ASTR 161 LECTURE #22

CHAPTER THIRTEEN TAKING THE MEASURE OF STARS

Section 13.3 Measuring the Masses of Stars in Binary Systems

As we have learned, the easiest way to determine the mass of a planet is to observe the motion of a satellite in orbit around it. How do we measure the mass of a star? There are exoplanets orbiting some of them, but their orbits are hard to observe with any precision. However, stars often revolve around other stars. Our Sun is a single star, of course, but many stars of the Sun’s mass or greater exist in binary systems. We can use these motions to determine the masses of the stars.

Not every pair of stars which appear to be close together are actually binaries. Two stars in almost the same direction but physically far removed from each other are called *optical doubles*.

Figure 13.9 shows the definition of the center of mass for two objects. The larger mass is closer to the center of mass such that

m1 d1 = m2 d2 EQUATION 1

Figure 13.10 (Image #17) shows two stars orbiting about their common center of mass. The center of mass is always closer to the star of larger mass. Both stars have elliptical orbits (with the center of mass at one common focus for *both* ellipses), and the two stars are always on opposite sides of the center of mass.

The Doppler shift (Chapter Five and also your Rotation of Saturn lab) allows us to determine the speed of an object if some component of the object’s velocity is toward or away from the observer. That is not true for the stars observed in Figure 13.10, but Figure 13.11 (Image #18) shows another perspective in which the star’s velocities always have some component pointed toward or away from the observer (except momentarily at a quarter period, three-quarter period, *etc*). We are observing a spectral line from each of the stars, and the green panel (b) shows how these spectral lines shift back and forth to track the motion. If we use the Doppler shift to interpret these spectral changes as velocities, we can see how the velocity of each star changes with time. (c) The more massive star has the smaller velocity such that

m1 v1 = m2 v2 . EQUATION 2

Either Equation 1 or 2 gives us the ratio of the masses. We need a second relation to find the individual masses. That additional relationship is just Newton’s version of Kepler’s Third Law (Chapter Four). When we use that equation to describe motions in our solar system, the “mass” in the equation is actually the sum of the masses of the Sun and the planet combined (or the masses of Jupiter and its moon combined, if that is where we are applying it). In these cases, the mass of the central object (the Sun or Jupiter) is so much larger than the mass of the object orbiting it, that we just use the mass of the central object. However, in the case of a binary star system, the masses of the two stars are often comparable – so we must use the sum. In other words, if we apply Kepler’s Third Law to a binary star system it gives us the sum of the masses of the two stars. If we combine this with either Equation 1 or 2, we can solve for the individual masses.

In practice, this is not so easy. Most of the time we cannot see the individual stars moving around their center of mass (because they are too close together or too far away). Your text gives a brief description of these cases:

visual binaries: the two stars can be seen

eclipsing binaries: we observe the system in the plane of the motion (like Figure 13.11), and an analysis can determine the period as well as the sizes of the orbits.

spectroscopic binaries: we see what looks like a single source of light, but the spectrum shows two sets of lines Doppler shifting back and forth periodically (like Figure 13.11 (b)). Analysis can yield an estimate of orbits and masses.

Results for stellar mass measurements yield masses from 0.08 times the mass of the Sun (still 80 times the mass of Jupiter) up to about 200 times the mass of the Sun.

Try the CQ in Image #18 in the PowerPoint file for Chapter 13.

Section 13.4 The Hertzsprung-Russell Diagram Is the Key to Understanding Stars

Stars have many characteristics: temperature, luminosity, and radius, for example. Are these properties just random, or are they correlated in some way? If they *are* correlated, that would tell us something about the structure and evolution of stars. We saw earlier in this chapter that these three characteristics can be related within a single equation: L = σ T4 4π R2. This might mean that any relationship is rather obscure. After all, how could L and T be related simply if R can vary?

But it turns out that L and T correlate very well. This is what is displayed in the Hertzsprung-Russell Diagram. See Image #20. Here Luminosity is plotted vertically from low to high values, and Temperature is plotted horizontally from *hot to cold*, the reverse of the way most graphs are plotted. This figure shows that there is a definite pattern in the relationship between L and T.

See Figure 13.15 (Image #21). Note that both the Luminosity and Temperature scales are *logarithmic* rather than linear (the space on the temperature axis between 40,000 K and 30,000 K is much smaller than the space between 20,000 K and 10,000 K) to accommodate the large ranges of values to be plotted. Note also that we could plot Absolute Magnitude M instead of L and Spectral Type instead of Temperature – and we would get essentially the same plot.

So, what do these plots show us? Each point on the graph corresponds to a particular star with a certain luminosity and a certain temperature. Ninety percent of all stars fall along a relatively narrow band across the diagram called the Main Sequence. So, there *is* a correlation between Luminosity and Temperature. The mass varies only gradually along this band (see also Figure 13.17). Note that, from the equation we have been discussing, once you know the luminosity and temperature, you can calculate the mass.

Along the Main Sequence, the temperature and the spectral type vary. This divides the stars into various Spectral Classes (O5, B0, etc.) Our Sun is a G2 type Main Sequence star. Stars not on the Main Sequence also occur in specific regions of the diagram: White Dwarfs, Giants, Supergiants, etc. These stars differ greatly from Main Sequence stars in luminosity, so these groupings are called Luminosity Classes (see Image #22).

Just a quick review of how the diagram is organized. Consider a star in the upper right. It has low temperature, so its flux (energy per second per unit area) is low (Stefan-Boltzmann Law F = σT4). But, it has a very large luminosity, so it must have a huge surface area from which to emit radiation. This is a Giant Star.

Consider a star in the lower left of the diagram. It has a high temperature, so its flux is large. But it has low luminosity. So it must have relatively little area from which to emit this large flux. This is a White Dwarf, a star typically the size of Earth.

Spectroscopic Parallax

To plot stars on the HR diagram we need to know temperature and luminosity. The temperature can be found from the spectrum (Wien’s Displacement Law). But how do we find the luminosity? If we know the distance, we can find the luminosity from the measured brightness: b = L/4πd2. The first HR diagrams were constructed from those stars close enough to us to measure the distance by parallax and thus calculate the luminosity.

Now we make an important assumption: the stars too far from us for a direct parallax measurement are no different from the stars closer to us. The HR diagram applies to them, too. This assumption is the key to Spectroscopic Parallax, using the HR diagram to find distances to stars too far for parallax measurement.

We look at a star which has no measurable parallax angle. We can still measure its spectrum and determine its temperature and spectral class. What is its luminosity class? There are spectral differences among the various luminosity classes caused by different stellar atmospheric pressures densities, etc. Suppose our star is a Main Sequence star. If we know its temperature, we can use the HR diagram to estimate its Luminosity. (See Image #23). Since the Luminosity and the Absolute Magnitude are related, we can now find M and use the distance modulus (Section 13.1) to find the distance to the star.

The method is only approximate. The Main Sequence has some width, and this leads to an uncertainly in the corresponding location on the luminosity axis. Remember, these axes are *logarithmic*: a small uncertainty in the position on the axis translates into a big uncertainty in the value of luminosity.

The HR diagram is also an important tool for tracking the evolution of a star from birth to death. Stellar evolution is outside the scope of this course. Consider ASTR 181 if you are interested.