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RV Aps: A UNIQUE ECLIPSING BINARY FOR GRAVITY-DARKENING STUDIES

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In the process of our work aimed at improving astrophysical information for GCVS stars in southern constellations (cf. Pastukhova et al., 2004; Antipin et al., 2005), we found an interesting case of the eclipsing star RV Aps.

The eclipsing binary RV Aps (HV 5079) was discovered by Swope (1931) who had published the variability range between $10\overset{\mathrm{m}}{.}6$ and $15\overset{\mathrm{m}}{.}2$ pg and the light elements Min $= 2425360.4 + 34\overset{\mathrm{d}}{.}074 \times E$. To our knowledge, no photometric studies of the star have been published since, probably because of no finding chart available. Stock & Wroblewski (1971) estimated the variable's spectral type as AF. This information refers to the correct star, as confirmed by a good coincidence of the coordinates published by Stock and Wroblewski with those we now find for the confirmed RV Aps ($14^{\mathrm{h}}24^{\mathrm{m}}17\overset{\mathrm{s}}{.}0$, $-73^\circ17'27''$, J2000.0; GSC 9269.00545). Our confirmation is based on the ASAS-3 data (Pojmanski, 2002): though the star is not listed in the ASAS-3 catalog of variable stars, about 300 V-band observations can be retrieved from the ASAS-3 photometric catalog. These data show the star to be an Algol eclipsing variable with the light elements (derived by us) Min I = HJD $2453574.517(18) + 34\overset{\mathrm{d}}{.}07502(06) \times E$, $12\overset{\mathrm{m}}{.}1$–$14\overset{\mathrm{m}}{.}0$: V, $D = 0\overset{\mathrm{P}}{.}08$. The light curve is shown in Fig. 1, it demonstrates a noticeable wave outside eclipses. Our analysis of the outside-eclipse observations reveals no other periods except the orbital one.

Table 1 presents the results of our preliminary analysis of the system's light curve using the iteration method described in Khaliullin & Khaliullina (2006). The method is based on the "sphere-ellipsoid" model, quite applicable to the star. We use the following notation in the table and in the text: i is the orbital inclination; $r_{1,2} = R_{1,2}/A$, $R_{1,2}$ being the components' radii and A, the radius of the relative orbit; $\mathrm{Sp}_{1,2}$, their spectral types; $M_{1,2}$, masses; $T_{1,2}$, effective temperatures; $u_{1,2}$, limb-darkening coefficients; $\mathrm{BC}_{1,2}$, bolometric corrections; $L_{1,2}$, relative luminosities; $E_{1,2}$, luminous efficiencies; $Y_{1,2}$, the gravity-darkening coefficients respectively for the primary and secondary; $a_{1,2}$ and $b_{1,2}$, the major and minor axes of the components' apparent disks in quadratures (phase $0\overset{\mathrm{P}}{.}25$). When searching for the optimal parameters, only $b_{1,2}$ were considered independent values, and $a_{1,2}$ were computed at each step of the iteration process on the base of $b_{1,2}$ using known analytic relations resulting from computations of equilibrium shapes of binaries' components (Chandrasekhar, 1933). It is the values of $b_{1,2}$ that are given in Table 1 as $r_{1,2}$. At all the iteration stages, the secondary was assumed to fill its critical Roche lobe.

The optimal spectral types of the components, $\mathrm{Sp}_{1,2}$, and the corresponding absolute parameters were found in the iterations using the following observational restrictions. First, we took into account the spectral type A–F from Stock & Wroblewski (1971). Second, we know the outside-eclipse magnitude, $V = 12\overset{\mathrm{m}}{.}12$, from the ASAS-3 light curve, and the 2MASS PSC infrared magnitudes: $J = 10\overset{\mathrm{m}}{.}35$, $H = 9\overset{\mathrm{m}}{.}70$, $K_S = 9\overset{\mathrm{m}}{.}50$. The main contribution to the IR range comes from the secondary, and these magnitudes, after taking into account the interstellar reddening and subtracting the small contribution from the primary in the iteration process, restrict Sp_2 rather seriously. (Our estimate of the interstellar extinction, from the $V - K_S$ and $J - K_S$ color indices, is $A_V \approx 0\overset{\mathrm{m}}{.}6$, in no contradiction to that expected from the maps in Burstein & Heiles, 1982.) Our computer code makes use of the empirical relations between stellar spectral types and absolute parameters from Popper (1980) and Straizys (1982).

Table 1. Parameters of the components

Parameter	Primary	Secondary
Sp	A2V	K4III
M	$2.20\,M_\odot$ (fixed)	$0.26\,M_\odot$
R	$2.72\,R_\odot$	$13.1\,R_\odot$
T	8 750 K	3 900 K
BC	$-0\overset{\mathrm{m}}{.}08$	$-0\overset{\mathrm{m}}{.}90$
r	0.0455	0.219
L	0.7 ± 0.02	0.3 ± 0.02
u	0.48 (fixed)	0.90 (fixed)
Y	0.79 (fixed)	0.88 ± 0.012
β	0.25 (fixed)	0.076 ± 0.011
i	$83\overset{\circ}{.}8$	
A	$59.7\,R_\odot$	

The physical and geometrical characteristics of RV Aps presented in Table 1 show that the system is unique for determination of the secondary's gravity-darkening coefficient, Y_2. To compute this coefficient in the first approximation, we write the system's brightness outside eclipses (in intensities) as (Kopal, 1950, 1959):

$$l = A_0 + A_1 cos\theta + A_2 \cos^2\theta, \tag{1}$$

where θ is the phase angle. By least squares, we derive the coefficients $A_0 = 1.054(5)$, $A_1 = -0.011(5)$, $A_2 = -0.107(10)$. The unity here is the brightness of a star with $V_0 = 12\overset{\mathrm{m}}{.}12$. The A_2 coefficient in (1) is known to be related to reflection and photometric ellipticity effects:

$$A_2 = (0.2(G_1 + G_2) - 0.5L_1N_1\varepsilon_1^2 - 0.5L_2N_2\varepsilon_2^2)\sin^2 i, \tag{2}$$

where

$$G_i = L_{3-i}r_i^2 \times E_i/E_{3-i},\ \varepsilon_i^2 = (a_i^2 - b_i^2)/a_i^2,\ N_i = \frac{15 + u_i}{15 - 5u_i}(1 + Y_i). \tag{3}$$

Here Y is the gravitational limb darkening coefficient for the i-th component, determined from the expression (Kopal, 1968):

$$J = J_0\left(1 + Y\left(\frac{g - g_0}{g_0}\right)\right),$$

J being the surface brightness in the direction of the normal; g, gravity; and J_0 and g_0, the corresponding values on the surface of an undeformed star. The first term in the right side of (2) is the combined reflection effect for the components; the second one is the primary's contribution to the photometric ellipticity; and the third one is the secondary's

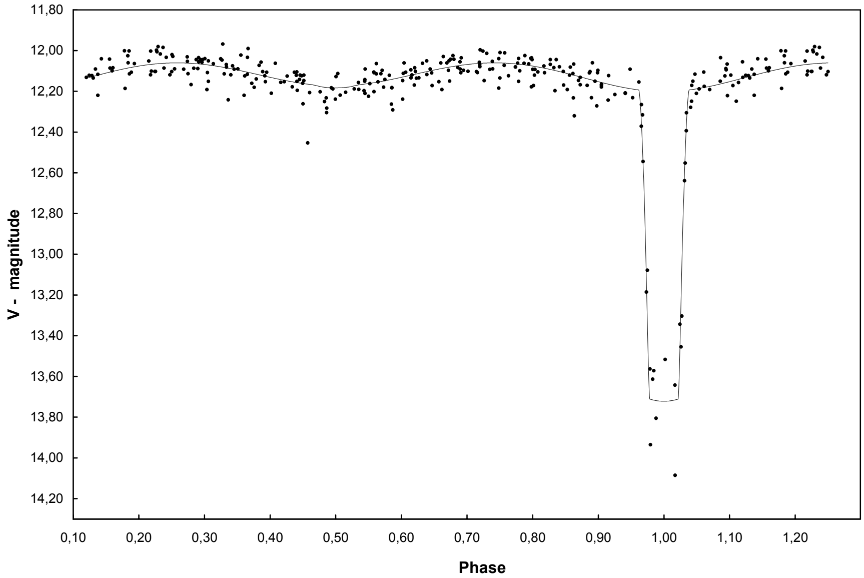

Figure 1. The ASAS-3 V-band light curve of RV Aps. The solid curve is the model one

contribution. The luminous efficiencies in (3) can be estimated from $E_i = 10^{0.4\mathrm{BC}_\lambda(T_i)}$ (Khaliullin & Khaliullina, 2006). Substituting the parameters from Table 1 into (2) and (3) and using the theoretical value, $Y_1 = 0.79$, computed using eq. (5) below, we find $Y_2 = 0.88 \pm 0.12$. Note that the third term in (2), due solely to photometric ellipticity of the secondary, contributes 97% (!) of A_2, this is one of the unique features of the studied system. If we now describe the secondary's spectral energy distribution, J_λ, with the Planck B_λ function, then, according to Kopal (1968),

$$Y = \beta \frac{c_2}{\lambda T(1 - e^{-c_2/\lambda T})}, \tag{4}$$

where $c_2 = 1.439\,\mathrm{cm} \times \mathrm{K}$, λ (for the V band) is 0.55×10^{-4} cm, and β is the exponent in the known gravity-darkening law, $T = g^\beta$, T and g being respectively the local effective temperature and gravity on the undeformed star's surface. Substituting the derived Y_2 into (4), we find: $\beta(B_\lambda) = 0.131$. However, J_λ can differ from B_λ significantly, and it is preferable to use the relation (Khaliullin & Khaliullina, 2006):

$$Y = 4\beta \left(1 + \frac{d(\mathrm{BC}_\lambda)}{10 \times d(\log T)} \,|_{T=T_0}\right), \tag{5}$$

where T_0 is the undeformed-surface temperature, and the relation $\mathrm{BC}_\lambda(T_e)$ and its derivatives (for the corresponding spectral band of observations) can be found using the compilations of empirical data from Popper (1980) and Straizys (1982). The resulting value, $\beta_2 = 0.076 \pm 0.011$, is close to that expected from the theory for stars with convective envelopes, $\beta_2^{\mathrm{th}} = 0.08$ (Lucy, 1967).

Thus, despite the information currently available for RV Aps being rather limited, the system's unique characteristics permitted us to determine β for its secondary quite accurately. According to Kitamura & Nakamura (1983), the relations (1)–(3) we have used can result in errors up to 10% in β. However, at this first-approximation stage, such uncertainties are quite acceptable. To verify and improve our results, spectroscopy and accurate multicolor light curves, especially near Min I, are needed for the system.

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