Detection of Pulsation and Additional Components in Eclipsing Binary RS Sct (Postprint)

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Full Text

Preamble

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Detection of Pulsation and Additional Components in Eclipsing Binary RS Sct

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Abstract

The eclipsing binary star RS Sct is a semi-detached system of the β Lyrae type. This system was photometrically observed for six nights in August 2019 and June-August 2020. The light and radial velocity curves were simultaneously analyzed to obtain the absolute physical and orbital parameters of the system, and the system geometry was determined. In this system, the primary component has filled its inner Roche lobe and the secondary component is close to filling it. Moreover, the change in the orbital period of this system was investigated. The presence of third or fourth components and mass transfer between the two components affect the orbital period of the system. In addition, pulsation of the primary component was detected, and several frequencies with high signal-to-noise ratios were identified. According to the position of the primary component in the H-R diagram and the values of the obtained frequencies, this component is likely a δ-Scuti pulsator.

Key words: (stars:) binaries: eclipsing – stars: individual (RS Sct) – methods: data analysis – techniques: photometric

1. Introduction

Based on recent findings, examples of pulsating stars can be found throughout the H-R diagram (Aerts et al. 2010). Asteroseismic studies have made significant progress with the initiation of projects such as CoRoT, Kepler, and recently TESS, which provide continuous and accurate light curves. These studies play an important role in determining stellar radii and can be very effective in establishing the physical parameters of stars.

Binaries, like pulsators, exist in all parts of the Hertzsprung–Russell diagram, and most stars are present in binary or multiple systems (Duchene & Kraus 2013). If an eclipsing binary system is also of the double-lined spectroscopic type, it is possible to directly determine the dynamical masses of the stars in these systems (Stebbins 1911). Therefore, when one or both components in a binary system are pulsating, the synergy created allows determination of the physical parameters of the stars with high accuracy, making it possible to carefully examine and test stellar structure and evolution using a theoretical basis (Murphy 2018).

The eclipsing binary RS Sct (BD+40 442) was first discovered in 1907 by Pickering (Pickering 1907), and the first light curve of the system was presented visually in 1910 by Ichinohe (1910). The first light curve analysis for this system was performed in 1913 by Shapley based on photometric observations by Weil and Bakker (Shapley 1913). In 1916, Zinner raised the possibility that the orbital period of this system is variable (Zinner 1915). In 1936 and 1949, Piotrovsky studied the O − C curve of the minimum times of this system and concluded that the data dispersion in this curve exceeds what can be attributed to observational errors, so the orbital period of the system is most likely variable (Piotrowski 1936, 1949). For the first time, Buckley performed photometry of the RS Sct system with a photometer in 1980 and presented the light curve using Johnson-Cousins BVRI filters (Buckley 1980). Then, in 1984, Buckley analyzed these light curves in "detached" mode and reported the orbital and relative parameters of RS Sct. However, Buckley stated that due to the low quality of the data, it was not possible to comment with certainty on whether this system is "detached" or "semi-detached," and the solutions tended toward a semi-detached system (Buckley 1984). The radial velocity curve of this system was presented by King and Hilditch in 1984 (King & Hilditch 1984). These authors found that both components of the system have filled a significant part of their lobes while each has a temperature associated with the main sequence, indicating that the two components have no temperature interaction with each other. In 1992, Cook studied the eclipse minimum times of this system and predicted the existence of a third component with a period of approximately 29 yr, reporting extreme and strange light changes that led to variation of the primary eclipse depth by about 0.5 mag (Cook 1992). Investigations show that simultaneous analysis of the light and radial velocity curves of this system has not been performed previously.

2. Photometry and Data Reduction

Photometric observations of this system were carried out for two nights in August 2019 and four nights in June-August 2020 at the Dr. Mojtahedi Observatory of the University of Birjand using V and R Johnson-Cousins filters. A 14-inch Schmidt–Cassegrain telescope equipped with an SBIG ST-7 CCD was used for the photometry. During the observations, Maxim DL software was utilized to control and communicate with the CCD camera. The following linear ephemeris (Equation (1)) was used to calculate the system phase (Buckley 1984):

Min I HJD =

During the photometric process, the star 2MASS 18490761-1014116 was used as the comparison star. The characteristics of this star and the variable star are presented in Table 1.

Over the six nights of observing this system, 1828 images were obtained in the V filter and 1794 in the R filter. Image processing and data reduction were performed using IRIS software with the aperture photometry method. Corrections for dark, bias, and flat field effects were applied to the astronomical images, and no zero-point shift was found between the nights. Figure 1 shows the light curves obtained in both V and R filters after normalizing to 1 at phase 0.25. The data quality across different nights is almost the same with no significant differences. Consequently, data dispersion can be attributed to the low accuracy of the observational instruments (telescope and CCD) and other error-producing factors. In Figure 1, no special behavior can be seen in the residuals because the curve is plotted in terms of orbital phase, so data from different nights with time intervals are overlapped; however, if the residuals are plotted against time, a periodic behavior can be observed (see Section 5).

3. Light Curve Analysis

The PHOEBE Legacy program (Prsa & Zwitter 2005) was applied to analyze the light curves and determine the physical and geometrical parameters of the binary star RS Sct. First, the light curves were analyzed in "detached" mode. After failing to find a good match between the simulated light curve and observational data in detached mode, the "semi-detached" mode was used. In detached mode, after running the program several times and leaving parameters free to find a better fit, one component filled its inner Roche lobe and the system transitioned from detached to semi-detached mode. Therefore, if we limit ourselves to working in detached mode, no stable solution is found for the system and the value of $\Sigma(\mathrm{O}-\mathrm{C})^2$ becomes large. Investigations showed that the primary star in this system is non-spherical and has filled its inner Roche lobe. Based on information from various catalogs, the temperature of the primary component is predicted to be between 6000 and 7200 K (Buckley 1984; Avvakumova et al. 2013; Brown et al. 2018). In the present study, the temperature of the primary component was chosen to be 7000 K. Moreover, the initial value of the secondary to primary mass ratio, q, was chosen as 0.6 based on the radial velocity curve presented by King & Hilditch (1984).

According to the temperature of the primary component ($\mathrm{T}_1 < 7200$ K), the values $\mathrm{A}_1 = \mathrm{A}_2 = 0.5$ (Rucinski 1969) and $\mathrm{g}_1 = \mathrm{g}_2 = 0.32$ (Lucy 1967) were used as fixed parameters for the bolometric reflection coefficients and gravitational darkening, respectively. Limb-darkening coefficients were automatically calculated by the software based on van Hamme tables (van Hamme 1993) using the logarithmic law.

Finally, photometric data were analyzed simultaneously with radial velocity data (King & Hilditch 1984). In Table 2, the results of this research are compared with those obtained by Buckley (1984). In this table, i is the orbital inclination, V_{com} is the radial velocity of the center of mass of the system, Ω is the surface potential of the components, L is the luminosity of the component, and r is the relative radius of the star. The synthesized light curves in the V and R filters are displayed in Figure 1, and the generated radial velocity curves are depicted in Figure 2. Figure 3 illustrates the three-dimensional (3D) structure of the RS Sct system at phase 0.75.

Based on the radial velocity curve produced in the simultaneous analysis of photometric and radial velocity data, the values of K_1 and K_2 were 115.24 ± 5.2 km s^{-1} and 189.73 ± 9.8 km s^{-1}, respectively. Using these values and the parameters reported in Table 2, the absolute parameters of the binary components of RS Sct were calculated. These parameters, along with values reported by Dryomova et al. (2005), are presented in Table 3.

With the absolute physical parameters of the components of RS Sct and the use of the H-R diagram, the evolutionary status of the stars in this system was investigated. In Figure 4, in addition to the positions of the components of this system, the positions of components from several semi-detached binaries (extracted from Malkov 2020) are presented for comparison. As seen in this figure, the primary component of RS Sct is located near the terminal age main sequence (TAMS) line, and the secondary component is above the main sequence.

In addition to the H-R diagram, the density–color index diagram can be used to check the evolutionary status of stars (Mochnacki 1981, 1984, 1985). The B − V color indices for the primary and secondary components of this binary system were obtained by referencing tables in Worthey & Lee (2011) as 0.327(20) and 0.710(20), respectively. When using these tables, we assume that the two stars in the binary system do not affect each other, so they behave similarly to two single stars with the same chemical composition as the Sun.

Figure 5 shows the positions of the components of this system in the density–color index diagram. For comparison, the positions of sample components obtained with a similar method in Malkov (2020) are also presented. The positions of the components in this diagram agree with the results obtained from the H-R diagram. Accordingly, the primary component of the system is close to the TAMS and the secondary component is outside the main sequence.

In 2006, based on statistical analysis, Eker et al. obtained critical orbital angular momenta for contact binary systems using the following equation (Eker et al. 2006):

log J_{crit} = 1.664 + 0.522 log M

In this equation, M is the total mass of the primary and secondary components in solar masses. If the orbital angular momentum of the system is less than this critical value, the system is in contact; otherwise, the system is semi-detached or detached. The magnitude of the orbital angular momentum for RS Sct is obtained using:

$J = (M_1 M_2/M)\ \surd[Ga(1 - e^2)]$

The position of this system is marked in the plot of orbital angular momentum versus total mass in Figure 6. As can be seen, RS Sct is located near and above the critical momentum line, so a non-spherical geometry of components and semi-detached structure are most probable for this system.

4. Investigating Orbital Period

During observations of the RS Sct binary system, four primary and two secondary minimum times were identified. To extract these minimum times, the method of Kwee & van Woerden (1956) was used; these minimum times are listed in Table 4. Minimum times reported for this system were collected from the AAVSO and $O - C$ gateway databases. After removing overlaps, the $O - C$ curve was plotted using these minimum times plus those listed in Table 4. To investigate changes in the orbital period, we had 318 minimum times, of which 261 were visual data, 17 photographic data, and 40 photoelectric/CCD data. Due to the lower accuracy of visual and photographic data compared to photoelectric and CCD data, different weights were assigned in the $O - C$ curve analysis: weights of 1, 3, and 10 for visual, photographic, and photoelectric/CCD data, respectively. This weighting method is common in the literature (e.g., Zasche et al. 2008; Hanna & Amin 2013; Ulas et al. 2020). The linear ephemeris given in Equation (1) was used to calculate the epoch and $O - C$ values. Figure 7 shows the $O - C$ curve of the minima of the eclipsing binary RS Sct.

In semi-detached and contact systems, mass transfer is one of the main mechanisms of orbital period change, which can be checked by fitting a second-order function to the $O - C$ curve. Therefore, a second-order function was fitted to the $O - C$ curve of RS Sct and its coefficients were obtained using the least squares method. Based on the obtained coefficients and following the Kalimeris method (Kalimeris et al. 1994), the new linear ephemeris of this system was calculated as:

Min I =

Considering the mass transfer effect, the nonlinear ephemeris of the system can be written as:

Min I =

The orbital period reduction rate of the system was also calculated as (Hilditch 2001):

$dP/dt = -0.000012$ day yr^{-1}

According to the semi-detached geometry and dimensions of the stars in this system, mass transfer between the components is probably conservative. With this assumption, the mass transfer rate is (Hilditch 2001):

$dM/dt = 1.22 \times 10^{-7}\ M\ \ yr^{-1}$

In Figure 7, the second-order function is fitted to the $O - C$ curve of RS Sct. After subtracting this second-order function from the $O - C$ curve, a periodic behavior can be seen in the residuals. These periodic changes can be attributed to the light-time effect caused by one or more additional components in this system.

To investigate the light-time effect in the $O - C$ curve, the following relationship was used (Irwin 1959):

$O - C = k[(1 - e^2)/(1 + e\cos\ \ )]\sin(\omega +\ \ )$

where k, e, ω, and   are the amplitude of $O - C$ changes, eccentricity, longitude of periastron, and true anomaly of the third or fourth body, respectively. To find the initial value of the orbital period of this additional component (or components) in RS Sct, we employed the Period04 program (Lenz & Breger 2005). However, to fit Equation (8) to the residuals of the O − C curve, the orbital period was taken as a free parameter.

The best fit to the residuals of the O − C curve was obtained by considering two light-time effects corresponding to possible third and fourth components in this system. The results of this analysis are given in Table 5 and Figure 7, which show the final fitting and residuals. By adding a fourth object to the system, the value of ^{2} is reduced from 0.02555 to 0.02075. To be absolutely sure, we applied a statistical F-test for comparing one- and two-additional-component models. For the model including mass transfer and the light-time effect of the third object, the F-value was 1.8769, with eight free parameters in the model, making it acceptable at up to 5% error. For the model including mass transfer and light-time effects of both third and fourth bodies with 13 free parameters, the F-value was 0.1574, making this model acceptable at up to 0.1% error. Accordingly, this statistical test clearly shows that adding a fourth body to the model has improved the results. After removing the effects of the second-order function and the two light-time effects associated with the third and fourth components, the final residuals are randomly distributed around the zero line with no systematic behavior. Therefore, it appears that almost no other factor causes changes in the orbital period of the system.

5. Checking the Presence of Pulsation in the Components

To investigate pulsations in the components of RS Sct, we obtained the residuals between the model and observations in the light curve. These residuals can be seen in Figures 8 and 9 for V and R filters, respectively. To better show the behavior of the residuals versus time, the horizontal axis of the graphs is broken.

Period04 was used to find possible oscillation frequencies in the residuals. This program is commonly utilized to find frequencies in pulsating stars (Chen et al. 2023; Kobzar et al. 2023; Pothuneni et al. 2023; Ulas & Ulusoy 2023). We calculated the frequency spectrum from 0 to 100 day^{-1}. The Nyquist frequencies for V and R filters were obtained as 500 and 710, respectively. Because there was no significant frequency above 100 day^{-1} in the frequency spectrum of these two filters, the frequency spectrum calculation window was considered from 0 to 100 day^{-1}. Figures 10 and 11 display the frequency spectra obtained for V and R filters, respectively. We selected only frequencies with signal-to-noise ratio (S/N) greater than 4 (Breger et al. 1993). In Table 6, these frequencies are listed in order of occurrence: four frequencies were found for the V filter and five for the R filter.

Figures 8 and 9 show the fitting of detected frequencies to the residuals of the simulated light curve after subtracting from observational data in V and R filters, respectively, with final residuals displayed. For the V and R filters, the variance reduction values (R = variance after fitting / variance before fitting) were 0.68 and 0.80, respectively. Therefore, the final residuals are improved and their variances are reduced relative to the initial data while the points are almost randomly distributed around the zero line.

6. Discussion and Conclusion

In this research, light curves of the eclipsing binary system RS Sct were obtained in V and R Johnson-Cousins filters. Furthermore, the physical and orbital parameters of this system were determined by simultaneously analyzing the light and radial velocity curves. These results and those of Buckley's analysis are given in Table 2. There are two important differences: (1) In the present research, for the first time, photometric and radial velocity data were analyzed simultaneously using the mass ratio obtained from spectroscopic observations, while Buckley did not employ this technique. (2) As Buckley mentioned, due to low data quality, he could not determine with certainty whether RS Sct is detached or semi-detached, so he assumed the system is detached. However, the present research used more accurate photometric data and simultaneous analysis of light and radial velocity curves to demonstrate that the system has a semi-detached configuration, which is also confirmed by the position of RS Sct in the orbital angular momentum versus total mass diagram (Figure 6). The remarkable aspect of RS Sct's geometry is that the secondary component is on the verge of filling its inner Roche lobe, which would transform this system into a contact system.

Table 3 presents the absolute parameters of this system, determined using radial velocity data from King & Hilditch (1984) along with results from Dryomova et al. (2005). Dryomova et al. obtained absolute parameters by combining results from King & Hilditch (1984) and Buckley (1984). However, due to the low accuracy of Buckley's results, the absolute parameters reported by these authors also have large uncertainties. For the reasons mentioned, the results of the present research are likely more reliable. By determining the absolute physical parameters of the components, the locations of the primary and secondary components were identified in the H-R diagram (Figure 4) and the color index–density diagram (Figure 5). In both figures, the primary (more massive) component is close to the TAMS, indicating it is at the beginning of its evolutionary stage and exiting the main sequence.

The $O - C$ curve of eclipse minima for this system was plotted. The parabolic form can be attributed to conserved mass transfer between components. The orbital period change rate and mass transfer rate from primary to secondary star were determined. After removing the mass transfer effect from the $O - C$ curve, periodic behavior was observed in the residuals. By fitting two light-time functions to the residuals, we suggest these periodic changes result from third and fourth components. After raising this possibility, the light curves were reanalyzed leaving the light of the third object as a free parameter, but its effect was estimated to be less than 1%, which can be ignored given the data dispersion. Therefore, the possible third and fourth components should not contribute significant light. The minimum masses obtained for these components fall in the dwarf mass range of 0.2M < M_{WD} < 1.2M (Kepler et al. 2007; Kilic et al. 2007), so the third and fourth components are probably white or brown dwarfs.

Cook's (1992) claim regarding extreme light changes in RS Sct and variation of the primary eclipse depth by about half a magnitude was investigated. However, photometry in the present research was carried out over two years during which no signs of extreme light changes or variation in primary eclipse depth were observed.

Periodic behavior was investigated in residuals after subtracting the simulated light curve from observational data in V and R filters. We detected four frequencies in the V filter and five in the R filter with S/N > 4 (Table 6). Frequencies f_2 and f_4 in the V filter and f_2 and f_4 in the R filter correspond to orbital motion (=1.505487041 day^{-1}), so they may be caused by orbital motion and apsidal forces (Maceroni et al. 2009; Fuller 2017) or by imperfect modeling of the binary light curve. Frequencies f_1 and f_3 in the V filter and f_1 and f_3 in the R filter are independent. These frequencies most likely result from stellar pulsation in one or both components of the RS Sct binary system. Another possibility for the origin of the dominant frequencies f_1 and f_1 could be differential rotation (with spots or surface inhomogeneities) or stellar activity (in the presence of a magnetic field). However, we found no evidence of spots or surface inhomogeneities in the light curve analysis, making these possibilities less likely. Gravity-mode (g-mode) pulsations cannot be considered as an origin for f_1 and f_1 . Frequency f_5 is not independent as it is a multiple of f_1. The amplitude range for these frequencies is 0.003–0.017 mag, which is consistent with δ-Scuti stars. Except for f_1 and f_1 , other frequencies fall in the usual range for δ-Scuti stars (5–100 day^{-1}) (Grigahcene et al. 2010). This evidence indicates that the pulsating component(s) in this system is probably of the δ-Scuti type.

Moreover, the position of the primary component in the surface gravity versus temperature diagram (Figure 12) shows it lies within the instability strip and in the range of δ-Scuti pulsators. Therefore, results from pulsation frequency analysis are confirmed, indicating that the pulsating component is likely the primary component and is of δ-Scuti type.

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Data Availability: The data underlying this paper will be shared upon reasonable request to the corresponding author.

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Note: Figure translations are in progress. See original paper for figures.