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Spectroscopy of an eclipsing binary star at a stellar observatory in Chile

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Abstract. This project presents a spectroscopic study of the eclipsing binary star BUL-SC16 335, aiming to determine its physical properties and dynamical behavior. First, we review the different types of binary systems and the experimental methods used for their detection, as well as the processes applied to obtain the spectral lines of BUL-SC16 335. The analyzed data, recorded at La Silla Astronomical Observatory (Chile) by Alfred Tillich in October 2008, include more than 35 observations. These were reduced using several packages and tasks of the IRAF software, while also considering the instrumental effects of CCD cameras and the spectroscopic techniques applied in observational astronomy. Subsequently, specific scripts were implemented for the efficient determination of radial velocity and Julian date. Finally, the use of gnuplot allowed us to construct the radial velocity curve of BUL-SC16 335, contributing to the characterization of its eclipsing nature.

Keywords. spectroscopic binary star, spectroscopy, radial velocity

1. Introduction

Today, we know that the Earth and the other planets orbit the Sun, and Newton's law of universal gravitation describes many of their properties. Modern observations have shown that there are as many planets as there are stars in the visible universe and that most stars belong to binary systems. These systems are essential for determining fundamental parameters, such as orbital periods and stellar masses. Since they are located at great distances, their study relies on analyzing the light that reaches Earth after traveling through interstellar gas and dust. The most common types include visual, astrometric, spectroscopic, and eclipsing binaries, which can be studied based on their observational characteristics. In particular, eclipsing binaries are often analyzed using spectroscopic or photometric techniques. Howell (2006) In this project, spectroscopy was applied to decompose stellar light and link spectral lines with properties such as temperature, age, and composition.

2. Methodology / Methods

2.1. *Binary Star*

Binary stars are systems composed of two stars that are gravitationally bound, orbiting around their common center of mass. Kallrath & Milone (2009) It is estimated that between one-third and one-half of the observed stars belong to binary systems. The main types include visual, spectroscopic, and eclipsing binaries. This work focuses on spectroscopic binaries, as they represent the primary objects of study.

• Spectroscopic Binary: If only the spectrum of one component is detected, the system is classified as a single-lined spectroscopic binary (SB1). Ostlie & Carroll (2007)

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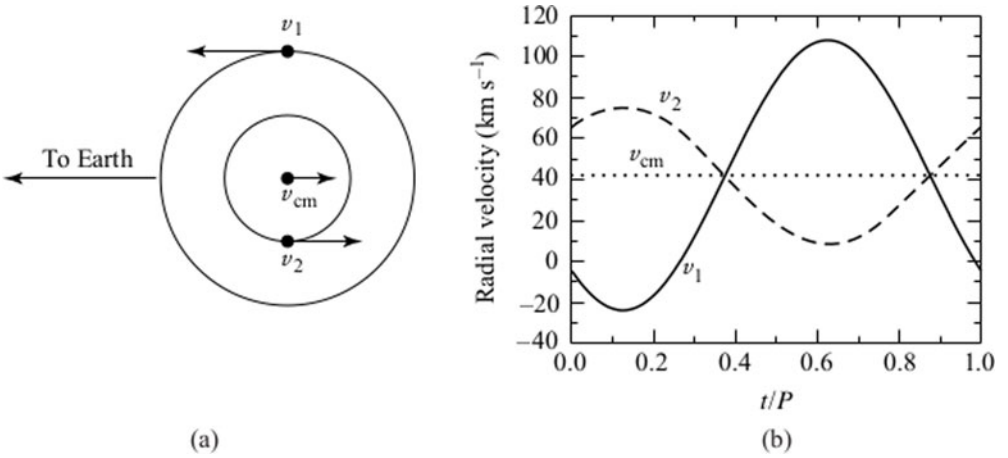


Figure 1. (a) Schematic diagram of a double-lined spectroscopic binary. (b) Radial velocity curves of each component at different orbital phases.

Conversely, if the spectra of both components can be observed (see Figure 1), it is referred to as a double-lined spectroscopic binary (SB2). In the latter case, the absorption lines in the composite spectrum periodically shift as each star moves in its orbit toward or away from us. Ostlie & Carroll (2007) These spectral shifts are best analyzed through radial velocity curves as a function of the orbital period for each component.

2.2. *BUL-SC16 335*

Hot subdwarf B stars are low-mass objects (∼0.5 $M_\odot$) that burn helium in their cores and evolve directly into white dwarfs, although their evolutionary status is not yet fully understood. Polubek et al. (2007) Determining fundamental parameters such as mass and radius is crucial for modeling their evolution, and eclipsing or spectroscopic binaries provide ideal conditions for this purpose.

Within the OGLE survey, which monitors variable stars toward the Galactic bulge, the eclipsing binary BUL-SC16 335 was identified with a very short orbital period of about 3 hours (0.12505 days). Polubek et al. (2007) Its light curve reveals a strong reflection effect and a deep primary eclipse, suggesting that it may be a pre-cataclysmic variable composed of an sdB star and a red main-sequence companion **?**. Additional spectroscopic data obtained with the 3.6 m telescope (see Figure 2) at La Silla Observatory (Chile) provided key information for its characterization.

2.3. *Spectroscopy of an binary star*

Spectroscopy of a binary star involves several steps once the observational data are available. Massey et al. (1992) First, the recorded spectra are reduced and calibrated in wavelength to ensure that absorption or emission lines can be accurately measured. Next, the Doppler shifts of these spectral lines are determined for each epoch of observation. These shifts are then converted into radial velocities, which are plotted as a function of orbital phase or time. By fitting the resulting radial velocity curves, the orbital parameters of the system can be derived, such as the orbital period, eccentricity, and semi-amplitudes. Finally, these parameters allow for the estimation of stellar masses and other fundamental properties of the binary system.

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Table 1. Radial velocity and Julian day data of the binary star.

	Bias	Flat	Lamp	Object (BUL-SC16 335)
October 15	10	20	-	-
October 18	-	-	3	6

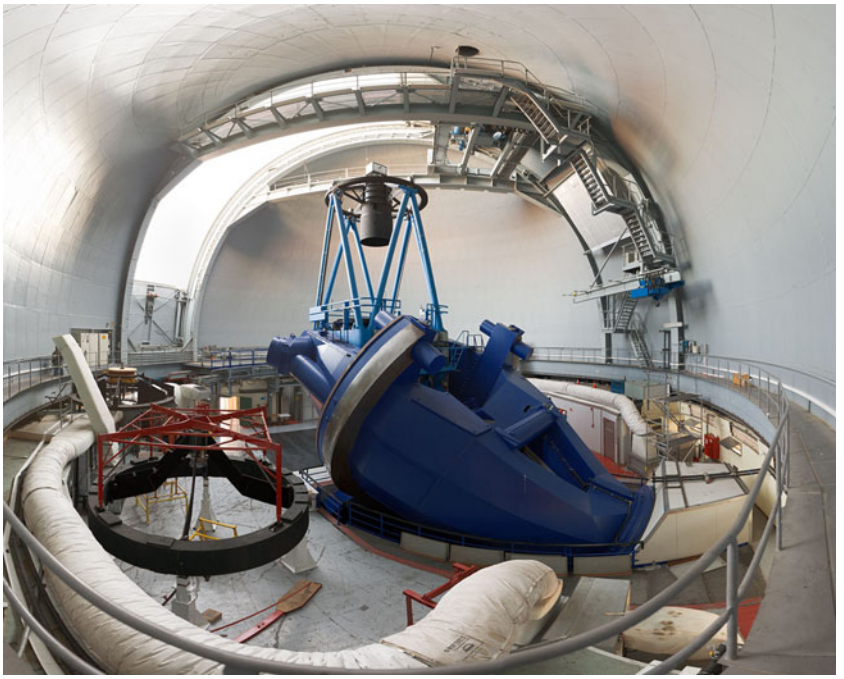


Figure 2. 3.6 m optical telescope of the European Southern Observatory (ESO). **Credits:** La Silla Observatory.

3. Results

In this project, observational data from the binary system BUL-SC16 335 were analyzed. The data were collected by the European Southern Observatory (**ESO**) during October 2008 and subsequently downloaded from its official website. The dataset included *bias*, *flat*, and *lamp* frames, as well as the target object BUL-SC16 335, with the lamp files corresponding to the mercury lamp spectra used for wavelength calibration.

Data processing was carried out using the *xgterm* console and the *ds9* image viewer, which enabled efficient handling and analysis of the spectroscopic data.

Table 1 presents a statistical summary of the number of observations recorded for each day of the observing campaign.

Subsequently, several IRAF tasks and packages were employed to perform the data reduction steps illustrated in Figure 3. As a result, the radial velocity curves of the spectroscopic binary system were obtained for the different observing nights.

Table 2 lists the heliocentric radial velocities (V_{helio}) and Julian dates (JHD) derived from the spectra, which served as the basis for the subsequent analysis and calculations.

Since the main objective of this study was to obtain the radial velocity curve of the binary star as a function of its orbital phase, it was necessary to define a general sinusoidal function and determine its parameters through statistical fitting. The function is

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Table 2. Results of Overloading for 3 Experimental Setups.

Object	HJD	V_{helio}
dpb_1602	4557.59	−62.82
dpb_1603	4758.5	26.32
dpb_1604	4758.5	42.67
dpb_1605	4758.59	−40.48
dpb_1606	4758.6	−42.96
dpb_1607	4758.61	−4.78

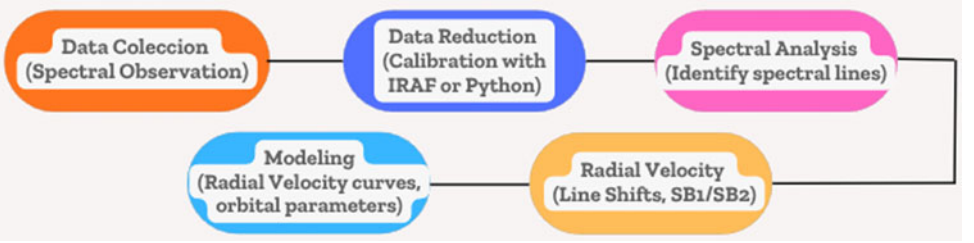


Figure 3. Schematic diagram of the spectroscopic processing of a binary star.

expressed as follows:

$$y = A \cdot sen\left(2\pi\frac{\Delta t}{P} + B\right) \tag{1}$$

where:

- P is the period of the binary star,
- A and B are constant parameters,
- t is the Julian Date (HJD) at which the observation was made, and
- y is the radial velocity (V_{helio}) of the binary star.

The term $\frac{\Delta t}{P} = \frac{t - t_0}{P}$ is commonly referred to as the orbital phase of a star. Its value indicates the fraction of the orbital period that the spectroscopic binary system has completed. This parameter ranges from 0 to 1, where 1 corresponds to one full orbital revolution.

In general, the value of t_0 can be chosen arbitrarily; however, in this study, it was selected so that the initial phase of the system would start close to zero. Specifically, we adopted $t_0 = 4758.49$. Using this value and an orbital period of $P = 0.125050278$ days, the orbital phase of the binary system was computed. The following calculation illustrates the process for the object `dpb_1602`:

- For a t=4557.58:

$$phase = \frac{4757.58 - 4758.49}{0.125050278} \tag{2}$$

$$phase = \frac{-0.91}{0.125050278} \tag{3}$$

$$phase = -7.21 \tag{4}$$

A negative phase value was initially obtained, which physically indicates that the binary system had completed more than seven orbital revolutions, but in the opposite direction of the original motion. To normalize the phase within the standard range of 0 to 1, eight orbital cycles were added. Consequently, the orbital phase for the object `dpb_1602` was found to be 0.79.

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Table 3. Phase and radial velocity data of the spectroscopic binary star.

Object	Phase	V_{helio}
dpb_1602	0.79	−62.82
dpb_1603	0.05	26.32
dpb_1604	0.11	42.67
dpb_1605	0.8	−40.48
dpb_1606	0.89	−42.96
dpb_1607	0.98	−4.78

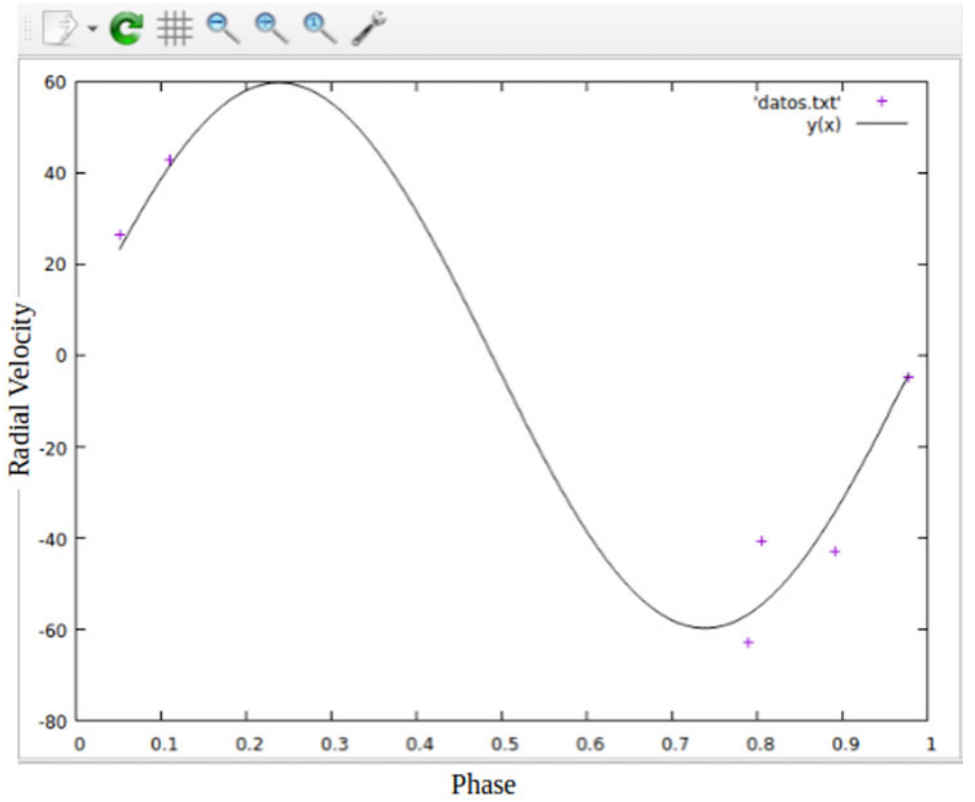


Figure 4. Radial velocity curve of the spectroscopic binary system BUL-SC16 335 obtained using `gnuplot`.

Applying the same procedure to the remaining `dpb` objects yielded a set of phase and radial velocity (V_{helio}) measurements for the binary system. Table 3 summarizes these results. From the calculated data, the obtained points were plotted and fitted with a sinusoidal function using the capabilities of the *gnuplot* software. As the final step of the analysis, a general sinusoidal function was defined in the terminal to determine the constant parameters A and B, and subsequently perform the fit to the observational data.

Figure 4 shows that the phase lies within the range of 0 to 1, while the radial velocity exhibits negative values. Physically, this indicates that the star is moving away from the observer, which corresponds to a redshift in its spectral lines.

Having the radial velocity curve expressed by an equation of the form:

$$y(x) = 59.7 \cdot sen\left(6.38\frac{\Delta t}{P} + 12.04\right) \tag{5}$$

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4. Discussion

The radial velocity curve obtained corresponds to a single-lined spectroscopic binary, since one of its components is hidden by the other. Thus, the observed curve mainly reflects the motion of the brighter component. Although the fitting performed with gnuplot was limited by the small number of available data points, the process remains rigorous and illustrative. It provides both the author and the reader with a clear sequence of steps to follow when a larger data set of a spectroscopic binary becomes available, allowing for a more complete and accurate representation of its radial velocity behavior.

From Figure 32, it can be observed that the peak of the radial velocity curve occurs at phase 0.28, while the minimum appears at approximately phase 0.74. In spectroscopic terms, this indicates that the star is moving away from the observer at phase 0.28 and approaching at phase 0.74. Furthermore, the sinusoidal shape of the radial velocity curve of the BUL-SC16 335 system suggests that its components follow an almost circular orbit, reinforcing the hypothesis of a stable binary configuration.

5. Conclusions

In this work, various packages and tasks from the IRAF software were implemented and mastered, enabling the effective completion of the full spectroscopic reduction process of a star. The influence of CCD camera performance on the quality and accuracy of astronomical observations was also evaluated. Using gnuplot, the data of the spectroscopic binary BUL-SC16 335 were reduced and analyzed, resulting in its radial velocity curve. The analysis of this curve revealed that the components of the system exhibit an essentially circular orbit, confirming their stable nature within the observational limits. These results contribute to a better understanding of the orbital dynamics of binary systems in the Galactic bulge and highlight the relevance of spectroscopic techniques for the characterization of their physical properties.

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