Lab 4. Binary Stars and Stellar Masses

1 Introduction

Our Sun appears to be a rarity in space. Approximately two-thirds of all solar-type field stars are members of binary systems, and recent studies suggest that virtually *all* stars begin life as members of multiple systems. Consequently, many of the stars you see at night are actually binaries, comprised of two stars gravitationally bound in orbit one another. These binary systems are important astrophysical laboratories because they allow us to deduce the properties of the constituent stars more accurately than we can with single stars. The physics that governs how stars orbit one another was developed by Newton and Kepler over three hundred years ago, and can be summarized by the equation

$$P^2 = \frac{4\pi^2}{G(M_p + M_s)} a^3, \tag{1}$$

where M_s and M_p are the masses of the stars, a is the semi-major axes of the two orbits, $a = a_s + a_p$, and G is the universal gravitational constant. In mks units, $G = 6.67 \times 10^{-11}$, but these units are not the units of choice. If masses are measured in solar masses, distances in astronomical units, and periods in years, then the application of Newton's law to the Earth-Sun system gives $4\pi^2/G = 1$.

2 Types of binaries

Binary stars fall into several categories, depending on their observed properties. Several of these are listed below.

Optical doubles: These are not really binary systems; they are just unrelated stars that happen to appear along the same line of sight. Because they are not part of a physical association, they can be at very different distances.

Visual binaries: In rare cases, the two stars of a relatively nearby binary system may be far enough apart that we can actually see the separate stars orbiting one another. (The periods of these systems may be several hundred years, but evidence of their motion may still be apparent.) Such a system is called a visual binary, since we can visually resolve the two stars with a telescope.

Composite spectrum binaries: More often, however, a binary star will be too far away, or be too compact to be resolved, *i.e.,* the binary will appear as a point source regardless of our image magnification. In this case the binary cannot be detected visually, but the spectrum may still indicate the presence of two separate stars. For instance, the signature of a cool K star is strong absorption at about 4000 Å due to calcium, but the primary absorption features in hot B stars are from helium. If an object exhibits both these lines, then the natural explanation is that it is actually two stars – a composite spectrum binary.

Astrometric binary: Sometimes the binary nature of a star can be detected via astrometry, *i.e.,* by measuring the exact position of the star on the sky. Because all stars are moving through space in an orbit about the center of the Galaxy, their astrometric coordinates will slowly change with time. This *proper motion* is exceedingly small — during a year, a typical nearby star moves only a fraction of an arcsecond. Nevertheless, this motion can be detected, especially if one compares pairs of photographic plates taken decades apart. Most of the time, this motion is in a straight line, but occasionally, a star's proper motion will have a periodic wobble. The cause of this wobble is the reflex motion of the star about an unseen companion. The white dwarf Sirius B was first detected by a wobble in the proper motion of Sirius.

Spectroscopic binaries: Many binaries cannot be detected visually or astrometrically, but can be detected spectroscopically via periodic changes in Doppler shift, again due to reflex motion. In these systems, the wavelengths of the spectral lines oscillate periodically about an average wavelength as the stars orbit one another. With modern detectors and high-resolution spectrographs, even binaries with small velocity amplitudes can be studied with precision. If one component in a binary is so dim that its spectral features are not detected, we have what is called a single-line spectroscopic binary. On the other hand, if the brightness of both components are comparable and we see both sets of spectral features, the system is called a double-line spectroscopic binary. Figure 1 shows the spectrum of such a binary. You can clearly see the spectral lines shifting back and forth as the stars orbit. By measuring the displacement of the lines, it is possible to determine the relative velocity of each star, and therefore their relative masses.

Eclipsing binaries (photometric binaries): If the orbital plane of the binary system lies so near our line of sight that one star occasionally gets in front of the other, then the system is called an eclipsing binary. Eclipsing binaries are especially valuable objects for several reasons. First, they allow a more accurate determination of the orbital elements[1] than other binaries do. The reason for this is that, in general, the inclination (the angle between the orbital plane and the plane of the sky, usually denoted as i) of a binary orbit cannot be determined, since it is manifested in the data only as a projection factor. (Are the velocities small because the separations are large, or because the system is almost face on?) As a result, astronomers are usually unable to explicitly determine both the stellar separation, a and orbital inclination, i; instead they are restricted to measuring a combination of the two variables, $a \ \sin i$. However, by definition, eclipsing systems are virtually edge-on with $i \approx 90^\circ$, so $\sin i \approx 1$. When combined with spectroscopic results, this enables an exact orbital solution to be determined, along with the stellar masses of each component.

A second reason that eclipsing binaries are valuable is that these systems display *light curves* similar to the one shown in Figure 2. This is a schematic of one of the most famous binaries, the bright star Algol in the constellation Perseus. As the stars eclipse one another, the magnitude of Algol changes. It should be obvious why: when one of the stars is obscured, less total light from the system reaches the observer. It should also be clear why the light diminishes more when the bright B star is eclipsed. (Think about temperature and the Stefan-Boltzmann law.) From a light curve such as this, we can determine, among other things, the relative brightnesses and the radii of the component stars.

3 The lab

Your primary task in this lab is to measure the wavelength of the Hα line vs time in a series of stellar spectra. This can be done simply with the IDL commands you are already familiar with. Once these measurements are done, you will be able to compute an orbital solution for the system. We note here that the components of the binary in question are assumed to follow *circular orbits*. This is not true for all binaries, but for the present system it is valid. This means that the orbital

---

[1] orbital period, eccentricity, semi-major axis, inclination of orbital plane (relative to plane of sky), longitude of periastron, time of periastron passage, and longitude of ascending node

eccentricity is zero and that the orbital velocities are constant at all times.

Table 1 lists the filenames for seven observations of a two-line spectroscopic binary star, along with the *Julian date* of observation. (Julian Days are the number of days which have elapsed since noon on Jan 1, 4713 B.C.) From this information, and the information contained in the spectra and the light curve, you will determine the properties of the two stars and the binary system.

The first quantity that you have to determine is the orbital period of the system. The classical way of determining this is by either trial and error or by relying on other knowledge such as the light curve if it is an eclipsing system. Here, you will get a first estimate of the period from the radial velocity variations of the components alone. Radial velocity can be determined from the Doppler shift of spectral features: if λ_0 is the rest wavelength of the spectral line, then the observed wavelength shift is simply given by

$$\frac{\Delta\lambda}{\lambda} = \frac{v}{c}. \tag{2}$$

3.1 Procedure

1. Enter IDL by typing **idl** and re-introduce IDL to your programs **reader** and **pixel** by typing

   .run pixel

   and

   .run reader

2. Choose one of the files listed in Table 1 (they can be downloaded from the class website in a .tar.gz compressed archive) and read in the data by typing

   reader, *filename,* **512, wave, flux**

   where, like last time, *filename* is the name of the file you chose, IN QUOTE MARKS, and **wave** and **flux** are your variable arrays. The arrays have 512 rows of data, hence the number 512 in the command.

3. See what you have by plotting the data with the usual

   plot, wave, flux

   command. Note that in addition to the strong Hα line, several other absorption features are observable.

4. Use **pixel** to measure the radial velocity of both stellar components in your spectrum. Do this by typing

   pixel, wave, flux, *x1, x2,* **'w'**

   As a reminder, *x1* and *x2* are the OPTIONAL beginning and ending x-values for your graph in PIXELS *unless you append* **'w'** *to the command, in which case it will interpret these numbers as* WAVELENGTHS. Carefully use the cursor to measure the observed wavelength of the Hα line and convert these measurements into radial velocities. Keep in mind that the lines from the two stars need not be the same strength, and they may be blended.

   Question 1: *Tabulate the values of the observed wavelength of the Hα line for both components and the corresponding radial velocity for each.*

5. Repeat the above steps 2 through 4 for the other 6 spectra of Table 1. Use your measurements and the Julian Dates given in the table to estimate the orbital period P of the binary.

6. **Question 2:** *Estimate the radial velocity of the system's center of mass, i.e., the system's "mean" velocity.* We usually call this the γ (gamma) velocity.

7. **Question 3:** *Estimate K_p, the orbital velocity of the primary component around the center of mass.* In binary star terminology, "primary" refers to the brighter or more massive star. To do this, recall that we are assuming circular orbits for both stars.

   Question 4: *Now estimate K_s, the orbital velocity of the secondary.*

8. **Question 5:** *Using your measurements, determine the mass ratio (primary mass/secondary mass) of the two components.*

9. **Question 6:** *Now calculate the orbital semi-major axes of the primary and secondary (in km and in A.U.). Call these numbers a_p and a_s.*

10. **Question 7:** *What are the masses of the two components in solar masses?*

    (Recall, from the definition of center of mass, $a_s M_s = a_p M_p$.) Your measurement demonstrates the importance of studying binary stars. Virtually everything we know about stellar masses comes from analyzing their motions.

11. **Question 8:** *If this were an eclipsing binary and Figure 3 was the observed light curve, explain how you would use it to determine the radius of each star and to calculate the radii, R_p and R_s.*

12. From the velocity curve, *i.e.*, the plot of velocity and time, suggest a way of improving the quality of the results that you have obtained above.

Note: In this lab, we have simplified the scenario by constraining the stellar orbits to be circular. In real situations, one must deal with elliptical orbits and determine the eccentricity from the velocity curve. Moreover, astronomers usually present their velocity measurements in terms of *phase* instead of time. Phase[2] is just the fraction of the orbital period completed at the time of observation and ranges from zero to one, with $\phi = 0$ defined to be periastron (*i.e.*, when the two stars are closest together. Of course, for circular orbits, the two stars are always the same distance apart, hence the $\phi = 0$ point is undefined, and one can choose any point in the orbit as zero phase.

Table 1: Dates of observation

Filename	Julian Date
binary1.dat	2441578.831
binary2.dat	2441579.581
binary3.dat	2441580.742
binary4.dat	2441581.943
binary5.dat	2441582.670
binary6.dat	2441582.982
binary7.dat	2441583.960

---

[2] Phase is usually denoted by the greek letter ϕ.

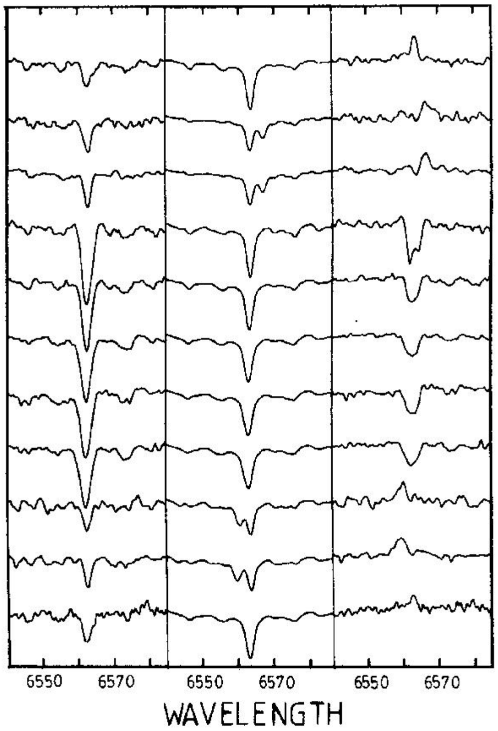

Figure 1: A composite of several binary star spectra. The vertical offset is arbitrary. Wavelength is plotted along the horizontal axis; the spectra are roughly centered on the Hα line. (Huenemoerder **AJ** 90, 499)

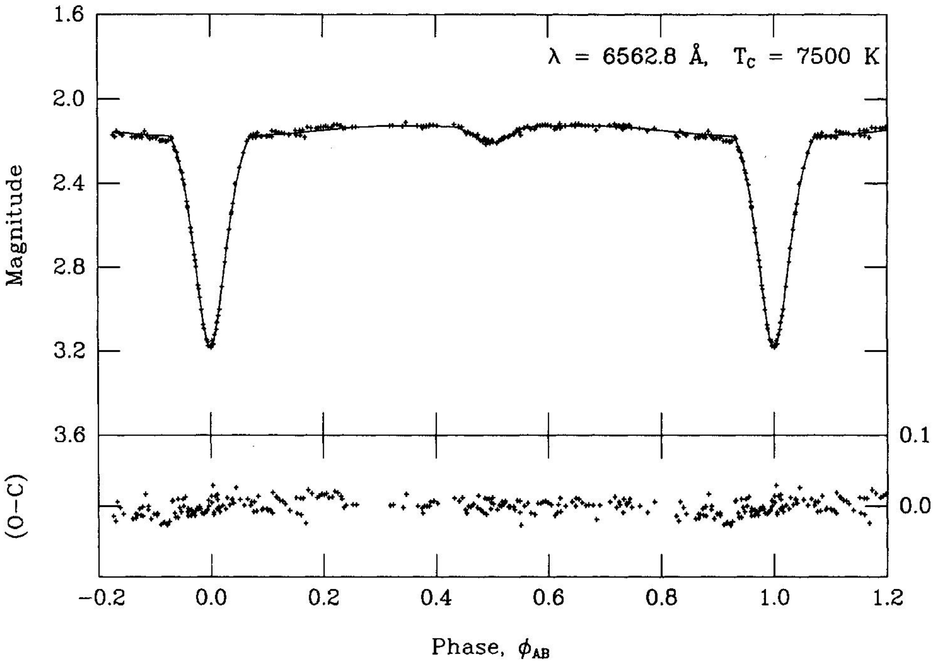

Figure 2: The light curve of Algol. (Richards et al. **AJ** 96, 326)

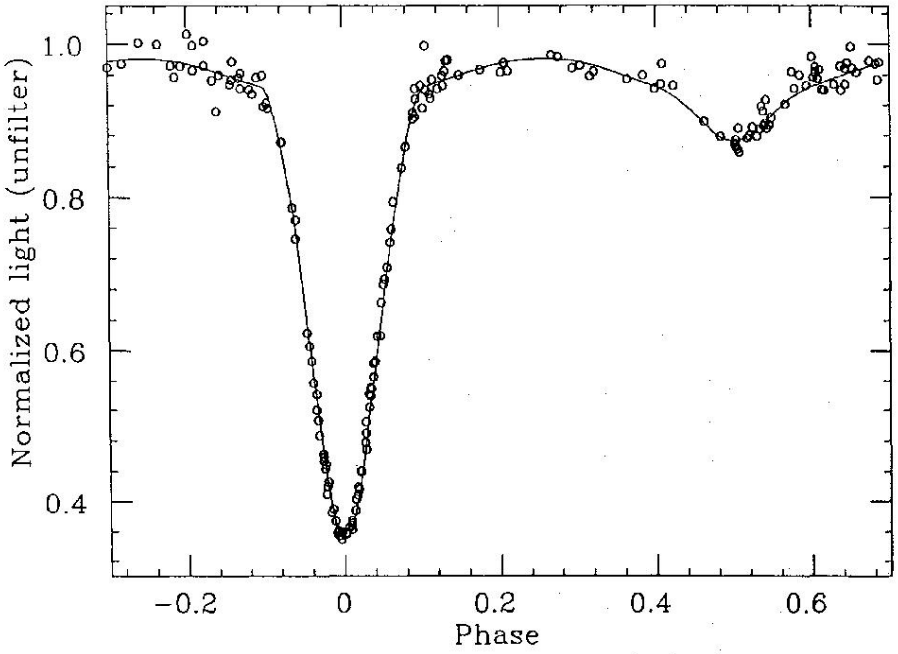

Figure 3: The adopted light curve for the binary under consideration. (Chambliss et al. **AJ** 106, 2058)