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Anomalous behavior in the light variations of RZ Cas

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Abstract

UBV light curves together with color curves of the semi-detached eclipsing binary RZ Cas are presented. The light curves are analyzed and the spectroscopic elements and the Hipparcos information are used to compute the absolute parameters of the system. The light curve anomalies and occasional flat minima are discussed. Based on the existing evidence, a straightforward explanation for the primary minimum anomalies is presented.

Keywords: Eclipsing binaries, photoectric photometry

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1. Introduction

RZ Cassiopeiae is a typical semi-detached eclipsing binary which has been observed for over one hundred years. According to the Hipparcos main catalogue, it has a visual magnitude of 6.26, and a B-V color of 0.151 in the Johnson system. The trigonometric parallax is indicated to be 15.99±0.46 milli-arc seconds. This parallax implies a distance of 62±2 parsecs for the system. With such a relatively small distance we expect a negligible interstellar reddening although the star is very near to the galactic plane.

Many photoelectric observations of this system have been made by various observers, including Chambliss [1] and Riazi et al. [2]. Spectroscopic studies of the system have been done by Horak [3] and Duerbeck et al. [4] and more recently by Maxted et al. [5]. Among the solutions obtained, those of Chambliss [1] and Maxted et al. [5] are probably the most reliable ones. Maxted and collaborators have solved the UBV light curves of Chambliss via frequency domain method and combined the results with their spectroscopic data to obtain the absolute parameters of the system [5]. These authors suggested spectral types of A3V&KOIII and a mass ratio of 0.331 for the system.

Observations and studies in some other parts of the spectrum have been made in addition to the enormous optical observations. These include the radio observations by Schmitt et al. [6] and the X-ray observations by Drake et al.

The period variability of RZ Cas has been known for a long time. Svechnilov and collaborators had measured photographic times of minima of this system for over 70 years after 1890. Enormous number of photoelectrically measured times of minima are also available, which as a whole have led to a rich O-C diagram containing more than 3000 individual points. This diagram can be found in Hegedus et al. [7]. They have done a Fourier analysis on the O-C diagram and claimed that there exist four periodic components indicating an apsidal motion due to a third component. Maxted et al. [5] also introduced further evidence for the existence of a third component. On the other hand, Hall et al. [8] properly described the

O-C diagram of the RZ Cas according to the Biermann-Hall model. The period variations in this model resulting from abrupt mass transfer are related to the exchange of orbital and the rotational angular momentum.

Beside the alternate period changes, RZ Cas has been interesting for it's light curve anomalies particularly during the primary minimum. The eclipses are normally partial. The system parameters also confirm this. However, flat minima up to 22 minutes, in Arganbright et al. [8], have been reported every now and then. The anomaly sometimes appears as a slight peak just before or after the zero phase, producing an asymmetrical W-shape minimum as in the observations of Riazi et al. [9]. This problem was finally resolved after the discovery of the δ-Scuti oscillations in the hot component [10]. As we shall see in this paper, it can now be admitted that the flat and W-shape minima are due to the same effect: superposition of the hot component pulsation with eclipse light variations depending on the relative phases of the oscillations and the eclipses. Oscillations occur with a period of about 22 minutes and a peak to peak amplitude of about 0.04 mag.

In this paper, we present UBV wide band observations of the RZ Cas showing more concern for the primary minimum. Then, we present a Willson-Devinney (WD) solution to our light curves and compute the absolute parameters of the system by using the spectroscopic elements of Maxted et al. [5]. We also present a simple model for the effect of oscillations on the shape of the primary minima.

2. Observations and preliminary implications

A differential photometry was carried out during October and November 1995 with BD+68215 and BD+69171 as the comparison and check stars respectively. Observations were made with the 51 cm cassegrainian reflector at Biruni Observatory (longitude 52.53E and latitude+29.6). An RCA4509 photomultiplier tube operating at 1600 volts was used. The output current was amplified and fed into a PC via an A/D converter. A set of UBV filters were used with peak wavelengths (widths) of 3500 Å (700 Å), 4350 Å (970 Å), and 5550 Å (850 Å) respectively. The atmospheric corrections were made using standard routines. A shift in the phase of the primary minimum with respect to the adopted ephemeris was obtained by fitting the parabolas to the observed minima. The results presented in Table 1 show that the O-C values are consistent with the observations made by Narusawa et al. at almost the same time [11]. The corresponding cycles and O-C values are calculated according to the ephemeris 2448484.5016+1.1952495.

We obtained more than 600 individual points for each filter and then reduced them to about 200 normal points. Figure 1 shows the corrected light curves. The probable error in the observed magnitudes is estimated to be about $0^{m}.03$ for the V-band observations. The B-V color curve is also shown in Figure 1. The observed primary minima covered in five nights are shown in Figure 2 on a larger scale, in order to magnify the details of the light variations during the primary eclipse. There is apparently no flat bottom, and the curves are relatively smooth and almost symmetrical with respect to the zero phase.

In order to monitor the light curve behavior around the minimum light, we carried out a few continuous photometries each for almost one-hour. The best attempt is presented in Figure 3 which shows intensity versus time from $16^{h}.33$ UT to $17^{h}.33$ UT on March 29, 1996. The data consists of about 80000 samples recorded through the V filter. The atmospheric correction for this particular observation was done by a linear correction of corresponding magnitudes in such a way as to make the descending and ascending branches as symmetrical as possible with respect to the zero phase. The purpose of this observation was to search for flatness or unusual fluctuations around the phase zero. A minor bump can be seen after the zero phase. It can be seen from this figure that there is a slight increase just before and after the primary minimum with a timescale of about 22 minutes. This curve yields a minimum time JD 2450172.2024±0.0005.

3. Analysis

We used the WD computer program to analyze the observed light curves. The computational procedure begins by fixing values for the Ω-potential components. The equation for the surface figures is then calculated, and the radiated flux is computed for each surface element with the desired accuracy [12]. By integrating over the observable parts of the stellar disks the total light of the system is estimated. The Ω-potential strongly

Table 1. Observed heliocentric times of the minimum light. The corresponding cycles and O-C values are calculated according to the ephemeris 2448484.5026+1.1952495

HJD	Cycle	O-C	Weight
2450007.2596	1274	+0.0101	34
2450014.4313	1280	+0.0103	46
2450020.4072	1285	+0.0100	103
2450044.3123	1305	+0.0101	74
2450045.5076	1306	+0.0100	76

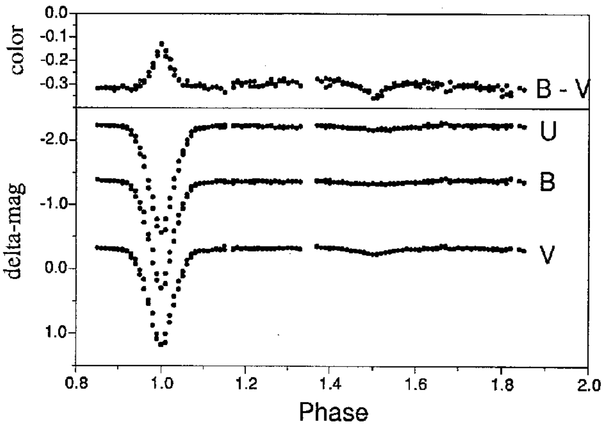

Figure 1. The light curves or RZ Cas for the U, B, and V filters.

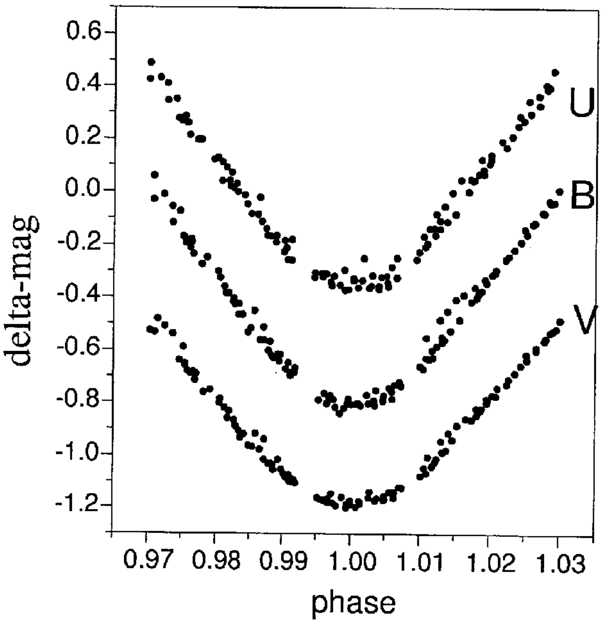

Figure 2. Expanded primary minimum light curves.

depends on the mass ratio of the system $\left(q = \frac{m_2}{m_1}\right)$. Unfortunately, the information from light curves is not usually sufficient to derive an accurate value for q. Spectroscopic observations, on the contrary, lead to a more reliable and relatively accurate value for the mass ratio. For the case of RZ Cas, a mass ratio of 0.331 has been reported from a radial velocity observation by Maxted et al. (1994). Previously, the mass ratio was obtained 0.35 [1,13] using the Plavec tables of the Roche model. We ran the program for these two mass ratios although only the solutions for q=0.331 have been presented in this paper. A set of parameters is summarized in Table 2. The temperature of the primary was fixed according to the spectral type A3V, but for the secondary we let it be adjustable. We ran the WD code in mode 2 (semi-detached systems), in which the temperature and luminosity of the secondary are coupled. These were chosen according to the existing references and in particular ref. 1. Limb darkening coefficients and the albedo of the primary were assumed to be the same for all the three filters, and the gravity darkening coefficient was assumed to be unity (i.e. obeying the von-Zeipel law). For the secondary's albedo, however, we used the adopted values of Maxted et al. (1994). In order to obtain a more realistic model of the system, a nonsynchronic rotation was considered for the hot primary component. The rotation of the primary leads to its flattening, which, via the gravity darkening affects the surface light distribution. We used $\frac{\upsilon_{rot}}{\upsilon_{orb}} = 1.22$ from $\upsilon_{rot} \sin i = 85$ km s^{-1} in accordance with [14]. The temperature of the primary (T_1) is chosen according to the references and the reported spectral type. A comparison of the observed and calculated light curves are presented in Figure 4. Using the spectroscopic elements of Maxted et al. we obtained the absolute parameters of the system. A comparison between the results of Maxted et al. and those of ours is presented in Table 3. It can be easily concluded that the primary fills its roche lobe while the secondary is well within its critical roche lobe.

4. Summary and discussion on the light curve anomalies

RZ Cassiopeiae is an interesting system from many aspects. Although many of its properties are known to a large extent, there remain some subtleties deserving further studies.

Table 2. Physical parameters estimated using the W-D code. Note that the values of T_1, x_1, x_2 and A_1 are not varied.

Parameter	U	B	V
i	82.95±0.05	83.10±0.05	82.96±0.05
L_1	0.977±0.005	0.965±0.005	0.918±0.005
L_2	0.023±0.005	0.035±0.005	0.082±0.005
Ω_1	4.395±0.015	4.503±0.015	4.483±0.015
Ω_2	2.535±0.015	2.551±0.015	2.545±0.015
T_1	8600	8600	8600
T_2	4800±100	4550±100	4620±100
x_1	0.6	0.6	0.6
x_2	0.8	0.8	0.8
A_1	1	1	1
A_2	1.23	0.73	0.47

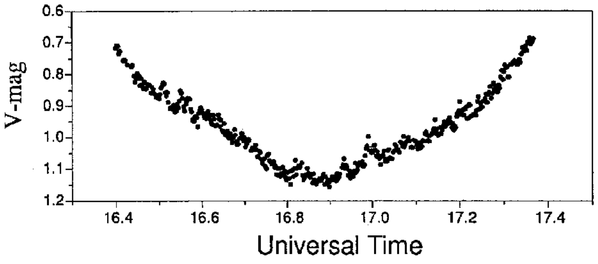

Figure 3. Rapid sampling of the primary minimum. It can be seen that there exists an increase before the minimum and a decrease after the minimum, with respect to a parabolic fit. This extra variation can be attributed to a periodic modulation of a period ~22 min. The horizontal axis is in hours.

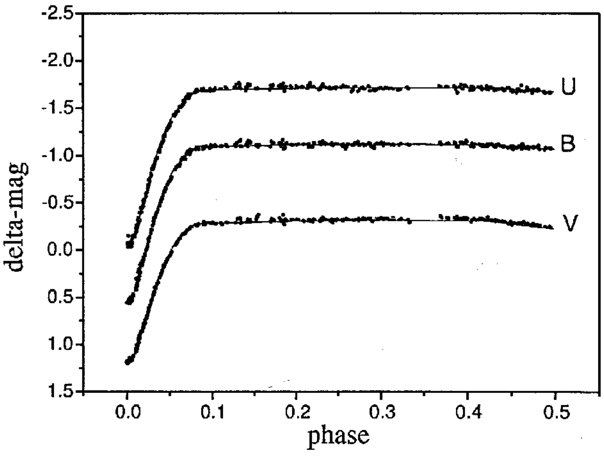

Figure 4. Comparison of theoretical and observed light curves.

Our calculated system parameters are shown in Table 3. It can be seen from this table that our calculated radius of the secondary component is slightly greater than the results of Maxted et al., while the two estimates of the primary radius agree within the error estimates. Our absolute visual magnitudes of the two components are larger than those obtained by these authors. This is mainly due to the difference between the distances assumed for this star. Note that the Hipparcos parallax used by us leads to a distance of 62 pc, which is 11 parsecs less than that used by Maxted et al. We are therefore assuming an intrinsically fainter system.

Table 3. Calculated absolute parameters of the system as compared with the results of Maxted et al. (1994). Radii are the average values. The relatively large error in the radius of the secondary is due to its larger degree of distortion.

Parameter	Present study	Maxted et al.
R_1	1.66±0.09	1.67±0.03
R_2	2.03±0.49	1.94±0.03
M_{v1}	2.39±0.016	1.96±0.06
M_{v2}	5.02±0.18	4.70±0.2
M_{bol1}	1.94±0.03	1.89±0.06
M_{bol2}	4.17±0.26	4.20±0.2

Using the calculated parameters we can display the position of the two components on a HR diagram. Figure 5 shows the absolute visual magnitudes versus temperature including the instability strip. The necessary

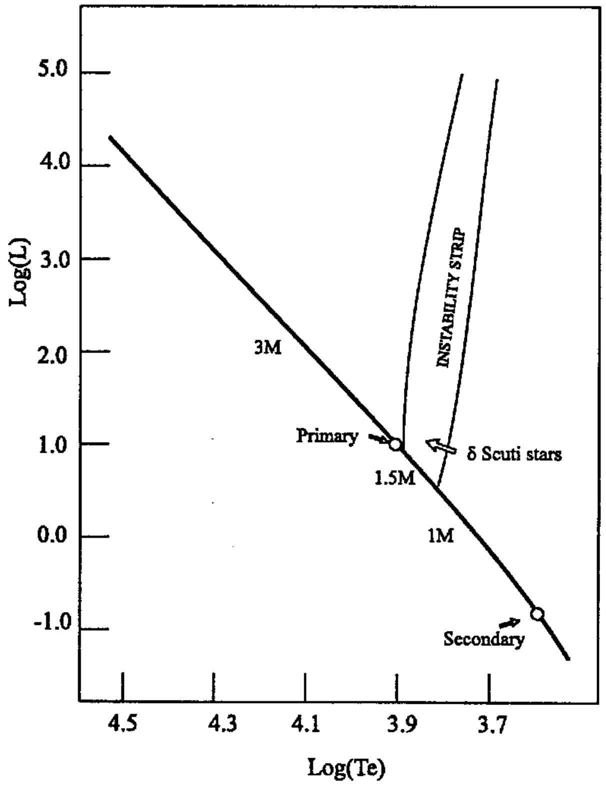

Figure 5. HR diagram of normal stars and the position of the primary component of RZ Cas. M is the mass of the sun.

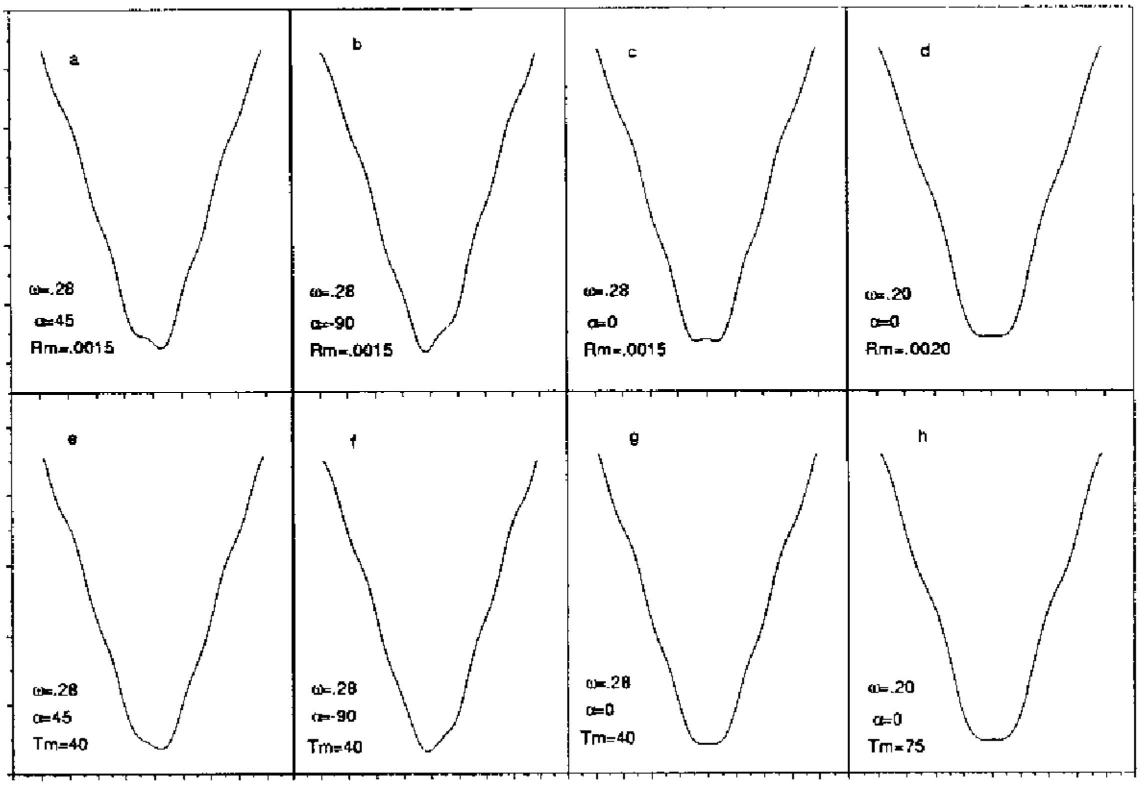

Figure 6. Different shapes of primary minimum based on the simple model explained in the paper. In (a) to (d) we have let the radius of the primary vary sinusoidally, while its temperature is kept constant. In (e) to (h) the radius is taken to be constant, while the temperature is assumed to vary sinusoidally. α is the phase shift of the pulsation with respect to the orbital zero phase. In these figures, ω is the angular frequency, and R_m and T_m are the amplitudes of the radius and temperature oscillations, respectively.

data for compiling Figure 5 were obtained from ref. 15. It is impossible to mark the exact edges of the strip by sharp lines because these limits are different according to different calculations. Furthermore, we know that the δ-Scuti stars are the least known systems among the pulsating stars. It can be seen that the primary component of RZ Cas is located at the extreme blue edge of the instability strip. For stars in this region oscillations are carried out in the outer layers and only the fundamental and the first overtone modes can be excited.

The discovery of the hot component pulsations made this system more favorite and interesting [10]. For a full study on the pulsations, one must apply the standard procedure of Baade and Wesselink, which needs simultaneous use of light and velocity curves. However, we have examined various shapes of the primary minimum via a simple model. In this model, the stars are assumed to have circular disks with uniform surface brightness, and the proximity effects between the two components are ignored. The primary component is considered to be oscillating radially. Light variations due to the eclipses and oscillations are then computed with a $\pi/2$ phase difference assumed for the radius and temperature variations. Typical primary minimum light curves are shown in Figure 6. It can be seen that the pulsations can lead to various shapes of the primary minimum with the bumps appearing at different phases. Flat minima are special cases in which the bump occurs at zero phase.

Olson presented a crude interpretation of the light fluctuations in terms of the eclipses of the dark gas stream and a bright spot caused by the stream hitting the surface of the hot component [16]. In our opinion, the main cause for the unusual shapes of the primary minima is due to the effect of pulsations. It is interesting to note that when our continuous photometry data (Figure 3) are compared with the non-oscillating model of the system, an oscillatory residual with almost the same period as reported by Narasuwa et al. (1997) is detected.

An important question still remains: is there any relationship between the mass transfer and the amplitude of pulsations? We know that the pulsations of the hot component are not always going on with the same amplitude.

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