CHAPTER 7

BEYOND THE SOLAR SYSTEM

The Stellar World

A. Constellations

A constellation is a visual grouping of stars that forms a pattern. There is no physical connection among the stars of a constellation and the stars are usually at vastly different distances. They just happen to be nearly along the same line of sight.

Today, there are 88 internationally recognized constellations covering the entire sky. Forty-eight of these constellations originate from the ancients of the Mediterranean Region, such as the Phoenicians. These original 48 constellations date back to about 2500 BC and are first described by the ancient Greek scholar Aratus, c. 270 BC. The 48 original constellations are related to the mythologies of the Mediterranean Peoples.

Forty new constellations, covering mostly the southern sky, were added beginning with the 16th century. These constellations are not associated with mythology but mostly depict inventions or devices.

Constellations are used by modern astronomers mainly for identifying stars. This is discussed below.

B. Stellar Nomenclature

The naming of stars was first done in pre-history. Some 50 bright stars have ancient names assigned by the Arabs, Phoenicians, and Greeks. Many of the names merely describe the position that a star marks in a constellation. For example, the star Betelgeuse has a name derived from Arabic meaning "the armpit of the giant." This was the only way of designating stars until the 17th century AD.

In 1603, Johann Bayer made star charts whereon he identified stars by lower case Greek letters. These were assigned to the stars of a given constellation in order of apparent brightness. For example, the brightest star in a constellation was assigned the letter alpha, and the next brightest was designated beta, and so on. For example, the star Betelgeuse, which is the brightest star in the constellation Orion, is referred to as Alpha Orionis. Orionis is the Latin genitive case of the constellation named Orion.

In the 18th century, the astronomer royal of Great Britain, John Flamsteed, made a catalog which assigns numbers to the stars in a constellation sequentially by right ascension. That is, the western most star of a constellation is designated 1 followed by the Latin genitive of the constellation, e.g. 1 Geminorum, which is abbreviated 1 Gem.

The BD (Bonner Durchmusterung) Catalog was an 1859-1862 undertaking of Argelander and his assistants at the Bonn Observatory in Germany. Charts were published in 1898. In the BD catalog, stars are designated by numbers according to right ascension in 1^{o} bands of declination around the sky. An example of a designation in the BD catalog would be: BD+22^{o}5428.

The Henry Draper (HD) catalog was an early 20th century effort at the Harvard College Observatory to classify the spectra of about 225,000 stars. In the catalog, stars were assigned a number according to right ascension. E.G., the star HD159176 has a right ascension of $17^{h}\ 28^{m}$, but you cannot discern the RA from the HD number.

The above designations are the primary ways that astronomers refer to the stars. There are a few other catalog designations that are of minor significance.

C. Solar Neighborhood

The Solar Neighborhood is the volume of space around the Sun extending to a distance of 100 parsecs. Some properties of the Solar Neighborhood are:

1. The solar neighborhood contains about 500 x 10^3 stars, most of which are very faint.
2. Stars in the immediate vicinity of the sun are spaced, on the average, about 4 LYs apart.
3. Of the approximate 4500 stars seen by the unaided eye over the entire celestial sphere, 2/3 of these are within 100pc. The other 1/3 are farther than 100 pc, that is, beyond the solar neighborhood. The latter stars must be extraordinarily bright, since the farther a star is, the fainter it's apparent brightness.
4. A large fraction of the stars are believed to be binary stars. Estimates range from 50% to 80%, but the exact fraction is not known

Binary Star: A gravitationally bound system, consisting of two stars in orbit around a common center of gravity, or barycenter.

For any two gravitationally interacting bodies, their barycenter is always closer to the more massive object. If the two stars have the same mass, their barycenter is midway between them.

There are also trinary star systems (3 stars) and other multiple star systems in the galaxy. Single stars like the Sun are in the minority.

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Astronomers have now detected hundreds of planetary bodies, called exoplanets, moving in orbit around other stars. Most of these are more massive than any of the Sun's planets. These planetary-like bodies are detected because of their strong gravitationally interactions with their stars. However, technology has now been developed to detect small planets like the Earth. The satellite telescope called Kepler is now finding planets by the small diming they cause in a star's brightness as they transit the surface a star.

In 2011, Kepler found a giant planet like Saturn moving in orbit within a binary star system. It was not known previously that planets could form in a binary star system.

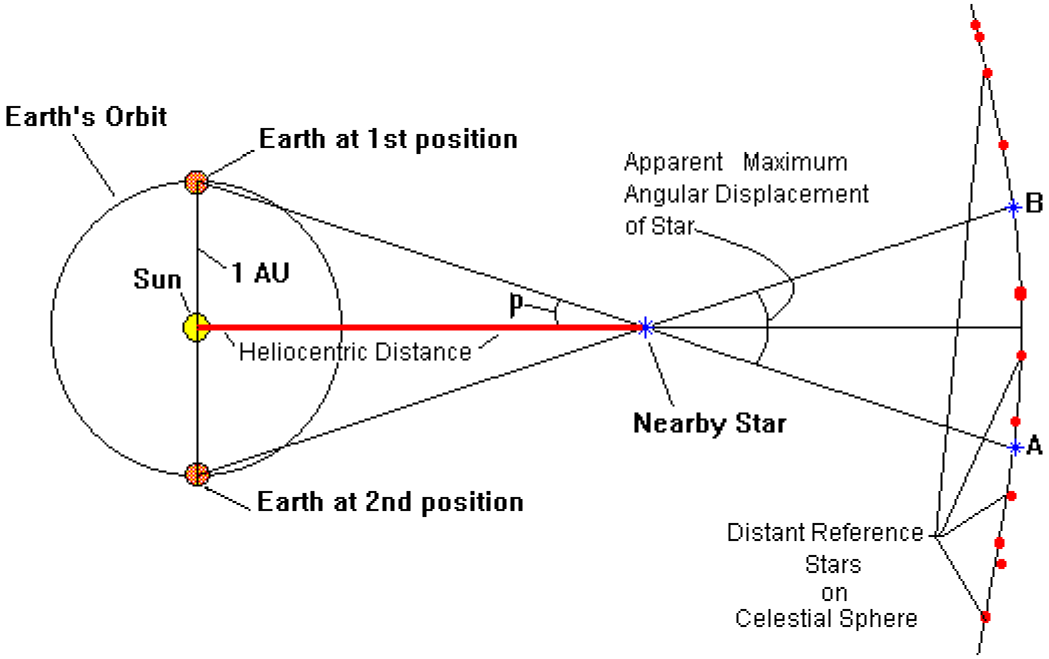
The nearest neighboring star of the Sun is a bright star called Alpha Centauri. This star is a circumpolar star of perpetual occultation for the latitudes of continental US. However it can be seen from regions of Mexico. This star is at a distance of 1.33 parsecs, or 4.35 LY, and is known to be a trinary star system. We shall next explain how the distance of a star may be determined.

D. Stellar Distances

The distance of a star may be calculated using trigonometry, if a very small angle called the parallax, p, of the star can be measured.

Parallaxes are very difficult to measure because the parallax of even the closest star is too small to be measured without a telescope. It took until 1837 A.D for the first parallax to be successfully measured. This was done independently by Bessel in Germany and Struve in Russia.

The geometry for determining the parallaxes of the stars, and, thereby, calculating their distances, is illustrated in the diagram below. In this diagram, the size of the Earth's orbit relative to the distance of the nearby star is greatly exaggerated for clarity.



In the above diagram, the parallactic triangle consists of the radius of the Earth's orbit, the heliocentric distance of the star, and the angle p. Since this is a right triangle, once p is measured, the heliocentric distance of the star can be calculated.

As the Earth moves in orbit around the Sun, a nearby star appears to change its position on the celestial sphere with respect to much more distant stars. Very distant stars have negligible parallactic displacements and, therefore, serve as reference points for measuring the changing position of the star whose parallax we want to determine.

When the Earth is at the 1st position in its orbit, the nearby star is seen on the celestial sphere at position A. Six months later, when the Earth has moved to the second position, the nearby star now is seen to be at position B on the celestial sphere. For any other position of the Earth in its orbit, the nearby star would be seen to have a position somewhere between these two extreme positions. Hence, in six months a star suffers its maximum angular displacement in the sky as a result of the Earth's revolution. **Half of this angle is the parallax, p.** (Read the introduction to Ex. 17.0 on stellar parallax in the course manual in addition to the assigned reading in the text).

In reality, the displacement of nearby stars as a result of the Earth's orbital motion is more complicated than that displayed in the diagram above. Stars actually describe an ellipse on the celestial sphere called the parallactic ellipse. The semi-major axis of the ellipse is the star's parallax.

A parsec is defined to be the heliocentric distance of a star that displays a parallax of exactly 1 arcsecond. If the parallax is expressed in arcseconds and the heliocentric distance in parsecs, the trigonometric relationship between these two parameters simplifies to:

$$HD\ (pc) = 1 / p\ ('').$$

For example, a star that has a measured parallax of 0.10 " would have a heliocentric distance of
HD (pc) =1 / 0.10" = 10 parsecs.

Even for the closest neighboring stars of the Sun, the heliocentric distances are at least 200 thousand times greater than the radius of the Earth's orbit. Hence, their parallaxes are very small fractions of a degree. Parallaxes can only be measured for stars within 130 parsecs. This is because parallax decreases with distance and becomes too small to be measured for stars that are farther than 130 pc. To determine stellar distances beyond this limit requires a different and more complicated technique that will be studied later.

E. The Nature of Light (Also read the appropriate chapter in the textbook)

Light is a phenomenon, which we may imagine consists of electromagnetic waves. The wavelength of an electromagnetic wave is the distance between adjacent crests of a wave. It is the wavelength of radiation that determines what color the human eye perceives. Red light consists of much longer wavelengths than violet. Orange, yellow, green and blue light have increasingly shorter wavelengths than red until we reach violet. Radiation with wavelengths shorter than violet wavelengths are called ultraviolet, then x-rays, and finally gamma rays. Wavelengths longer than those of red light are infrared (discovered by William Herschel), then microwaves, and finally radio waves.

All of these groups or bandpasses of EM waves comprise what is called **the total electromagnetic spectrum.**

The term **bandpass** refers to some definite or specific band or interval of contiguous wavelengths of the spectrum that is being measured.

Radiation consisting of a unique wavelength is referred to as monochromatic (one color) radiation, whereas a beam of radiation that consists of many different wavelengths is called polychromatic radiation.

All EM radiations travel with the same speed, which we call the speed of light, c. The measured value for c is 300,000 km/sec.

A clear distinction must be made between emission and reflection. We see things by reflection when they are cool. In this case, the source of the light (the illuminating source) is external to the object we see. The Sun and light bulbs are illuminating sources of white light. The walls of a room at room temperature, you, the Moon, and the planets are seen by reflected light.

Emitted light comes from an internal source of energy. Things that emit light are the Sun, stars, light bulbs, and fires, that is, things that are hot and have a lot of thermal energy. Actually, all objects possess heat or thermal energy, but if an object's temperature is <1000K, it is not hot enough to emit discernible visible light. However, it may emit weak infrared radiation.

F. Photometry (Measuring Stellar Brightness)

1. Brightness

Brightness may be defined as the amount of radiant energy received from a light source per second. Brightness depends on what portion of the spectrum is observed, the area of the detector or sensor, and the sensitivity of the detecting device that is used.

2. Apparent brightness

Apparent brightness is the brightness of an object as seen from the Earth. That is, how bright an object appears to be depends on the distance of the object from the observer. One cannot use apparent brightness to compare stars as to which are truly bright or faint, since stars are at different distances from the Earth.

Hipparchus, circa 150 BC, devised what is called the magnitude system for expressing stellar brightness. He divided all the stars visible to the unaided eye into 6 different classes of brightness. He identified a number of stars that he considered were the brightest that could be seen and called them 1st magnitude (designated as m=1). The faintest stars visible to unaided eye he classified to be 6th magnitude (m=6). The remaining stars were assigned magnitudes from 2 to 5.

Note: These are apparent magnitudes because they are an attempt to measure brightness as seen from Earth. Furthermore, they are apparent visual magnitudes, since the human eye only detects or is sensitive to a limited portion of all the radiations emitted by an object. This portion is called the visible spectrum or the visible bandpass.

After the invention of the telescope, fainter stars could be seen and these have been assigned magnitudes >6. With today's technology, stars as faint as m=28 can be detected with very sensitive electronic devices. Furthermore, the magnitude system has been defined more precisely so that fractions of a magnitude may be assigned, and more objectively, using instruments rather than the human eye.

In the modern magnitude system, a step or difference of 5 magnitudes ($\Delta m=5$) is defined to represent a brightness ratio of exactly 100. That is, we receive 100 times more light energy per second from a first magnitude star than we do from a 6th magnitude star, and we receive 100 times more light energy from a 4th magnitude star than we do from a 9th magnitude star.

A difference of 1 magnitude ($\Delta m=1$) corresponds to a brightness ratio equal to the fifth root of 100, which is approximately 2.512. The brightness ratio of two stars that differ in magnitude by any amount is then 2.512 raised to a power equal to their difference in magnitude, Δm, that is,
$B_1/B_2 = (2.512)^{\Delta m.}$

If we now assume that the faintest stars seen by the unaided eye are exactly 6th magnitude, then some of the stars that Hipparchus had called 1st magnitude were actually brighter than 6th by more than 100 times. This necessitated introducing negative magnitudes, so that the apparent magnitude of the brightest star, Sirius, is now m= -1.47.

The magnitude system may also be assigned to any object, including the Sun (m=-27), Moon (m=-12.5, when full), planets (Venus gets as bright as -4.4), comets, galaxies, etc. If the Sun were viewed from the outskirts of the Solar System it would appear to have an apparent magnitude of about -2.

3. Absolute, Intrinsic or true Brightness

This is the true brightness of an object, independent of its distance. The intrinsic brightness of star depends only on its: Surface brightness, B_* and Radius, R, or surface area.

4. Surface Brightness (B_*)

This is the total amount of radiant energy emitted from, passing through, or falling on a square centimeter per second.

The surface brightness or flux of a star, B_*, expresses how much energy is radiated into space from every square centimeter of a star's surface per second. The surface brightness of a star depends only on the surface temperature of the star, T, and is given by the Stefan-Boltzmann Law:

$$B_* = \sigma T^4$$

where σ (or lower case Greek sigma) is a constant of proportionality, which must be measured in the laboratory. That is, the flux of a star is directly proportional to the fourth power of the absolute temperature and no other physical property of the star.

5. Luminosity:

This is an expression of the total amount of radiant energy that a star emits into space every second. The symbol for luminosity is L. Luminosity is a way of expressing the intrinsic or true brightness of a star. Therefore, luminosity depends only on the surface temperature and radius of the star and it does not depend on the distance of the star. That is

$$L_* = B_* \text{ x (surface area)},$$

where the surface area depends on the radius of the star, such that Area = $4\pi R_*^2$. A commonly used unit of luminosity is the watt. For example, the Sun's Luminosity is

$L_\odot = 3.90 \text{ x } 10^{26}$ watts.

Luminosities for other stars are usually given in terms of the Sun's luminosity, $L_\odot$. That is, the total amount of energy that the Sun emits per second is called 1 solar unit of luminosity. A star that has a luminosity 100 times greater than the Sun's would be written as $L_* = 100L_\odot$

As the total light from a body travels outwards into space, it must pass through successive, concentric spheres of larger and larger surface area. Hence, the brightness of the light must decrease with distance from the source. Since the area of a sphere depends on the square of its radius, the brightness must be inversely proportional to the square of the distance (which is the radius of a sphere) from the light source. In other words, the brightness of light obeys and inverse square law, just like gravity does.

Hence, very distant stars are going to appear faint or have large magnitudes while nearby stars are going to appear to be very bright or have small magnitudes. So apparent magnitudes cannot indicate which stars are intrinsically bright and which are intrinsically faint. To determine this, we must eliminate the distance factor when assigning magnitudes. The inverse-square law makes it possible to calculate what magnitude would be seen at any distance, if we measure the magnitude for a known distance.

6. Absolute magnitude, M.

This is the magnitude of an object when it is seen from a distance of 10 parsecs. The absolute magnitude scale is a relative scale of absolute or intrinsic brightness. Astronomers use absolute magnitudes to express which stars are truly bright and which are truly faint, because distance is no longer a variable.

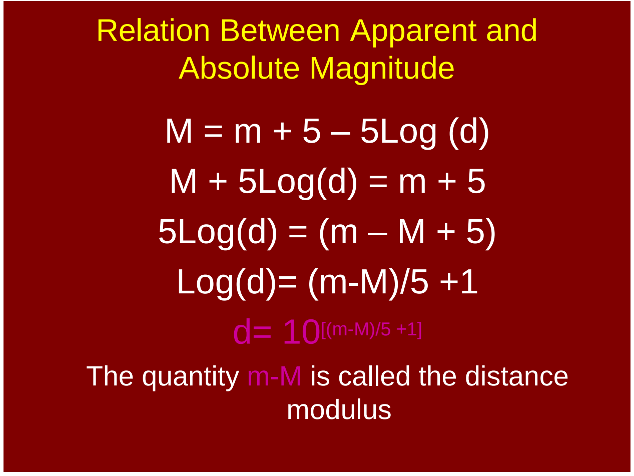
The absolute magnitude scale works the same way the apparent magnitude scale works. For example, a star that is 100 times more luminous than the Sun would have an absolute magnitude that is 5 magnitudes smaller (brighter) than the Sun's absolute magnitude (remember, a step of 5 mags. is defined to correspond to a brightness ratio of exactly 100.) Since the Sun's absolute magnitude is approximately +5 (4.72 to be exact), a star with a luminosity 100 times the Sun's would have a value of M* = 0.

Absolute magnitude, M, is a number that can only be computed, not measured. To compute M for a star we must first:

1. Measure the apparent magnitude of the star.
2. Determine the distance of the star by measuring its parallax.
3. Use the inverse-square law to compute the magnitude the star would have if seen from 10 parsecs.

Knowing the distance and apparent magnitude of a star, one can use the inverse square law to compute what the magnitude of a star would be at 10 pc. This would then be the absolute magnitude of the star. This can be done for more than 2,000 stars, most of which are within the solar neighborhood.

It has been found that the absolute magnitudes of stars range from -10 (the intrinsically brightest stars) down to +18. The Sun's absolute magnitude is about +4.72, making it an average star when compared with the other stars.



Relation Between Apparent and Absolute Magnitude

$$M = m + 5 - 5\mathrm{Log}(d)$$

$$M + 5\mathrm{Log}(d) = m + 5$$

$$5\mathrm{Log}(d) = (m - M + 5)$$

$$\mathrm{Log}(d) = (m-M)/5 + 1$$

$$d = 10^{[(m-M)/5 + 1]}$$

The quantity m-M is called the distance modulus

Example: The star Rigel has an apparent magnitude that has been measured to be 0.18 and it is known that the star also has an absolute magnitude that is -6.60. What is the distance of the star in parsecs?

First calculate the distance modulus of the star, m-M = 0.18-(-6.60) = 6.78. When the distance modulus is greater than 0.00, the star has a distance greater than 10 parsecs. If the distance modulus is negative, that is, less than 0.00, the star is closer than 10 parsecs. If the distance modulus is exactly 0.00, then m=M, and the star has a distance of 10 parsecs.

Now [(m-M)/5] +1.00 = [(6.78)/5] +1.00 = 1.37 + 1.00 = 2.37.

Hence the distance of Rigel is $10^{2.37}$ = 234 parsecs.

Homework practice problem: What is the distance of a star that has m = 2.55 and M = 5.02?

Go to Chapter 8