indicates that the Sun is not anywhere near the center of the galaxy, let alone the universe which was what the theories at the time believed
    - Measuring the direction and distance of each cluster, he determined the 3-dimensional distribution of globular clusters in space
      - The globular clusters map out a nearly spherical region about 30 kpc across
        - This is the galactic halo
      - The Galactic Center is the collection of globular clusters about 8 kpc from the Sun in the constellation Sagittarius

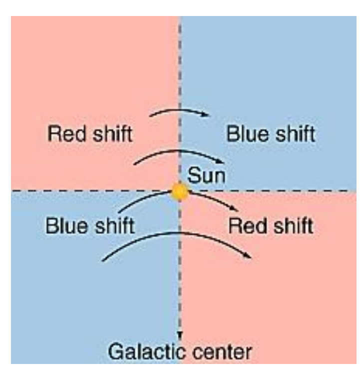


14.3 Galactic Structure

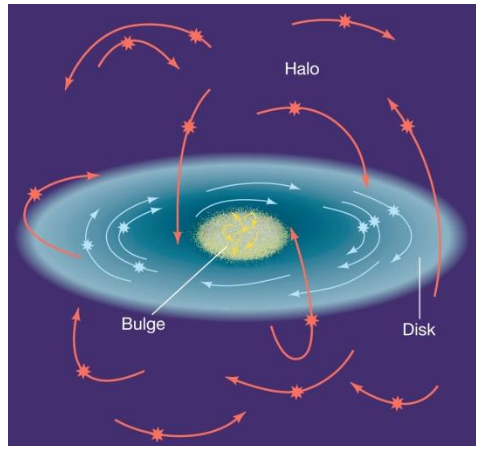
- Mapping the Galaxy
  - The entire disk is mapped using the 21-cm radiation that can penetrate the clouds of dust and gas
  - The galactic diameter is about 30 kpc across
  - The galactic plane is only about 300 pc across
    - This seems small compared to the 300,000 pc diameter, but would take 1000 years to cross traveling at the speed of light
  - The bulge is about 6 kpc across and 4 kpc thick



- Stellar Populations
  - There are patterns that distinguish between each of the three components of the Milky Way
    - The Halo consists of basically NO gas or dust… while the disk and bulge are full of it
    - Stars in the bulge and halo are much more red than those found in the disk
      - Other spiral galaxies show this trend as the disk tends to be blue-white in color and the bulge is generally yellow in color
    - All of the bright, blue stars visible in our night sky ar part of the Galactic disk as are the young open star clusters and star-forming regions, while the old globular clusters and the cooler redder stars are more evenly distributed throughout all three
    - Halo stars tend to be made of almost no heavy elements (Population I stars) an old halo stars (Population II stars)
- Orbital Motion
  - Looking at the galactic disk in different directions, we notice a clear pattern of motion which has stars redshifted or blueshifted based on where they are in relation to the Sun and the galactic center
    - Upper left and lower right are redshifted
    - Upper right and lower left are blueshifted
  - This indicates that the disk has differential rotation



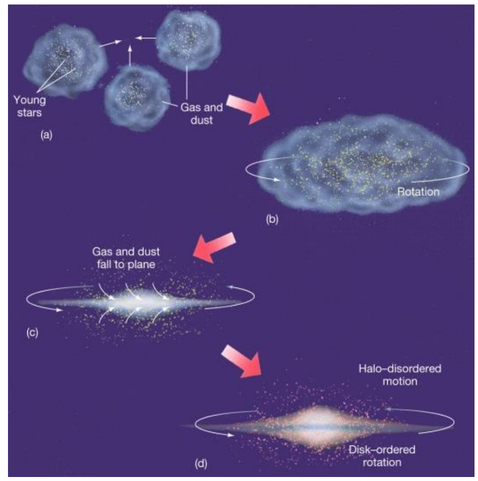
- At any distance from the galactic center, stars in all three parts orbit the center at similar rates
    - These rates are differential being faster near the center and slower when further away from the center
- Bulge and halo stars orbit in all directions not just in the circular path like the disk stars
    - The halo stars actually cross the disk as they orbit over time and will be above the disk for half of their orbit and below the disk the other half
    - The distances between stars is so great, the halo stars pass through the disk relatively unaffected



Galactic Rotation

14.4 Formation of the Milky Way

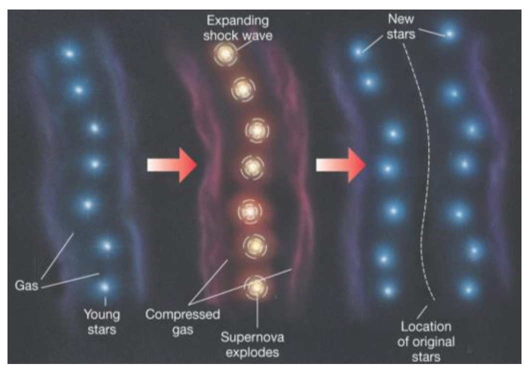
- Using the information about the stars in the three different regions of the galaxy a model for how the Milky Way formed was created
    - Several dwarf galaxies form in nearby regions of space
        - Gravity pulls them together into one mass
    - A large irregularly shaped galaxy starts to rotate
        - The individual dwarf galaxies no longer evident
    - As the gas compresses and spins faster, it creates a disk
        - Just like pizza dough or a pottery wheel
    - Current structure of Milky Way
        - Most stars in the halo have burned out and we can only see the red long-living ones that remain
        - Disk continues to produce new stars and has signs of complete stellar evolution
        - Halo stars formed and settled into orbits without being pulled into the disk, allowing them to maintain their distance from the bulge/disk



Formation of the Milky Way

14.5 Galactic Spiral Arms

- The clouds of gas and dust within the disk are moving at different speeds consistent with differential rotation discussed earlier in the chapter
- Spiral Arms are the pinwheel-like structures originating close to the bulge and extending outward throughout the disk
    - Our Sun lies within one of these spiral arms
    - Manny emission nebulae, O- and B-type stars, and recently formed open clusters exist within these arms
        - The spiral arms are the locations in which star formation occur
- Cannot explain how they maintain their structure over long periods of time
    - Spiral Density Waves are coiled waves of gas compression that move through the galactic disk, squeezing clouds of interstellar gas and triggering the process of star formation as they go
        - This density wave slows gas down and makes it more dense as it passes
        - This idea means that the spirals we see are merely patterns moving through the disk, not actually the disk moving
    - Self-Propagating Star Formation is the formation of stars from another group of stars and creating a type of "wave" of star formation and dust lanes due to the dispersion of interstellar matter
        - The death of a first group of stars disperses matter on the outsides of where they first formed, which then creates two lanes of stars, which will then create 3, and so on.



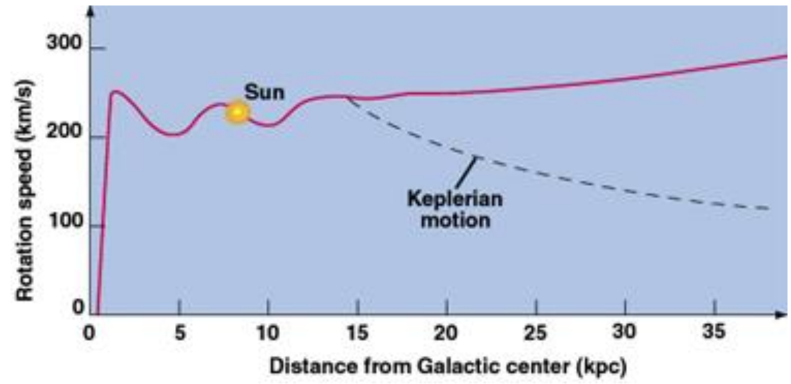
Self-Propagating Star Formation of Spiral Arm

14.6 The Mass of the Milky Way Galaxy

- Remember Kepler's third law as modified by Newton connects orbital period, size and mass of any two objects that orbit each other:

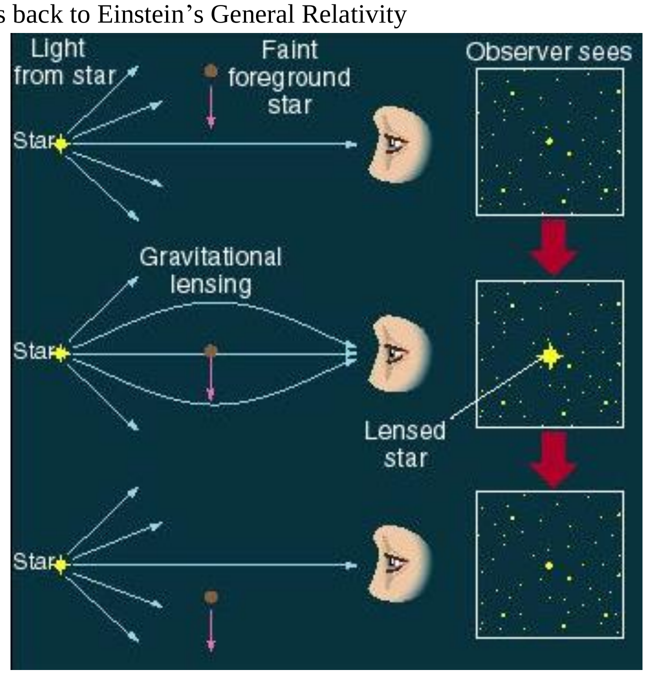
$$Total\ Mass\ (M_{\odot}) = \frac{orbit\ size^3 (AU^3)}{orbit\ period^2 (years^2)}$$

  - Using this formula, the calculated mass of the Milky Way is $6\text{x}10^{11}$ $M_{\odot}$
- Dark Matter
  - Galactic Rotation Curve is the plot of rotation speed versus distance from the center for a galaxy
    - This galactic curve for the Milky Way does not follow the expected path predicted
    - The rotation speed is much too high past the 15 kpc distance!!!
      - There must be mass outside of 15 kpc making the rotation to not follow the rotation from the matter within 15 kpc from the center
    - The mass of all the visible objects of the galaxy (within 15 kpc) is $2\text{x}10^{11}$ $M_{\odot}$



Galactic Rotation Curve of Milky Way Galaxy

      - This means that the visible mass of the galaxy is only 1/3 of the total mass!!!
      - The concept of dark matter is the explanation for this discrepancy
  - There must be something beyond the 15 kpc distance from the center of the galaxy with mass producing the motion with its gravity
    - The Dark Halo is an invisible sphere surrounding the visible region of the galaxy which is much larger and contains much more mass than the visible region
    - Dark Matter is matter that cannot be seen but has enough gravity that we can measure its effects, but we still do not fully understand
- The Search fort Stellar Dark Matter
  - By definition, dark matter makes it almost impossible to detect because it is "dark"
  - Current theory of how to detect dark matter goes back to Einstein's General Relativity
    - Gravitational Lensing is the process of mass bending light from very distant stars about a mass as predicted by Einstein's theory of general relativity
      - Even not being able to see the mass located in the dark halo, it should have the ability due to its mass to warp spacetime and have the effect of gravitational lensing
      - The apparent brightening of a star due to an unseeable mass would indicate the warping of spacetime and would lead to the "discovery" of dark matter



14.7 The Galactic Center

- Galactic Activity
  - The interior of the galaxy has emission of all kinds of EM radiation including X-ray, Gamma-Ray, Supernova, and other very active processes
  - There is also very rapid movement of stars and gas around the center of the galaxy
- The Central Black Hole
  - In the heart of Sagittarius A, lies an object called Sgr A*, which is known as the Galactic Nucleus
    - It appears to be very small and not "energetic" (do not see radiation)
    - Radio observations made in the last few decades as well as X-ray and Gamma-Ray imaging show that it has an energy output of about 10^{33} W, which is more than 1 million times the output of the Sun
    - Imaging indicates that it is much smaller than 10 AU in size
    - Using a combination of imaging techniques, one of the brightest stars known as "S2" has been able to be tracked in its orbit around Sgr A*
      - The orbit of this object creates an ellipse which can then be used to calculate the mass of the object Sgr A* by using the same Kepler's law that we use for our own solar system
      - The mass of Sgr A* is equal to 4 million solar masses!!!

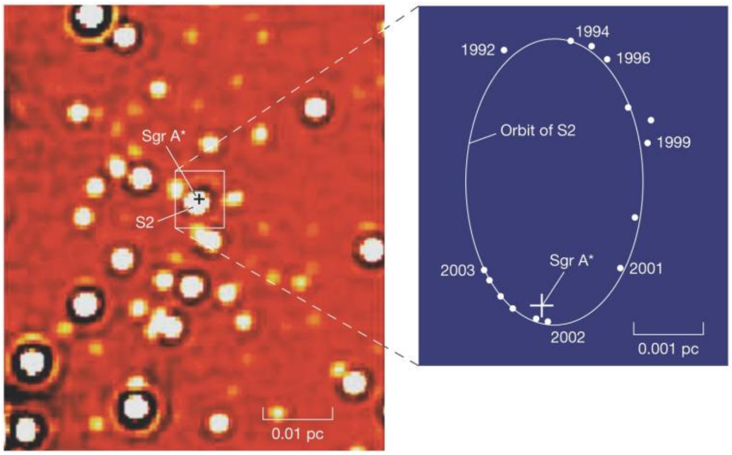


Image of Galactic Nucleus and the Orbit of S2 around Sgr A*

  - What type of object can have a mass 4 million times the mass of our Sun, be relatively tiny, invisible, yet have massive amounts of energy output as well as gravitational force…

    A SUPERMASSIVE BLACK HOLE!