What do eclipsing binary stars tell us about star formation?

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For broadsheet readers everywhere who love star formation!

1 Introduction

The Sun is like a single parent to the planets, moons and asteroids in our Solar System. The majority of stars, however, have at least one other companion. In a system with two stars, the stars orbit each other; one full orbit is known as the period. The brightest (and often most massive) star is known as the primary, and the dimmer is the secondary. If the separation of these stars is small, the system is known as a ”close binary”. The ratio of the masses of the primary and secondary stars is an important parameter known as the mass ratio. Several properties of binary systems depend on the mass ratio and separation. The inclination of the system is important for observers, as it is possible to observe different properties depending on the angle you view it from. For example, we see the Milky Way galaxy from edge-on, so we can see the bulge at the Galactic centre, but not the spiral arms in the disc (with the naked eye).

The majority of stars in the Universe, including our Sun, are main sequence (MS) stars (see Figure 1). At least half of these stars are believed to be in binary or multiple systems [1]. It is now believed that almost all pre-main sequence (PMS) stars are formed in binary or multiple systems, and that solitary stars may have broken free from their systems at some point [2]. With the mass of a star, other parameters such as temperature and radius can be determined. Astronomers can use these to characterise MS stars. Thus, accurate measurements of star masses are paramount in the study of star formation.

Mass determination of stars can be tricky due to inaccuracies in distance measurements and other factors. To determine the mass of a celestial object, one must study the gravitational effect of its mass on another object [3]. The area between young stars often contains gas and dust known as the interstellar medium. The effect of a mass on a fluid such as the interstellar medium is very difficult to determine due to the complex dynamics within the system. Similarly, detecting the effect of a large mass on a very small mass such as a star and planet requires very sensitive equipment. Enter multiple star systems! Stars with similar masses have strong gravitational effects on each other, allowing astronomers to study their properties and parametrise these systems. The simplest multiple systems are binaries, and they are also the most common.

Binary systems can be classified based on their visual properties. Visual binaries are those where both stars can be resolved (seen) with a telescope. Photometric binaries typically appear as one star which varies in brightness. These stars appear older and redder than they should be on a Hertzsprung-Russell diagram (see Figure 1). Spectroscopic binaries can be indirectly imaged to determine properties of the stars such as spectral type, separation and radial velocity (the velocity directly towards or away from the observer). Astrometric binaries involve measuring the tiny ”wobble” of a star thanks to its companion [1]. Finally, eclipsing binary (EB) systems appear as a variable star, which periodically becomes brighter and darker in the night sky due to an eclipse.

EB stars are angled edge-on to us, just like the Milky Way. A consequence of this is that eclipses occur and cause more variations in brightness. Using photometry and spectroscopy, astronomers can learn a lot about eclipsing binary systems, thanks to the eclipse revealing its inclination. EBs typically have short periods (less than 10 days, most less than 1 day) [4]. Therefore, EB stars are very good tools for helping us to learn about star formation.

2 MS and PMS stars

Stars can be classified by their spectral type and their brightness [5][6]. The Hertzsprung-Russell (HR) diagram in Figure 1 shows how stars differ based on these properties. Brightness (or ”luminosity”) in astronomy is often quantified in magnitudes, a log scale of flux where smaller magnitudes indicate brighter objects. The spectral type of a star depends on its emission. Hotter stars emit higher energy (bluer) light than cooler (redder) stars. The majority of stars lie on the main sequence, shown in Figure 1 as a grey diagonal curve.

Stars form due to the collapse of cold gas in the interstellar medium known as giant molecular clouds. Dense ”cores” of gas build up in mass by accreting material from the surrounding envelope of gas and a protoplanetary disc [7]. Once the envelope of this ”protostar” has depleted, it is considered a PMS star. PMS stars with masses less

[1] See the textbook by Kallrath & Milrone (2009) for more detail [4]

than around twice that of the Sun are the most common and widely studied. Temperatures are similar to those of MS stars, however, as they have not completely collapsed they have a larger radius. Due to this, PMS stars tend to have higher luminosities as the luminosity of a source is proportional to the square of its radius (see Equation 1). PMS stars begin near the top right of the HR diagram and migrate downwards as they collapse under their own gravity. Then they shift to the left as they evolve towards the MS, where they begin fusing hydrogen.

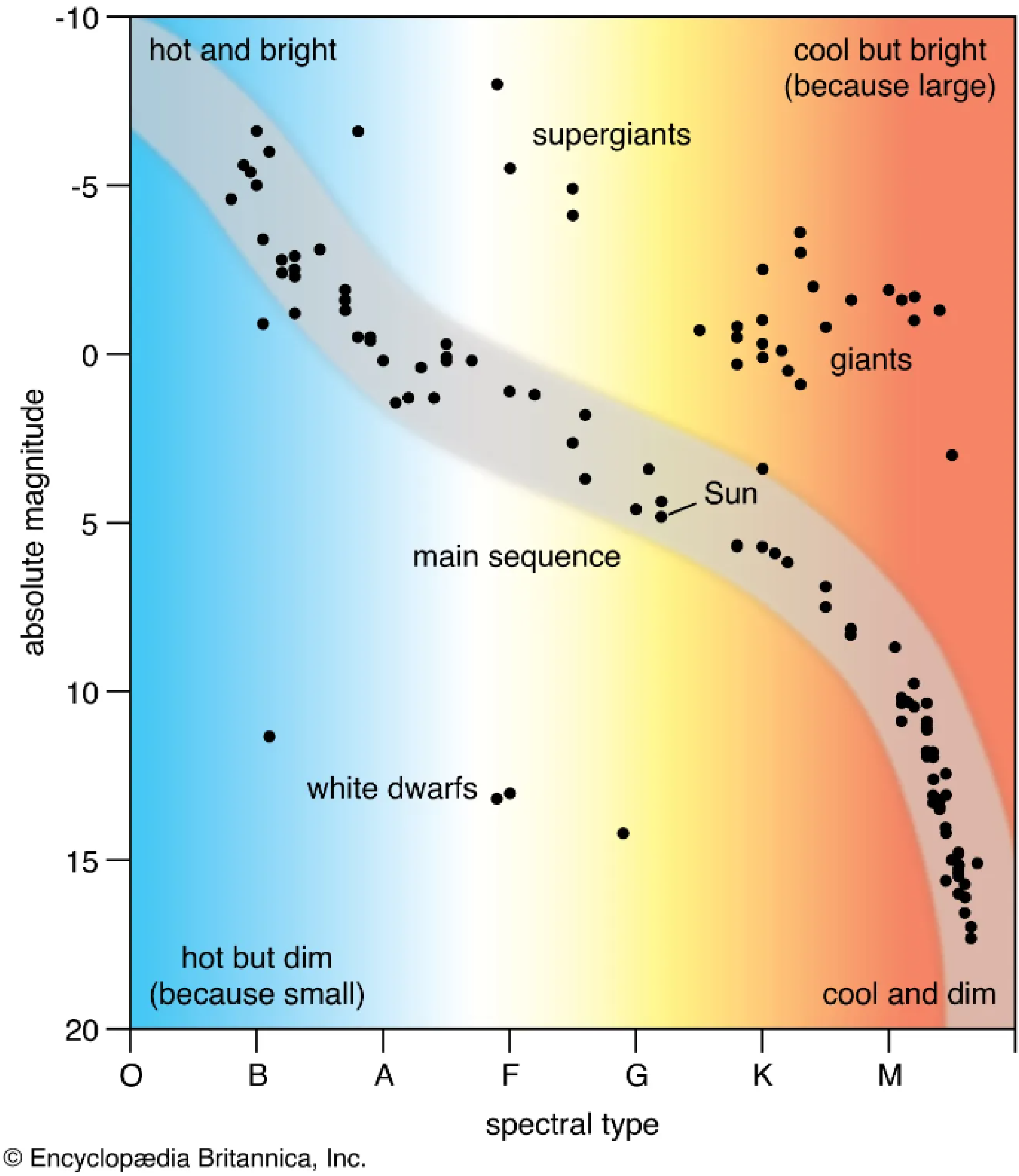

Figure 1: A HR diagram showing different magnitudes of stars as a function of their spectral type. The main sequence, white dwarf, giant and supergiant stars are shown. The main sequence follows a diagonal path; from hot, bright and blue stars to cool, dim and red stars. The range of colours for each spectral type is shown. O and B type stars are blue, while K and M stars are red. Image: Encyclopædia Britannica [8].

3 EBs and MS stars

The abundance of observed multiple systems cannot be explained by dynamical processes combining single stars together, so it is accepted that stars must form this way [9]. While it is accepted that the interstellar medium is the same wherever you look in the Universe, binary systems provide a more detailed insight into the differences in star formation in different environments [10]. However, there are biases associated with observing visual, photometric and spectroscopic binaries. Systems where the primary and secondary stars have similar masses (or sometimes luminosities) are more likely to be observed with these methods. To account for this, the mass of the primary star, the mass ratio, and the separation should be well known for systems [11].

There are many observed differences in binary populations, with systems showing wide variety in their periods, component masses and mass ratios [12]. These differences and the study of the environments and conditions in which the binaries were formed provide insight into universal star formation, and allow astronomers to improve on current models.

EBs are the best subjects for measuring parameters such as this. The eclipse often provides a large magnitude change, allowing the period to be measured accurately using the time difference between two. Furthermore, the masses and radii of the component stars can be determined directly, unlike in non-eclipsing binary systems [13]. These provide extremely useful information about a star, especially when combined with other properties. For example, using photometry, the luminosity, L, of a system may be found. If the individual component masses are known, then it is possible to find their individual luminosities. With this information and knowledge of the radii ,R, of the component stars, their temperatures, T, can also be found as:

$$L \propto R^2 T^4. \tag{1}$$

4 Problems with observing EB systems

The main problem with observing EBs is that they are rare! While binaries are common in the Universe, the proportion of those that are almost edge-on to us is small. Furthermore, the separation must be small enough that one star passes behind the other from the point of view of the observer. They must also be bright enough to be observed. "Invisible" populations of binary stars likely exist which are simply too dim to observe and study. These may contain low-mass secondary stars such as brown dwarfs, which also provide clues into the mechanisms of star formation [14].

While the short periods of many binary systems mean detailed observations can be made of an entire orbit, they cannot be continuously monitored at professional observatories. Large telescopes simply cannot devote continuous time to studying the variability of eclipsing binary systems in great detail.

Finally, as mentioned in the previous section, observational biases occur which must be accounted for. For example, astronomical surveys tend to favour visual binaries which have a much larger separation than close binaries [11]. In addition, the density of a star forming region affects the number of binaries within it; so the regions of stars we are capable of observing may not be summative of the universal population [15].

5 Finding and identifying EB systems

Individual binary stars cannot be continually monitored by astronomers with large telescopes at professional observatories. However, surveys do provide regular photometry of many sources [4]. Furthermore, amateur astronomers are among the most useful source of data in variable star astronomy, performing photometry almost constantly on some sources [16]. A graph showing the change in brightness over time known as a light curve can be used to determine the period, mass ratio and radii of components in an EB.

6 Summary

The majority of stars lie on the main sequence of the HR diagram. Of these stars, almost all are believed to have formed in multiple systems. Binary systems are by far the most common and widely studied. They can be defined by the period, separation of their component stars, and their masses. Binaries display such variation from system to system that current star forming theories cannot yet completely explain their formation. Models of these systems tell astronomers a great deal about their component stars, and therefore details of how they formed. Different observational methods are used to study and characterise these stars, but only with an eclipsing binary with a visible secondary star can the component masses be directly measured. Eclipsing binary stars are rare due to the specific circumstances required for their existence, however more are constantly found through surveys. Amateur astronomers provide valuable data by doing what the professionals can't - continually monitoring the state of many variable stars.

Ultimately, as professional astronomers continue to learn more about the formation of the building blocks of the Universe, it is the enthusiasm that their discoveries inspire in amateur astronomers that allows them to collect data outside of large observatories!

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