101: PART I - PRE-LAB READING

Binary stars

A *binary star system* comprises two stars which are gravitationally bound to each other and orbit around a common centre-of-mass (called the *barycentre*). This is in contrast to *double stars* which may not be bound to each other or even at the same distance, and are in many cases just chance alignments along the line of sight. Up to 85% of stars in the Galaxy may be members of true binary systems, with some in triple or even higher-multiple systems. As a single star, the Sun is therefore somewhat unusual. Hierarchical multiple systems are also possible, for instance a close-separation binary system which is orbited by a wide tertiary star, or two tight binaries orbiting each other in a quadruple system.

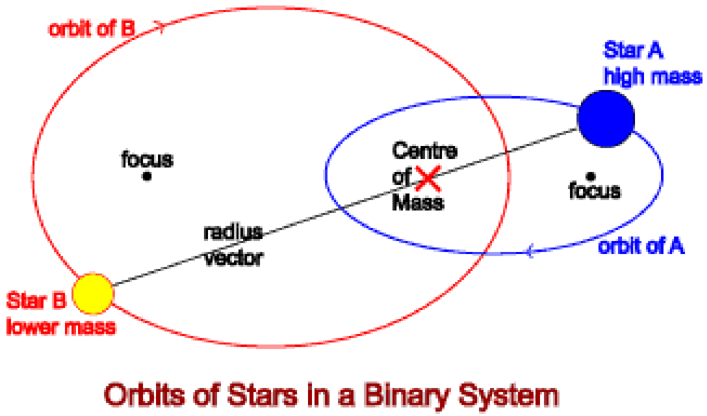

Figure 1: *Orbits of a binary system comprising two stars of unequal masses. Both stars have elliptical orbits around a shared focus at the centre-of-mass of the system, however the lower mass star (Star B) has a larger semi-major axis than the higher mass star (Star A). A line between the two stars always intercepts the centre-of-mass. Image taken from* https://www.atnf.csiro.au/outreach//education/senior/astrophysics/binary_intro.html

Binary stars are very important for stellar astrophysics because calculations of their orbits allow the masses of their components to be *directly* determined through application of Kepler's Laws. This in turn allows other stellar parameters, such as radius, density, luminosity and temperature to be *indirectly* estimated. In the case of *eclipsing binaries* (the focus of this lab), where one star passes in front of the other along our line of sight, it is also possible to directly measure the radii of the stars using simple geometry. This is one of only a few methods to directly measure stellar radii (the other important one being *optical interferometry*).

The orbital periods and separations of binary stars vary enormously. Some systems are so close that the surfaces of the stars are touching each other (*contact binaries*) and they can exchange material throughout their lives. Others may be loosely bound and separated by hundreds or thousands of astronomical units, with orbital periods of centuries or more.

Types of binary system

For practical reasons, binary systems are generally classified according to their method of detection. There are several key classes to be aware of:

Visual binaries

Systems which can be resolved by a telescope into individual stars are called *visual binaries.* Although most binaries could technically be resolved with a sufficiently large telescope, given the constraints of angular resolution ($\theta = 1.22\lambda/d$ for wavelength λ and telescope diameter d), visual binaries are typically nearby and have large (>10-100 au) orbital semi-major axes. This in turn means they have orbital periods of decades or centuries.

By observing the system over time, the sky positions of the components can be measured and the orbit determined (e.g. Figure 1). Such representations are only the "apparent" orbit however; finding the *true orbit* requires calculating the inclination and orientation of the orbit to the plane of the sky. The linear scale of the orbit is also unknown until the distance to the system can be measured, for instance by a trigonometric parallax. Once the true orbit has been determined and the semi-major axes and period are known, Kepler's Third Law ($a^3/P^2 = M_1 + M_2$, for a in au, P in yrs, M in solar masses) can be used to measure the masses.

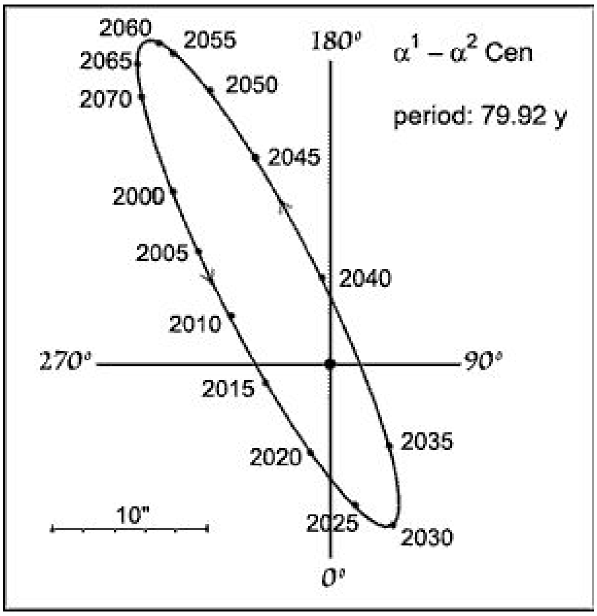

Figure 2: *Apparent relative orbit of the well-known "pointer" star and visual binary α Centaurus AB. In reality both stars orbit their common barycentre and would trace a complex sinusoidal pattern on the sky (see Fig. 4). However, by fixing the position of α Cen A and measuring the position and separation of α Cen B relative to it over time, an elliptical orbit of period 79.92 yr is found. This apparent orbit is the projection of the true orbit on the plane of the sky. Image taken from* https://www.atnf.csiro.au/outreach//education/senior/astrophysics/binary_types.html

Spectroscopic binaries

Most binary systems are either too distant or too close together to be resolved into individual stars by even the largest telescopes. We can however detect the presence of a companion by observing the periodic Doppler shift of absorption (and sometimes emission, see Fig. 9) lines in the spectrum of a binary system caused by the orbital motion of its components. Such systems are called *spectroscopic binaries* (not to be confused with *spectrum binaries,* where stationary spectral features from two clearly different stars are visible in the observed spectrum).

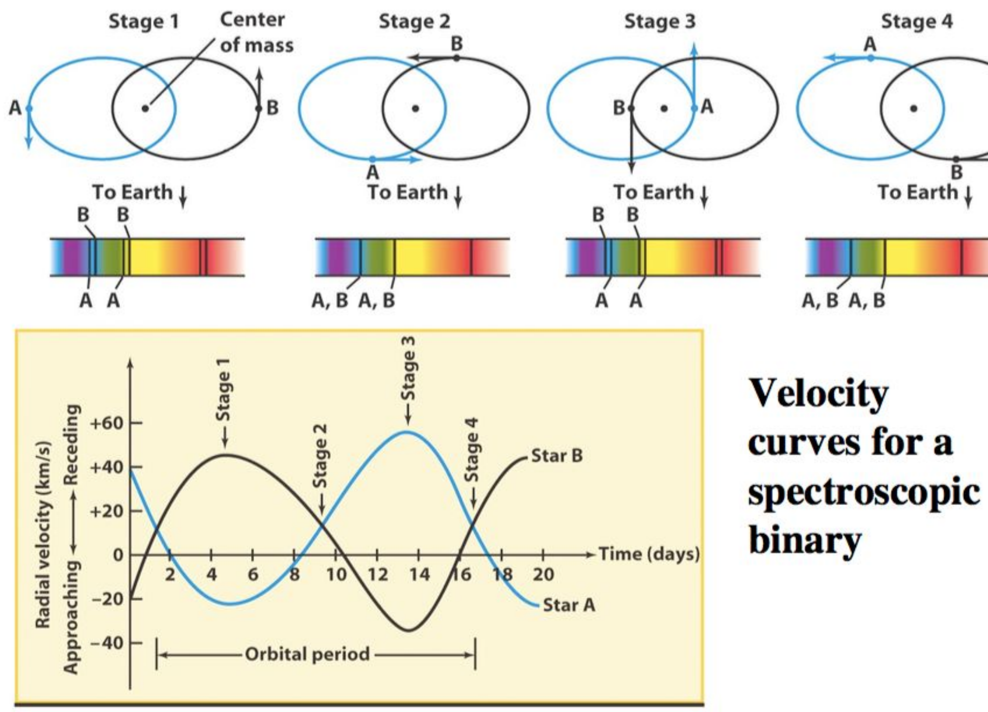

Figure 3: *Radial velocity curves for a double-lined spectroscopic binary. In this diagram Stars A and B orbit their common centre-of-mass in elliptical orbits which are edge-on to the line of sight. In Stage 1, the absorption lines of Star A are blue shifted while Star B's are red shifted. The reverse is true at Stage 3 when the stars are at periastron (closest approach). At Stages 2 and 4 both stars are moving tangentially to the line of sight so there is no shift of the lines. Over time the stars trace out radial velocity curves (bottom panel) which depend on the masses, semi-major axes, eccentricity and orientation of the orbits to the line of sight. For circular orbits the radial velocity curves are purely sinusoidal. Image taken from* https://www.astro.caltech.edu/~george/ay20/Ay20-Lec4x.pdf

As the stars move in their orbits, spectral lines from each component are Doppler shifted towards bluer wavelengths when the star moves towards us, then towards redder wavelengths as the star recedes (Figure 3). These wavelength shifts are usually converted to line of sight (or *radial*) velocities, which trace sinusoid-like curves with time. Unless the orbits are completely perpendicular to the line of sight (i.e. the orbital plane is the same as the sky plane, or $i=0°$), there will always be some component of the orbital velocity in the radial direction.

In situations where the two components have close-to-equal masses and therefore equal brightnesses, spectral features from both stars can be seen with opposing velocities (one star moving away and one towards). These systems are called *double-lined spectroscopic binaries,* and allow both masses to be determined by tracing the radial velocities over an orbit. However, if one component is much brighter than the other (for instance a faint 0.2 $M_{\odot}$ M dwarf orbiting a 1.0 $M_{\odot}$ G dwarf like the Sun), only lines from the brighter star are seen and the system is *single-lined.* In this case the mass of the unseen companion can only be estimated as a function of the orbital period, eccentricity and velocity amplitude of the more massive star.

As you will see in Part III, it is impossible to separately determine the semi-major axis a and the inclination i of the orbit using just the radial velocities. We are limited to deriving the quantity $a\sin i$ (in linear units, unlike for a visual binary where a is an angular distance). However, if a or $\sin i$ can be estimated by other means (e.g. in an eclipsing binary where $i \cong 90°$ by definition), then a complete orbital solution for the spectroscopic binary can be found.

Astrometric binaries

Much like the effect of the faint companion on the velocities of a single-lined spectroscopic binary, some stars exhibit a perturbation or “wobble” in their *angular* motion on the sky (called a *proper motion*) over time with no visible companion. If this motion is periodic then the perturbation must be due to the gravitational influence of an unseen companion. Such systems are called *astrometric binaries.* The faint companion may be a lower-mass star (e.g. an M dwarf or brown dwarf) or a massive object which emits little or no electromagnetic radiation, like a neutron star or black hole.

Like visual binaries (where both components emit light), astrometric binaries are typically nearby systems with relatively large separations and orbital periods of tens to hundreds of years. Nearby stars often have high proper motions even without a companion, so astrometric (and visual) binaries will appear to follow a sinusoidal-like path on the sky (e.g. Figure 4).

Compared to other detection methods, relatively few astrometric binaries are known due to the necessity of long-term observations and the uncertainty of ground-based position and proper motion measurements. This is changing with the arrival of new space-based astrometric missions like *Gaia*, which is currently measuring ultra-precise positions and proper motions (as well as brightnesses and some radial velocities) of more than 1.5 *billion* Milky Way stars.

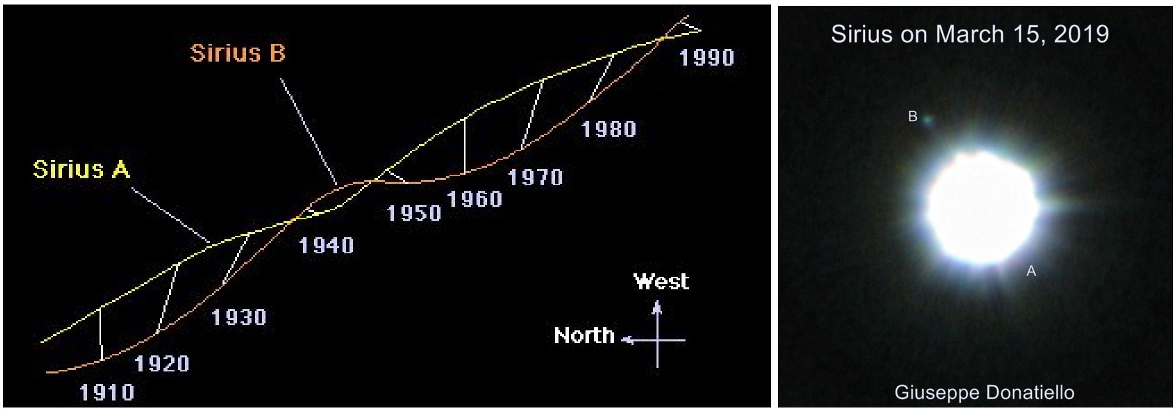

Figure 4: *Left panel: Proper motion of the bright star Sirius (α Canis Majoris) over ~80 years. The wobble in the yellow line (Sirius A) is due to the presence of its much fainter white dwarf companion (Sirius B). Sirius was first recognised as an astrometric binary in 1844 by the German astronomer Friedrich Bessel (who was also the first to measure a stellar parallax), but it was not until 1862 that the Earth-sized faint companion (right panel) was discovered. Orbital image taken from https://www.atnf.csiro.au/outreach//education/senior/astrophysics/binary_types.html. Sirius B image from Giuseppe Donatiello via Flickr (https://flic.kr/p/2e6H1WJ).*

Eclipsing binaries

Although many stars show *intrinsic* variations in brightness, due to star spots rotating in and out of view or a change in luminosity due to interior pulsations, *eclipsing binaries* (EBs) are systems in which the orbital plane is close enough to edge-on ($i \cong 90°$) that one star periodically eclipses the other, resulting in a temporary dip in brightness (Figure 5). For eclipses to occur the two stars must also be quite close together. This means most EBs are also spectroscopic binaries, and if the mass ratio is not extreme they will be double-lined systems.

As you will see later in the lab, if this is the case then the individual masses and radii of both stars can be determined with high precision from the brightness and velocity variations. Despite being relatively rare due to the geometry required for eclipses to occur, EBs are a cornerstone of stellar astrophysics and a key laboratory for testing the predictions of theoretical stellar structure and evolution models.

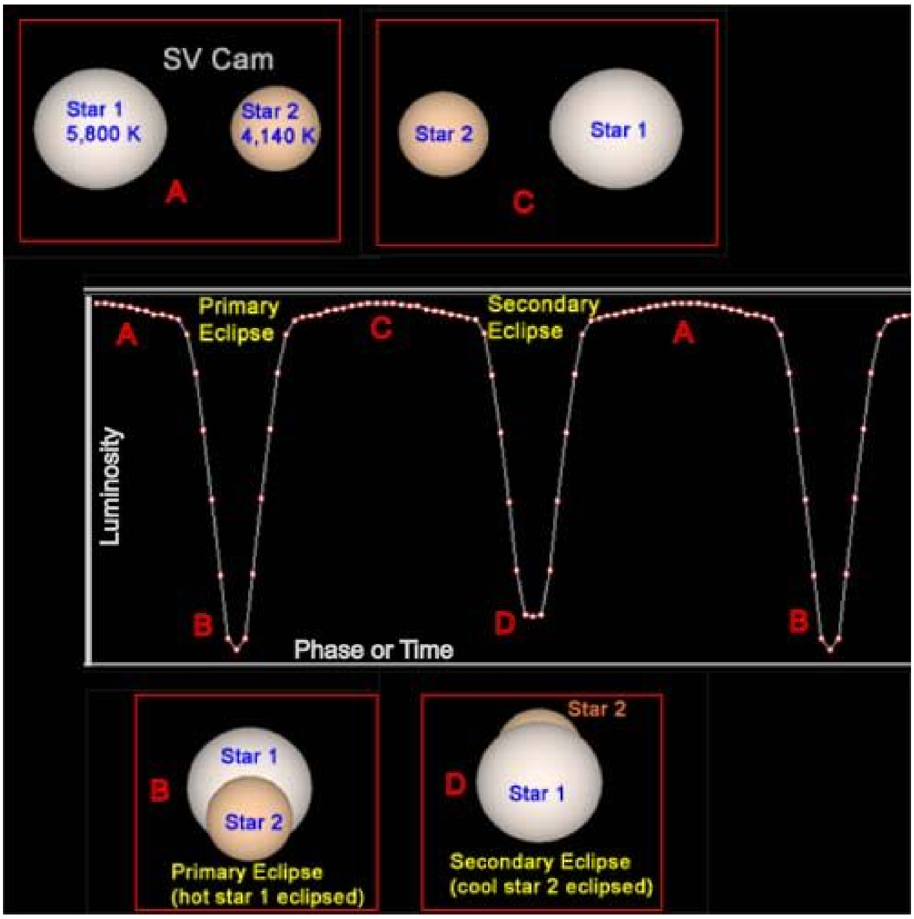

Figure 5: *Schematic diagram of the eclipsing binary SV Camelopardalis. During times A and C both stars are visible and the light curve is approximately flat. The slight variation between eclipses is caused by the ellipsoidal shape of the stars, in particular Star 1. As they orbit the amount of visible area slightly changes, hence the brightness. The ellipsoidal shapes are due to the stars mutually distorting each other at close separation. At time B the fainter, cooler star has eclipsed the hotter star, giving a deep primary eclipse. Half an orbit later the cooler star is occulted by the hotter star, giving the shallower secondary eclipse. From the V-shaped eclipses and the system geometry at times B and D, the inclination of the orbits is close to but less than 90°. Image taken from* *https://www.atnf.csiro.au/outreach//education/senior/astrophysics/binary_types.html*

A *light curve* must be obtained to classify the system as an eclipsing binary. This is simply a plot of the stellar flux or apparent magnitude versus time in a particular photometric filter. Light curves are often 'folded' onto a particular *phase* (the fraction of an orbit between 0 and 1) by dividing the observation times by the period of the binary. This allows multiple observations from different times to be overlaid onto the same set of axes.

For a *detached* EB where the stars are well separated and spherical to good approximation, the light curve is characterised by periods of near-constant brightness, with short, periodic dips in brightness when one star eclipses the other. If one of the eclipses is not as deep as the other, then the two stars must have unequal surface brightnesses and therefore different surface temperatures (because of the Stefan-Boltzmann law). The eclipse of the brighter star by the fainter star produces the deeper eclipse, called the *primary eclipse*. For main sequence stars this will always be caused by a smaller, less massive star eclipsing a larger, more massive one. Other configurations are possible (e.g. a small, bright white dwarf orbiting a main sequence star, or a bright giant star orbiting a main sequence star), making the interpretation of EB light curves somewhat nuanced. The shallower eclipse (if present) is called the *secondary eclipse*.

If the orbit is exactly edge-on and the stars have different radii, then we would expect the eclipses to be total and have "flat" bottoms. If neither eclipse reaches a constant minimum and is instead V-shaped, then either the stars have the same size or the inclination is not exactly 90°. The eclipses are briefest and sharpest for stars that are widely separated compared to their radii. Broad eclipses mean the two stars have large sizes compared to their orbital semi-major axis. Very close binaries may even fill their gravitational potential (*Roche Lobe*) and be "touching"; such systems are called *contact binaries.* This close proximity distorts the stars from spheres into teardrop shapes, making the eclipses even broader. When only one of the stars completely fills its potential the system is classified as *semi-detached* (Figure 6).

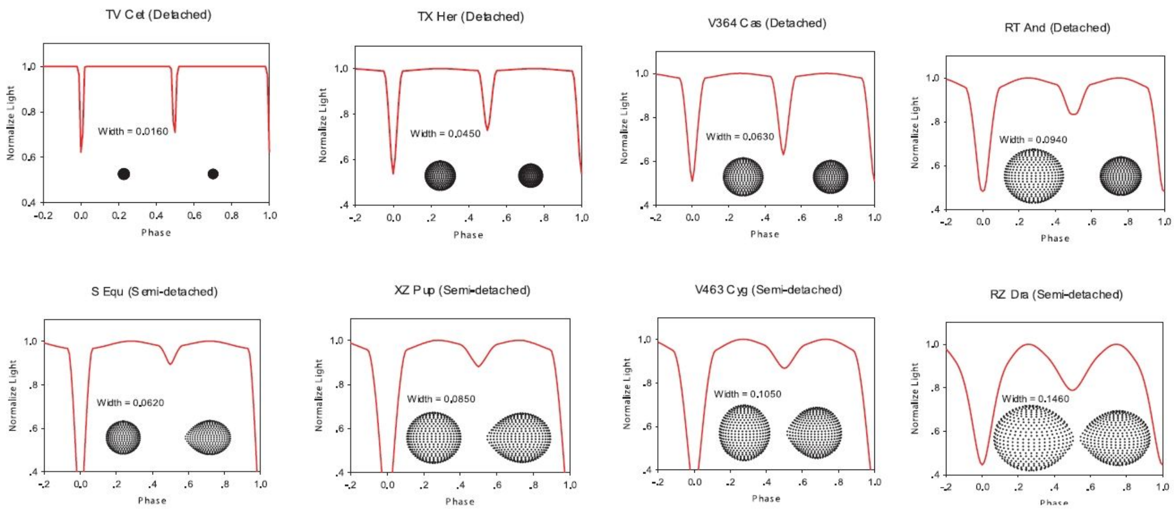

Figure 6: *Typical EB light curves. Depending on the relative size and separation of the components, the light curves can look very different. Unlike widely separated 'detached' systems which are approximately constant outside of eclipses, the effects of ellipsoidal variation can result in constantly varying light curves. In extreme cases (semi-detached and contact binaries), one or both stars fill their Roche Lobes (the teardrop-shaped surface of gravitational potential) and may transfer material.*
Taken from Young-Woon (2010), Journal of Astronomy & Space Sciences, 27, p75

The radii of the stars in an EB can be calculated from the duration and depth of the eclipses, while the masses are derived from the radial velocity curves. The light and radial velocity curves can be mutually beneficial to an analysis. For example, the inclination and period can be determined from the light curve, which allows the true orbital semi-major axis to be found from the velocity curves, which in turn allows the absolute radii to be found. Some parameters, such as the eccentricity, are constrained from both the light and radial velocity curves.