Photometric and Spectroscopic Study of PU Pup

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Abstract

We present the analysis of photometric and spectroscopic observations of the Southern eclipsing binary star PU Pup. We solved the HIPPARCOS light curve of PU Pup and proposed a relatively close binary star model with a rather low mass ratio and low inclination to give the ellipsoidal form of its light variation. Spectroscopic observations of the system were made at the Mt. John University Observatory in 2008 and 2014. Since the light contribution of the secondary component was only 1% of the light contribution of the primary component in the optical wavelengths, the radial velocities of the primary component could be measured. A single-lined spectroscopic orbital solution of PU Pup then was obtained.

Keywords: Close binary systems, Early type stars, Observational techniques, Photometry, Spectroscopy

1. Introduction

The system PU Pup (=HR2944, HD61429, HIP 31373), also known as m Pup, is a relatively bright (B = 4.59, V = 4.70) early type giant (B8III, Garrison & Gray, 1994) located at a distance of about 190 pc at galactic co-ordinates λ~ 240.7, $\beta \sim -1.8$. Garrison and Gray (1994) noted its strong rotation, though without any significant effect apparent in its 4-colour photometric indices. While Jaschek, et al. (1969) have given the spectral type of PU Pup to be B9V from its UBV colour indices, Stock et al. (2002) determined the type to be B8IV from the system's $(B-V)_0$.

The photometric variability was announced by Stift (1979) during a programme monitoring other stars in the sky region nearby. Stift noticed that the variable had been reported as a component of the close visual double ADS 6246, the companion being of similar spectral type and magnitude, with a separation of about 0.1 arcsec or about 20 AU perpendicular to the line of sight. A corresponding period of the order of 30 y or greater for this wide pair might then be expected. Stift surmised that the close binary might be of the W UMa or β Lyr types, but the relatively early type and long period would make PU Pup a very atypical representative of the first of these types. The star appears to have received relatively little individual attention, but its variability was confirmed by the HIPPARCOS satellite (ESA, 1997).

2. Photometric analysis

We examined the HIPPARCOS (ESA, 1997) photometry of PU Pup. A handful of wild points were cropped from the data, leaving the reasonably well-defined EB type light curve shown in Fig. 1. There does not appear to have been any detailed previous light curve analysis, so we took our starting parameters influenced by the spectrographic information (next Section) as well as the general shape of the curve. Thus, there is no third component identified spectroscopically, but the light variation amplitude is low, around 8%. The indications then point to a low inclination value. Only one spectrum is seen, and the amplitude of its variation also relatively low, though the rotational velocity high. The general information is therefore strongly suggestive of a rather low mass ratio relatively close binary, seen at low inclination producing the so-called 'ellipsoidal' form of variability and with a relatively massive, early type primary.

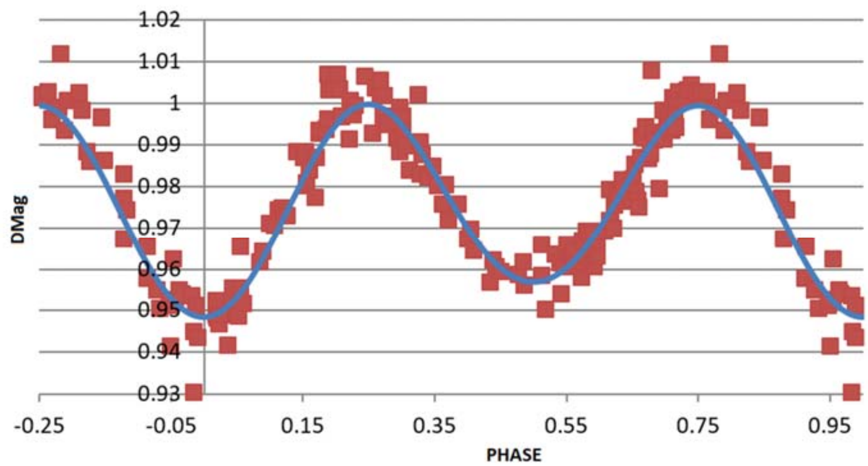

Figure 1. HIPPARCOS photometry of PU Pup and a model fitting. The horizontal axis gives orbital phase values, while the vertical axis shows corresponding relative flux values

Table 1: Parameters of Radau model fitting to PU Pup system

L_1	0.98	0.01
L_2	0.02	0.01
$\Delta\phi_0$	0.0006	0.0049
r_1	0.54	0.02
r_2	0.12	0.01
i (deg)	36	0.5
u*1*	0.30	-
u_2	0.60	-
e	0.0	-
ω	0.0	-
q	0.3	-
τ_1	0.53	-
τ_2	1.10	-
E_1	0.20	-

Starting from some trial parameter values based on this approximate view of the system the best-fit light curve modelling program WinFitter (Walker et al. 2017, Rhodes 2018) was applied to the HIPPARCOS data and the results given in Table 1 with a corresponding illustration in Fig. 2.

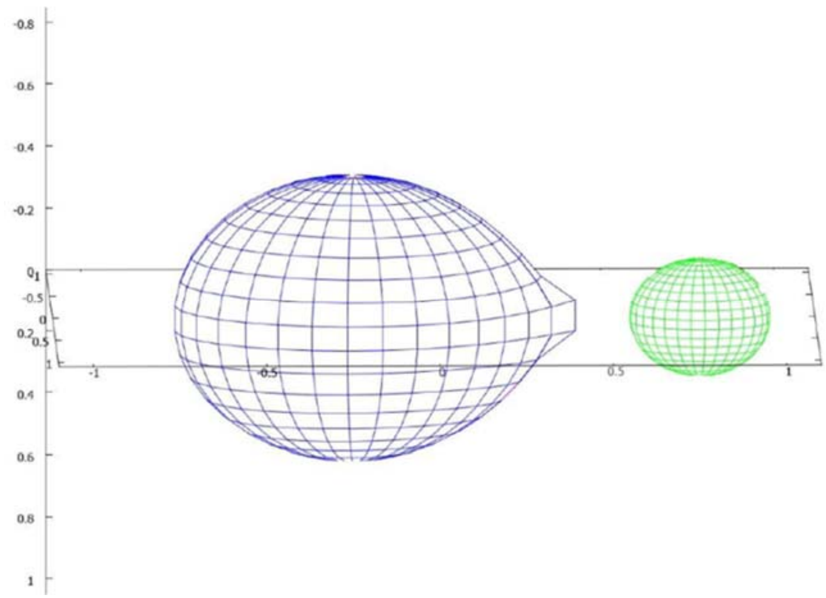

Figure 2. Gnuplot rendering of the model appearance of PU Pup

3. Spectroscopy

3.1 Spectroscopic observations and their reduction

High-resolution spectra of PU Pup were taken at the Mt. John University Observatory (MJUO, New Zealand) in 2008 and 2014. HERCULES (High Efficiency and Resolution Canterbury University Large Echelle Spectrograph) and a 4k x 4k Spectral Instruments 600 series (SI600s) CCD camera on the 1-m McLellan telescope were used. The data were reduced using the HRSP (Hercules Reduction Software Package, version 5.4; Skuljan 2012).

3.2 Radial velocities and orbital solution

The IRAF routine SPLOT was used to measure radial velocities (RVs) of PU Pup. All observed spectra of PU Pup were examined. The spectral lines of the secondary component could not be detected as its light contribution was only 2% of the total light of the binary in the HIPPARCOS light curve modeling of PU Pup. The absorption lines of neutral hydrogen, He I, Fe II and Si II in the echelle's spectral orders between 85 and 127 were then fitted to derive the RVs of primary component. The representative radial velocities are given in Table 2. The listed dates and velocities were corrected to heliocentric values as in Budding & Butland (2011), with the aid of the HRSP and IRAF program suites.

Table 2. Radial velocity data for the primary component of PU Pup in 2008 and 2014

HJD (2400000+)	RV1 (km/s)	Sigma (km/s)
54802.9063	-2.76	5.90
54803.0954	-0.91	8.89
54803.1365	3.58	3.76
54803.9003	54.87	10.00
54803.9004	55.04	8.75
54803.9118	52.18	10.00
54803.9124	54.34	7.63
54803.9553	54.83	10.00

54803.9554	57.07	7.22
54804.9119	24.79	3.02
54804.9812	18.31	4.46
54805.0601	11.62	5.24
54805.0946	9.83	3.92
54805.1247	7.98	3.14
54805.1478	6.99	4.08
54806.9436	57.64	5.22
54806.9594	57.81	5.73
54807.0531	50.56	7.83
54807.0595	55.29	4.23
54807.1052	50.59	7.07
54807.1101	51.37	7.49
54807.1157	53.48	5.82
56667.0814	6.22	2.07
56668.0849	40.75	5.02
56668.8805	53.56	4.07
56668.9080	54.99	5.63
56668.9366	53.55	5.32
56669.8787	0.37	1.96
56669.8871	-0.02	3.36
56669.9238	0.77	3.91
56670.0036	0.69	4.51
56670.8790	52.38	5.56
56670.9174	56.68	7.23
56671.0332	59.59	7.04
56671.8804	25.44	1.93
56674.8775	1.33	4.19
56675.9159	44.79	2.83
56675.9567	47.08	5.49

The RVs from Table 2 were fitted with a binary system optimized model using the program SPEL (Horn et al. 1994). The RVs were weighted according to their measurement errors ($W_i=1/\sigma_i^2$). During the iterations, the orbital period (P_{orb}) - as taken from the Hipparcos Catalogue (ESA, 1997) - was kept constant. The radial velocity semi-amplitude (K), gamma velocity (V_γ) and epoch of maximum RV curve (T_{max}) were chosen as the free/adjusted parameters.

Circular and elliptical orbit models were applied to all RVs of PU Pup. Lucy & Sweeney (1971) suggest a 5% probability threshold for the eccentricity to be significant. Using the Lucy & Sweeney (1971) test, the significance of the eccentricity was found p=0.41 for PU Pup. Therefore, circular orbit was adopted for the system. The final spectroscopic orbital parameters are given in Table 3. The best theoretical fit to the radial velocity data is also shown in Fig. 3.

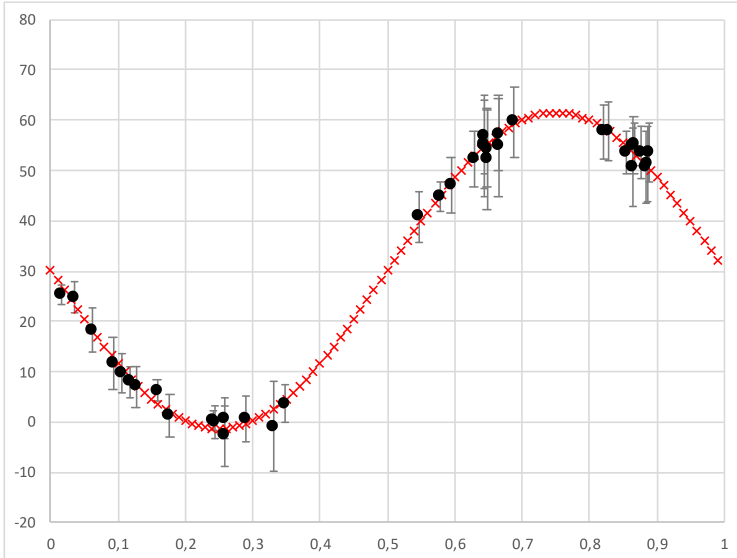

Figure 3. Best Keplerian orbital fit to the RV measurements of PU Pup. Horizontal axis gives orbital phases, vertical axis gives radial velocities

Table 3. SB1 orbital solution of PU Pup

Parameter	Value
P_{orb} (d)	2.582320 (fixed)
T_0 (HJD)	48501.3785 (±0.0079)
K_1 (km s^{-1})	31.43 (±0.60)
V_γ (km s^{-1})	30.08 (±0.42)
$f(M)$ (M$_\odot$)	0.0083 (±0.0001)
$a_1$sin$i$ (R$_\odot$)	1.60 (±0.03)

4. Discussion

From MJUO spectrographs of PU Pup, the equivalent width (ew) of Hβ was measured to be typically ~7.5, that of He I 6678 ~0.12. While the He I ew points to a spectral type of about B8, the corresponding Hβ would be higher for a normal dwarf at B8. The situation is resolved by the giant luminosity classification of Garrison & Gray (1994).

Utilizing the mass function formula (Torres, 2010)

$$f(M)= C(1-e^2)^{3/2} K_1^3 P, \qquad (1)$$

where the constant C = $\mathbf{1.03615{\times}10^{-7}}$ when K_1 is in km/s and P is in days, gives $f(M)$ = 0.0083 M$_\odot$. This can be written as $q^3/(1+q)^2 = f(M)/ M_1 \sin^3 i$. With the photometric value of sin i as 0.588 and a plausible estimate for M_1 as 4 M$_\odot$, we can derive q = 0.26, which is self-consistent with the value given in Table 1. This leads to the secondary being a G0 type dwarf with V-magnitude ~1% that of the primary and therefore not detectable spectroscopically. The separation of the components, using Kepler's 3rd law, turns out to be about 13.6 R$_\odot$, so the rotational velocity of the primary, if synchronized, would be ~144 km/s. With the derived inclination, a measured rotation speed of about 84 km/s would then be expected.

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