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Eclipsing binaries and related photometry

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Abstract. This work mainly focuses on eclipsing binaries. It classifies binary stars based on the way they are discovered and chooses eclipsing binaries as the major topic. Firstly, the paper defines that the criteria for classifying eclipsing binaries in this work are Roche lobe by conductions, which divides eclipsing binaries into three kinds. To further explore the characteristics of three different types of eclipsing binaries, this paper applies light curve analysis, an extremely useful method for finding and analyzing binaries on them, and conducts some special features. Based on the analysis, this paper connects the conduction of the Roche lobe with observation data together. Nowadays, research on binary stars is prevalent because they are related to discovering exoplanets. Research on binary stars contributes to the development of discovering exoplanets as well. A couple of methods in finding binary stars can be applied in finding exoplanets, which have dramatic practical utilizations.

Keywords: Binary star, Photometry, Light curve.

1. Introduction

1.1. Binary Star

Our solar system, with its eight planets orbiting a solitary sun, seems familiar because we live there. But in the galaxy as a whole, planetary systems like ours are clearly in the minority. Over half of all stars in the sky have one or more partners [1]. These multiple star systems come in an amazing variety: large, hot stars orbited by smaller, cooler ones; binary stars orbited by planets; pairs pulsating with X-rays as one star sheds material that is gobbled up by the other.

A binary star system consists of two celestial bodies that are gravitationally bound and revolve around each other. While some binary stars may appear as a single entity when viewed through a telescope, they can be seen as two distinct stars, known as visual double stars. However, anticipating the movements of certain visual double stars can be difficult due to their long orbits, which can extend over centuries or even millennia. Other types of binary stars can be identified through spectroscopy or astrometry. When a binary star system is directly in our line of sight and the two stars eclipse and overlap each other, they are classified as eclipsing binaries. Similarly, photometric binaries are referred to as such if they change brightness during their orbit.

In a binary star system, the gravitational pull between two stars nearby can distort their outer atmospheres. This interaction may even lead to mass exchange between the stars, resulting in evolutionary stages that single stars cannot achieve. Binary stars, such as Sirius (as seen in Fig. 1(a))

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and Cygnus X-1 (as seen in Fig. 1(b)), often form the cores of planetary nebulae and generate novae and type Ia supernovae.

(a) Sirius A and B [2] (b) Cygnus X-1 and Cygnus OB3 [3]

Figure 1. Well-known examples of binary stars.

1.2. Classification

Binary stars can be classified based on how they are discovered, including visual binaries, spectroscopic binaries, astrometric binaries, and eclipsing binaries.

1.2.1. Visual Binaries. A pair of binary stars separated by a sufficient distance to be viewed through a telescope or high-powered binoculars is a visual binary star (see Figure 2). The detection of visual binaries is contingent upon the telescope's angular solution, and as technology continues to advance, more visual binaries will undoubtedly be discovered. Additionally, the star's brightness is a crucial factor, as a brighter star's glare may obscure a fainter one, making detection more challenging. A pair of binary stars separated by a sufficient distance to be viewed through a telescope or high-powered binoculars is a visual binary star (see Figure 2). The detection of visual binaries is contingent upon the telescope's angular solution, and as technology advances, more visual binaries will undoubtedly be discovered. Additionally, the star's brightness is a crucial factor, as a brighter star's glare may obscure a fainter one, making detection more challenging. In a binary star system. The primary star is the one that shines brighter. while the dimmer one is known as the secondary star. In the past, the secondary star was sometimes called "comes" (plural comites) if it was faint. When both stars have the same brightness, the discoverer of the system has the authority to name the primary star.

Figure 2. Albireo is a double-star system [4].

1.2.2. Spectroscopic Binaries. In certain instances, the only indication of a binary star is through the Doppler effect on the light it emits. In such scenarios, the binary comprises two stars. The light's spectral lines emitted from each star shift from blue to red as they move towards and away from us during their motion around their shared center of mass, with the duration of their mutual orbit. In such systems, the distance between the stars is minimal, and they move at a high orbital velocity. Unless the orbit is perfectly perpendicular to the line of sight, the velocity of the stars' movement has components. As a result, the radial velocity that is observed in the system fluctuates periodically. By using a spectrometer to measure the spectral lines' Doppler shift of the star, the spectroscopic binaries can be detected. Even with the most advanced telescopes available, these systems cannot be distinguished as a visual binary.

1.2.3. Astrometric Binaries. Recently, astronomers have made a fascinating discovery of stars that appear to orbit around a void in space. These stars, known as astrometric binaries, are located relatively close to us and can be observed to move in a circular path around an unseen object. By applying mathematical models used for ordinary binary systems, scientists can estimate the mass of the missing object. This missing star could be too faint to detect or be hidden by the brightness of the primary star. Alternatively, it could be an entity that emits minimal or zero electromagnetic radiation, like a neutron star (refer to Figure 1(a)) [5]. The position of a visible star is meticulously measured and observed for any changes caused by the gravitational pull of another star. To do this, the star's position is compared to that of more distant stars multiple times, looking for recurring shifts in position. This method is usually used on stars within 10 parsecs since they tend to have a higher proper motion. Due to this, the movement of astrometric binaries across the sky may appear irregular, as depicted in Figure 3.

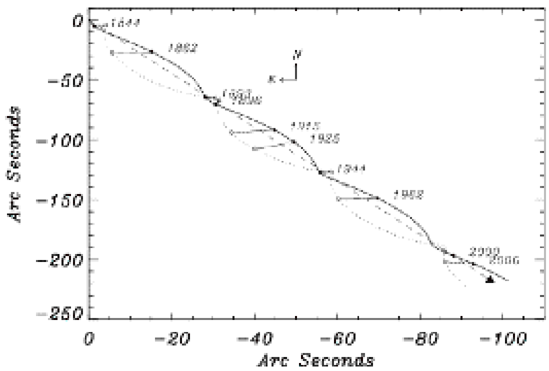

Figure 3. The "wobbly" path of Sirius A [6].

1.2.4. Eclipsing Binaries. An eclipsing binary star system occurs when two stars orbit each other in a way that causes them to periodically pass by each other, as seen from Earth. This phenomenon is immensely useful for studying stars, particularly if the system is also a spectroscopic binary and its distance from us is established. Algol, located in the Perseus constellation, is a well-known example of an eclipsing binary, and its features have been extensively studied by experts [7]. Eclipsing binaries are stars that exhibit changes in brightness solely due to eclipses rather than any shifts in the individual components' radiance. An eclipsing binary's light curve showcases periods of steady light interrupted by periodic intense drops, whichever star eclipses in front of the other [8]. Throughout the orbit, the brightness may decrease twice - once when the secondary star passes by the other and again when the primary star obstructs the secondary. It's important to note that the deeper eclipse is the primary, no matter which star is covered. In contrast, a secondary eclipse is labeled as such only if it's shallow and occurs.

Figure 4. Algol star system [9].

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2. Focus on Eclipsing Binaries

2.1. Introduction

Eclipsing binaries are divided into three types: Algol variables, EA; Beta Lyrae variables, EB; and W Ursae Majoris variables, EW, based on their light curve figures.

2.2. Algol Variables

2.2.1. Introduction. Algol in Figure 4, variables are named after Beta Perseus (Algol) in the constellation Perseus. When a cooler star passes in front of a hotter star, it will block part or all of the light of the rear star, which is the luminosity of this pair of stars. It is the primary minimum, so the brightness of the binary star observed by the earth will decrease; later, when the hotter star passes by the cooler star, it will also cause a decline in luminosity, called the second minimum or sub-minimum.

Most Algol variables are fairly close binary stars, and their periods are not long, usually within a few days. It is known that the shortest cycle is VZ Sculptoris (0.145 days), and the longest is ε Aurigae, which lasts 9892 days (27 years). Usually, the luminosity change of the Algol variable star is about one apparent magnitude, and the one known to have the largest change is V342 Aquila, whose luminosity change reaches 3.4 magnitudes. Member stars can be of any spectral type, but the brighter ones are of type B, A, F, or G.

The difference between the Algol variable star and the subsequent eclipse binary star lies in its clear primary minimum and secondary minimum—meaning that the binary star does not belong to the contact binary star (see Figure 5) or is not deformed by the gravitational force between the binary star, which means It is very important in the later type distinction.

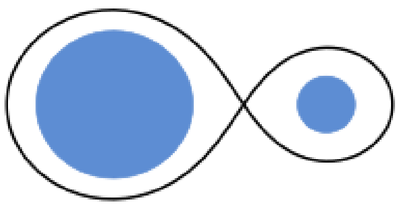

Figure 5. Algol variables are (mostly) detached binaries [10].

To explain the differences between detached, semi-detached, and contacted stars, it is necessary to apply the Roche lobe. Consider two binary stars with mass M_a and M_b, distance A, period P. It is easy to get the equation of angular speed ω (see Figure 6):

$$\omega = \frac{2\pi}{P} \tag{1.}$$

Then:

$$\omega^2 A^3 = G(M_a + M_b) \tag{2.}$$

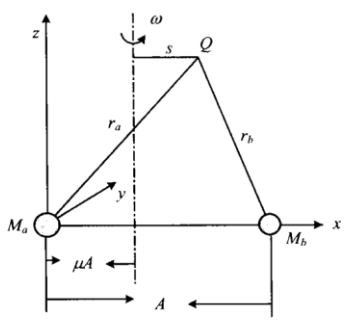

Figure 6. The coordinate with Star A at the origin [11].

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After calculation, here is the equation of Roche equipotentials, where μ means reduced mass, Ψ represents Roche potential:

$$\frac{A\Psi}{G(M_a + M_b)} = \frac{1-\mu}{\sqrt{x^2+y^2+z^2}} + \frac{\mu}{\sqrt{(x-1)^2+y^2+z^2}} + \frac{1}{2}\left(x^2 - 2\mu x + \mu^2 + y^2\right) \quad (3.)$$

Draw the graph of Roche equipotentials. It is easy to spot the Roche lobe in Figure 7:

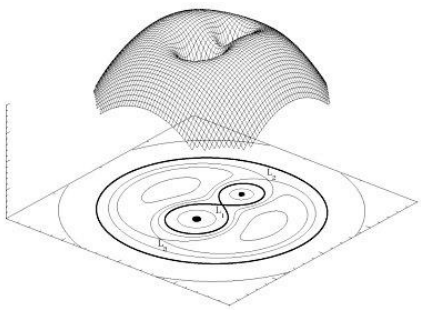

Figure 7. Roche equipotentials and Roche lobe [12].

Binary Stars' sizes and the one of their Roche lobe determine which kind of binaries they are.

2.2.2. Analysis. Algol variables are known for their sharp and direct changes in light curve graphs [13]. Sharp changes enable accurate period calculation. In Figure 8, the period between the primary and secondary minimum is easy to measure and represents the half-orbiting period.

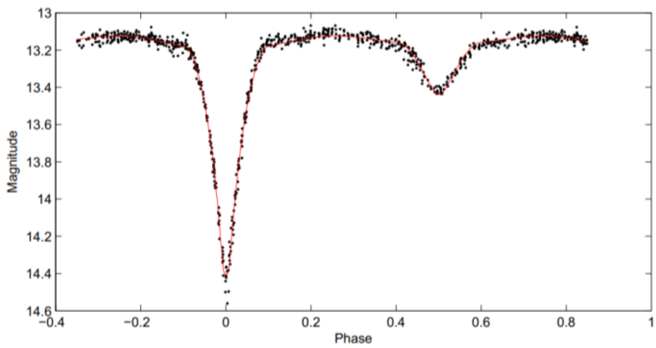

Figure 8. Algol-type variable's light curve graph [14].

2.3. *β Lyrae variables*

2.3.1. Introduction. In essence, it is the same as the Algol variable star. Still, the member stars of the β Lyrae variables are closer to each other so that their shape is affected by gravity and presents an ellipsoidal shape, which may even exceed the Roche limit (the limit a member star can maintain its own material content) resulting in a loss, or exchange, of mass (see Figure 9).

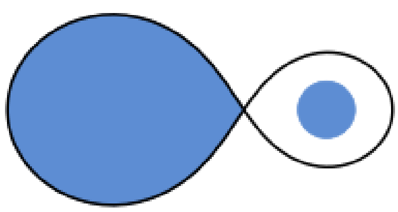

Figure 9. Semi-detached binaries [15].

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Because of the ellipsoidal appearance, although there are still primary and secondary minima in AGII variables, the smoothness of the light curve makes it impossible to determine the beginning and end of the eclipse. An example of a typical β Lyrae variable star is β Lyrae itself (Sheliak), of course (see Figure 10). There are nearly a thousand known AGII variable stars, and 941 AGII variable stars are listed in the 2003 edition of the General Catalog of Variable Stars (GCVS), accounting for 2.2% of the total. Among them, the brightest is π Scorpio (Fang Su Yi) at magnitude 2.8, and the range of variation is 2.82-2.85 magnitudes.

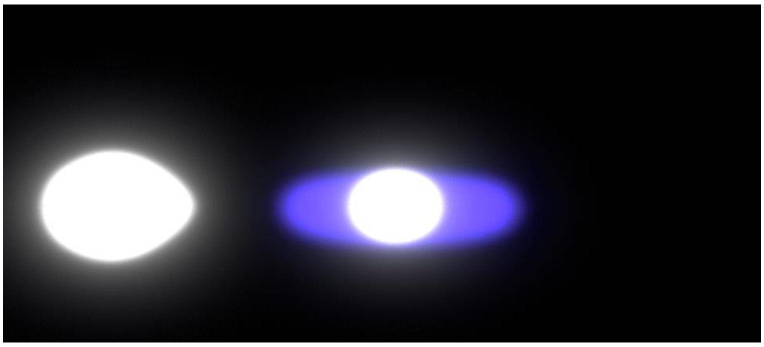

Figure 10. β Lyrae binaries [16].

2.3.2. Analysis. The β Lyrae variables' light curves appear smooth, with gradual starting and ending eclipses, rendering it impossible to determine exact moments. This phenomenon is due to the massive flow between the components, which generates a common atmosphere that covers the entire system. In most instances, brightness variations have an amplitude of less than one magnitude, with the most significant known amplitude being 2.3 magnitudes (V480 Lyrae).

The brightness of these systems follows a highly predictable pattern determined by the orbital period of the binary components. These periods are typically brief, lasting only a few days, with the shortest known period being 0.29 days (found in QY Hydrae), and the longest being 198.5 days (found in W Crucis). Supergiants are typically present in β Lyrae systems with periods that last longer than 100 days.

The light curve graphs of B Lyrae systems may resemble those of Algol variables, but they lack the sharp definition of eclipses. While some may consider them a subtype of Algol variables, they are distinct in their details. As for β Lyrae variables, they may appear similar to W Ursae Majoris variables, but the latter are generally closer contact binaries with lighter component stars. It should be noted that the components of the beta Lyrae system each possess around $1M_{\odot}$. Figure 11 provides a clear depiction of the light curve graphs.

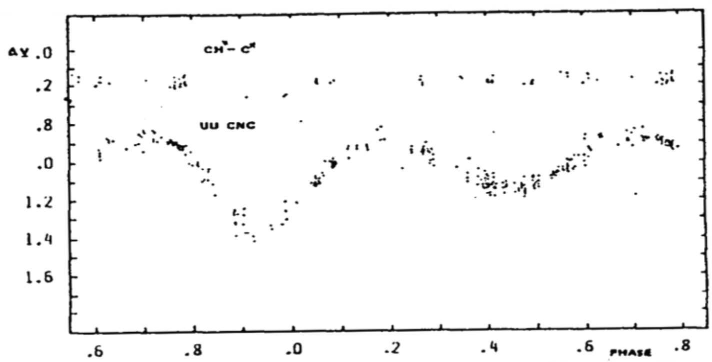

Figure 11. β Lyrae-type variable's light curve graph [17].

Besides, β Lyrae-type is known for a known correlation between orbital and long periods (Figure 12, MNIC V99 has a period ratio of 21.67. The average Pl/Po = 31.9 is indicated).

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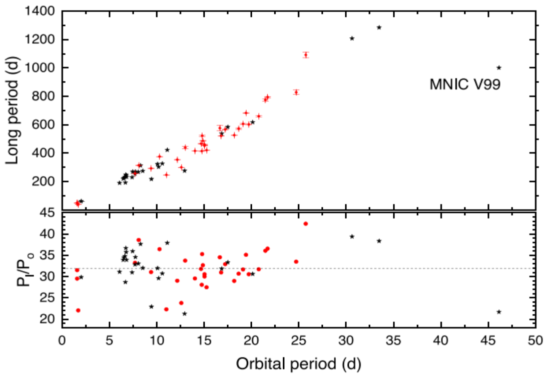

Figure 12. Long period and period ratio vs. orbital period for Galactic DPVs [18].

2.4. *W Ursae Majoris variables*

2.4.1. Introduction. Going a step further than β Lyrae variable star, the member stars are closer to each other, resulting in the exchange of matter between the two, so the two stars share an envelope, forming a so-called "contact binary star" (see Figure 13). Although the eclipse will still cause luminosity changes, the curve is smoother due to the sharing of matter, and the sharing of the surface layers flattens the surface temperature of the member stars so that the primary minimum and secondary minimum are almost the same. Eventually, the two-member stars may merge into a single star.

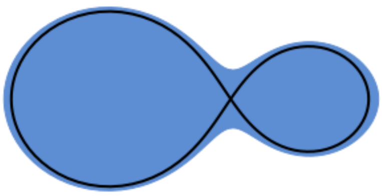

Figure 13. Contact Binaries [19].

The prototype of the W Ursae Majoris-type variable star is W Ursae Majoris (see Figure 14). 1111 W Ursae Majoris-type variable stars are listed in the 2003 edition of the General Catalog of Variable Stars (GCVS), accounting for 2.6% of the total. One of the brightest ones is ε Corona Australis. The brightest is 4.7 magnitude, and the variation range is 4.7-5 magnitude.

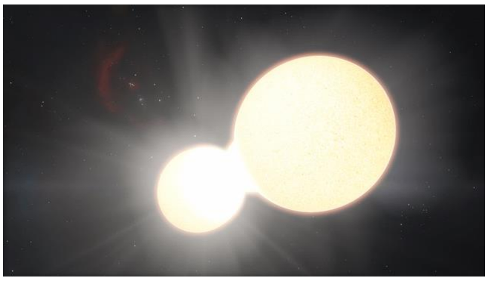

Figure 14. W Ursae Majoris binaries [20].

2.4.2. Analysis. How the light appears to alter for these stars deviates from that of classical eclipsing binaries. There are no clear eclipses; instead, their luminosity is constantly shifting in an elliptical pattern. This is due to the stars being distorted by each other's gravity, resulting in a change in the projected area of the stars. The brightness dips are typically of the same depth as the stars have comparable surface temperatures, as shown in Figure 15.

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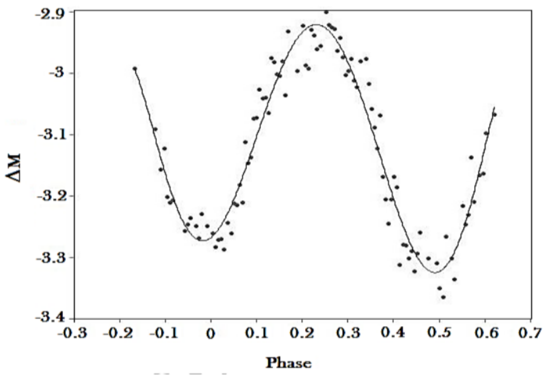

Figure 15. The observed LC of V0449 Peg in the I filter.

Based on a formula, it is easy to draw the relationship between W Ursae Majoris variables' epoch (E) and T Min (see Figure 16):

$$TminI = (2453233.55902 \pm 0.00168) + \left(0.352656818 \pm 2.44 \times 10^{-7}\right) \times E \quad (4.)$$

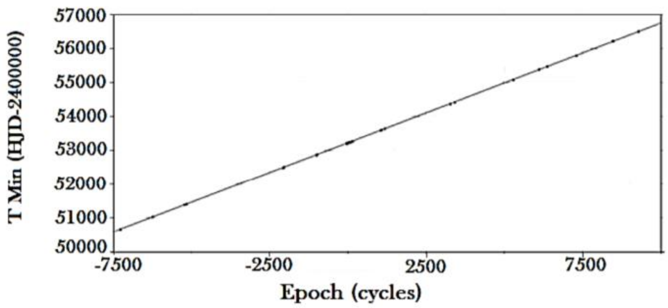

Figure 16. The ephemeris of V0449 Peg with the derived best linear fit to the data.

According to the O-C values of V0449 Peg (see Figure 17), a possible invisible third body may exist [21]:

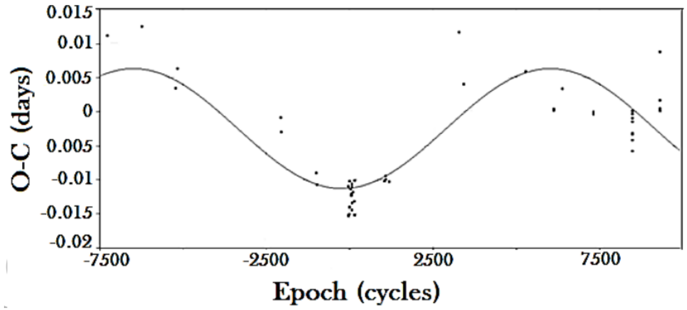

Figure 17. O-C values of V0449 Peg and their fit by a cyclic change.

3. Conclusion

Light curves play an indispensable role in the research of eclipsing binary stars. They are depicted as a graph representing the object's luminosity over a specific time frame. The luminosity can be presented in physical units such as magnitude or normalized to a specific value, making it dimensionless. The x-axis represents the passage of time, commonly expressed in Julian dates or photometric phase, a unitless quantity. Light curves are particularly valuable for studying objects with variable light intensity over time, such as supernovae or novae. They provide essential information, including period, T Min, details about other bodies, variable type, and an easy way to study such objects [22].

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