LECTURE 2 (1/8): DISTANCES AND LUMINOSITIES OF STARS

2.1 STELLAR MOTIONS

The apparent daily path of a star is a circle in the sky, reflecting the rotation of the earth on its axis. Some stars rise and set, so we don't see the whole circle from one point on the earth.

We can't see stars during the day because the sun is too bright. Over the year, the earth moves around the sun, and different parts of the sky are visible.

The relative positions of stars on the sky are nearly fixed; they barely change over a day or a year. But we expect to see *parallax* of nearby stars as the earth moves around the sun (illustration in Figure 9-4).

2.2 PARALLAX AND DISTANCE

1 arc-second (1") is the angle subtended by a dime at a distance of 2.3 miles.

If a star has an accurately measured parallax, we can determine its distance from geometry alone. The unit of distance used most often in astronomy is the *parsec*, the distance at which the annual parallax would be 1".

$$\begin{aligned} 1 \text{ pc} &= 206,265 \text{ AU} = 3.26 \text{ light years} \\ &= 3.1 \times 10^{13} \text{ km} = 1.9 \times 10^{13} \text{ miles.} \end{aligned}$$

The distance of a star in pc is simply

$$d = 1/p \text{ pc},$$

where p is the parallax in arc-seconds.

The nearest stars are more than 1 parsec away, so it's no surprise that the ancients could not measure stellar parallaxes.

With modern instruments and careful, repeated observations, astronomers can measure parallaxes as small as 0.01" from the ground, reaching distances of up to 100 pc.

The Hipparcos satellite has measured parallaxes of many stars with p as small as 0.002", reaching as far as 500 pc.

For objects that are further away, we must estimate distances indirectly.

IMPORTANT EQUATIONS

1: THE PARALLAX-DISTANCE EQUATION

In symbols:

$$d = 1/p.$$

d = distance in parsecs
p = parallax in arc-seconds

In words: The distance of a star in parsecs is one over its parallax in arc-seconds.

Example:

An astronomer at the U.S. Naval Observatory measures the parallax of a star to be 0.1 arc-seconds. What is the distance of the star in parsecs? How long did light from the star take to reach the earth?

The distance is $1/0.1 = 10$ parsecs. One parsec is 3.26 light-years, so light from the star took $3.26 \times 10 = 32.6$ years to get to earth.

2.3 LUMINOSITY AND APPARENT FLUX

The luminosity of a star is the amount of energy that it radiates into space every second.

Luminosity is an *intrinsic* quantity that does not depend on distance.

The *apparent brightness* (a.k.a. *apparent flux*) of a star depends on how far away it is.

A star that is twice as far away appears four times fainter. More generally, the luminosity, apparent flux, and distance are related by the equation $f = L/4\pi d^2$.

If we measure a star's parallax and its apparent brightness, we can determine its luminosity, which is an important intrinsic property.

IMPORTANT EQUATIONS

2: THE FLUX-LUMINOSITY-DISTANCE EQUATION

In symbols:

$$f = \frac{L}{4\pi d^2}.$$

L = intrinsic luminosity of the source [ergs/second]
d = distance of the source [centimeters]
f = apparent brightness (flux) of the source [$\mathrm{ergs/s/cm^2}$]

In words: The apparent brightness of a source is equal to the intrinsic luminosity divided by 4π times the square of the distance.

We can interpret this equation by thinking of the photons being "spread out" over a sphere whose area is $4\pi d^2$ (see Figure 5-7).

Examples:

(1) Star B has twice the intrinsic luminosity of star A, but it is twice as far away. What is its apparent brightness relative to that of star A?

The apparent brightness is proportional to the luminosity and to the inverse square of the distance, so star B appears $2/2^2 = 1/2$ as bright as star A.

More formally:

$$\frac{f_B}{f_A} = \frac{L_B/4\pi d_B^2}{L_A/4\pi d_A^2} = \frac{L_B}{L_A}\frac{4\pi d_A^2}{4\pi d_B^2} = \frac{1}{2}.$$

(2) Stars A and B have the same intrinsic luminosity, but star B appears 100 times fainter. How much further away is star B?

Since the stars have the same luminosity, apparent brightness is just proportional to the inverse square of the distance. Star B will be 100 times fainter if it is 10 times further away.

More formally:

$$\frac{d_B^2}{d_A^2} = \frac{L_B/4\pi f_B}{L_A/4\pi f_A}$$

so

$$\frac{d_B}{d_A} = \sqrt{\frac{f_A}{f_B}} = 10.$$

2.4 THE MAGNITUDE SYSTEM

Following the tradition of the ancient Greeks, astronomers often refer to the apparent brightness of a star by its *apparent magnitude*. A star that is five magnitudes brighter than another has a flux 100 times higher. Two important features of the magnitude scale:

(1) Brighter stars have smaller magnitudes.

(2) It is logarithmic, with 5 magnitudes corresponding to a factor of 100. A 1st magnitude star is 100 times brighter than a 6th magnitude star, a sixth magnitude star is 100 times brighter than an 11th magnitude star, and so on.

Astronomers often refer to the intrinsic brightness of a star by its *absolute magnitude*, which is the apparent magnitude that the star would have if it were at a distance of 10 pc.

Whenever practical, we will talk of apparent flux and luminosity instead of apparent magnitude and absolute magnitude.

2.5 TECHNICAL DEFINITION OF COLOR

We usually measure the brightness (flux) of a star through a filter, which only allows certain wavelengths of light to pass through. Also, detectors (photographic plates or electronic devices) only respond to light within some range of wavelengths.

A *color* of a star is defined as the *ratio* of its flux through filters that cover different ranges of wavelength, e.g. a blue filter and a yellow filter.

The color of a star does not depend on its distance, because the fluxes through each filter are equally affected by distance.

Astronomers often use a "color index" $B-V$, the difference in a star's apparent magnitude through a blue filter and a yellow ("visual") filter. A bluer star has a smaller $B-V$.

2.6 PROPER MOTION

The motion of a star produced by parallax repeats every year – the star appears to move back and forth. However, a star that is moving perpendicular to our line of sight will also change its position in a way that builds up from one year to the next. This is called *proper motion.*

2.7 SUMMARY

The easily detectable motions of "the sky" simply reflect the earth's daily rotation and its annual path around the sun.

With high-precision measurements of relative positions, we can determine the parallax of nearby stars. From the parallax and simple geometry, we learn the distance to the star, $d = 1/p$ pc.

Knowing the distance and apparent brightness of a star, we can determine its intrinsic luminosity using the equation $f = L/4\pi d^2$.

A color of a star is defined by the ratio of its apparent brightness (flux) through two different filters, which cover different ranges of wavelength.

Observed stars have an enormous range of apparent brightness. Some of this range arises because stars are at different distances. However, stars also have a wide range of intrinsic luminosities. Understanding what determines a star's luminosity, and why the range of luminosities is so large, will be a major theme of the next three weeks.