A&A 545, A121 (2012)
DOI: 10.1051/0004-6361/201219679

Astronomy & Astrophysics

o Puppis: another Be+sdO binary?*,**,*** (Research Note)

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Received 25 May 2012 / Accepted 10 August 2012

ABSTRACT

The spectrum of the Be star *o* Pup is shown to vary periodically with a period of 28.9 days. A radial-velocity variable He I 6678 Å emission component suggests that the star is the same type as ϕ Per, 59 Cyg, and FY CMa, i.e. binaries consisting of a Be star and a hot companion that illuminates the Be star disk (also called ϕ Per-type binaries or Be+sdO binaries). The range of radial-velocity variations of the stronger emission component in the helium line observed in *o* Pup is about 270 km s^{-1}, a value in good agreement with the range derived for ϕ Per-type binaries. The radial velocity curves defined by the prominent emission peak in He I 6678 Å line and Hα + Paschen emission move in anti-phase. We suggest that *o* Pup is generically similar to ϕ Per-type systems and may represent the fourth case of a Be star with a hot subdwarf companion.

Key words. binaries: spectroscopic – stars: emission-line, Be – stars: individual: *o* Puppis – binaries: close

1. Introduction

The Be star *o* Puppis (HD 63462, HR 3034, MWC 186, HIP 38070) is a bright Be star (V = 4$^{\rm m}\!\!.$50, B1IV:nne). This is a relatively little studied bright Be star. Merrill (1913) reports that Hα was fuzzy bright in November and December 1912. The target *o* Pup is listed in the first edition of the MWC catalogue – Merrill & Burwell (1913), see also references therein. The published profiles of Hα confirm the variability of peak intensity $I_{\rm c}$ in the range from 2.03 to 2.31 in the period 1978–2008. Altogether, about a dozen of Hα profiles can be found in the literature covering this period of time (see Dachs et al. 1981; Hanuschik 1986, 1987; Dachs et al. 1992; Slettebak et al. 1992; Hanuschik et al. 1996; Silaj et al. 2010, for details). Hα profiles show V/R variability. By V/R we mean the ratio of the intensities of violet $I_v = V$ and $I_r = R$ emission peaks of double peaked emission lines measured in units of continuum level. Two quasi-periods of V/R variations in *o* Pup – 2.5 and 8 years – have been suggested by various authors (Okazaki 1997, and references therein). Only three SWP high-resolution *IUE* spectra of *o* Pup are available. The C IV and N V resonance lines show similar variations to those in 59 Cyg (Doazan et al. 1985) or FY CMa (Peters et al. 2008). Buscombe & Kennedy (1965) list *o* Pup as a star with variable radial velocity. Baade (1992) searched for lines of late-type companions in the infrared spectra of 35 Be stars, including *o* Pup. The spectroscopic survey did not identify any new candidate for a Be star with Roche-lobe overflowing cool companion. Ground-based photometry of *o* Pup only shows marginal variations (Feinstein 1968; Stift 1979). Much more numerous Hipparcos data show photometric variations in the range of 0$^{\rm m}\!\!.$02 to 0$^{\rm m}\!\!.$03.

In November 2011, *o* Pup was put on the observing list of the Ondřejov Perek 2 m Telescope. A changing pattern in the helium line He I 6678 Å was very visible at first inspection of the data: an emission component swaying from the red side of the profile to the blue one and back. We continued the observations till mid-April 2012, which is the visibility limit of *o* Pup in Ondřejov. In this study we present preliminary results of the analysis of the emission Hα, He I 6678 Å, and Paschen profiles in the spectra of *o* Pup.

2. Spectroscopic observations and their reductions

Most of the spectra of *o* Pup used in this study were obtained with Ondřejov single-order spectrograph + SITe 2000 × 800 chip in the focus of a 702-mm camera (R = 12 000, ranges 6250–6750 and 8392–8900 Å). The spectrograph was attached to the Coudé focus of the 2 m telescope. In all cases, calibration arc frames were secured before and after each stellar frame. During each night, a series of flat field and bias exposures were obtained. The stellar and calibration spectra (Th-Ar and tungsten lamps) were reduced using IRAF. All together, 13 red and 5 infrared spectra were secured. In addition, we downloaded five spectra of *o* Pup from the BeSS database. Four of them were obtained with LhiresIII spectrograph (R = 17 000) attached to a C11 telescope located at Biot-Les Quatre Chemins near Antibes, France and at at the Castanet Tolosan Observatory near Toulouse, France, and one spectrum with the echelle spectrograph eShel (R = 10 000) attached to a C11 telescope located at the Castanet Tolosan Observatory. The details describing the

* Based partly on observations collected with the Perek 2-m Telescope of the Ondřejov Observatory.
** This work has made use of the BeSS database, operated at LESIA, Observatoire de Meudon, France.
*** The Ondrejov spectra are only available at the CDS via anonymous ftp to cdsarc.u-strasbg.fr (130.79.128.5) or via http://cdsarc.u-strasbg.fr/viz-bin/qcat?J/A+A/545/A121

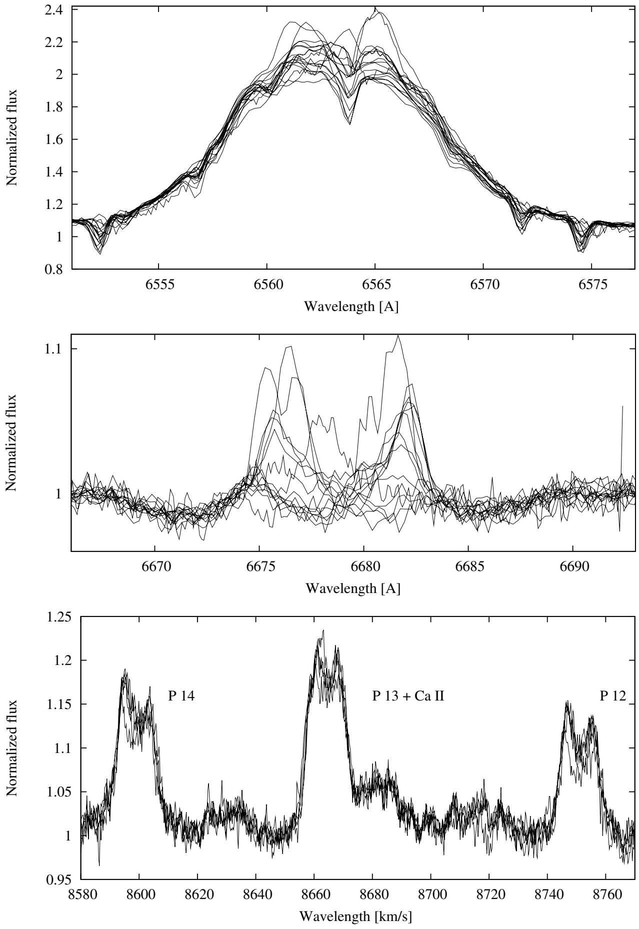

Fig. 1. Plots of available spectra of *o* Pup: Hα – *top*, He I 6678 Å – *middle*, and Paschen lines – *bottom*.

reduction of the last five spectra can be found in the BeSS database. In all cases, the heliocentric corrections were applied. The spectra were rectified to a unit continuum and measured for radial velocity (RV) with the help of the SPEFO code written by Dr. J. Horn and more recently improved by Dr. P. Škoda and Mr. J. Krpata (see Horn et al. 1996; Škoda 1996). The zero point of RV scale was corrected through the use of reliable telluric lines. The stellar RVs were measured interactively by comparing the direct and reverse images in the profile seen on a monitor. This way a position in the middle of a profile was obtained. The SPEFO code transforms the obtained position to the wavelength using the dispersion curve determined from the measurement of calibration spectra. The wavelengths are then transformed to RVs using the particular laboratory wavelength. As we did for some other Be stars, we focussed on the steep wings of Hα, Paschen emission, and the main emission component of the He I 6678 Å line. This method works very well for objects with symmetrical profiles (see e.g. Božić et al. 1996; Koubský et al. 2010; or Nemravová et al. 2012). The basic reasons that the measurements of strong Hα emission should give the most realistic estimate of the radial velocity of a Be primary can be found in Ruždjak et al. (2009). The errors of the method depend on the signal-to-noise ratio (S/N) of the particular spectrum and on the shape of the profile. In the case of asymmetrical profiles, we set the coincidence of the two images at the 0.5 level of the maximum intensity. The profiles used for RV measurements are shown in Fig. 1. Table 1 lists the heliocentric Julian dates and the

Table 1. Radial velocity measurements.

Date (HJD-2 400 000)	Hα km s^{-1}	P12+14 km s^{-1}	He I 6678 Å km s^{-1}
46124.7			150:
54110.5558	37.5 ± 6.3		
54422.7003	30.3 ± 6.0		
54879.4724	15.3 ± 8.0		
55229.4946	21.9 ± 7.5		−4.3 ± 5.0
55644.3648	24.8 ± 5.0		132.2 ± 9.1
55905.6117	35.3 ± 9.5		15.1 ± 6.2
55957.4222	9.6 ± 7.5		140.3 ± 5.5
55957.4342		0.8 ± 5.4	
55996.2874	16.9 ± 7.2		−94.8 ± 6.3
55996.2950		34.0 ± 7.1	
56002.3044		21.8 ± 6.0	
56002.3142	20.0 ± 5.0		−103.1 ± 4.2
56003.2906		14.7 ± 8.4	
56003.3062	15.3 ± 7.5		−96.7 ± 8.5
56006.3020		11.2 ± 5.2	
56006.3173	7.5 ± 5.0		148.6 ± 7.0
56009.2493	0.8 ± 4.0		175.8 ± 5.3
56011.2812	−4.1 ± 6.0		178.0 ± 5.6
56012.2772	4.9 ± 6.0		176.7 ± 5.6
56013.2897	5.1 ± 6.8		178.6 ± 7.0
56015.2577	12.3 ± 7.0		132.2 ± 8.1
56022.2694	23.9 ± 5.0		−75.1 ± 9.2
56030.2734	29.9 ± 7.5		−99.4 ± 7.0

Table 2. Orbital elements for *o* Pup as an SB2.

P (d)	28.903 ± 0.004
$T_{\rm maxRV}$	2 456 012.93 ± 0.04
e	0 (fixed)
K_1 (km s^{-1})	10.3 ± 9.6
K_2 (km s^{-1})	159.7 ± 11.7
γ (km s^{-1})	25.0 ± 5.1
Number of spectra	comp. 1: 23; comp. 2: 16
rms (km s^{-1})	29.436

Notes. Comp. 1 – RV of Hα and Paschen emission lines, comp. 2 – RV of prominent emission peak in the He I 6678 Å line.

radial velocities for the emission of Hα line, the mean of Paschen P14 + P12 emission, and the main emission component of the helium line He I 6678 Å. The errors were determined from the repeated measurements made by members of the team. The radial velocity for the emission component in the He I 6678 Å line on JD 2 446 124.7 was read from Fig. 3 in Hanuschik (1987). The spectrum was secured with Coudé Echelle Spectrograph (CES) attached to the ESO 3.6-m Telescope at La Silla, Chile.

3. Data analysis

The inspection of Table 1 clearly shows that the radial velocity of the main emission component in the helium line He I 6678 Å varies with time – see also the profiles in the middle panel in Fig. 1. First we tried to estimate the possible periodicity of RVs with Stellingwerf's (1978) phase dispersion minimization (PDM) method in the range of frequencies 0.01–0.2 cd^{-1}. Owing to the poor observing window – most of the data were obtained

Table 3. Comparison of *o* Pup with ϕ Per-type binaries.

Star	Sp. type	V mag	$v \sin i$ km s^{-1}	Orbital period d	K_1 km s^{-1}	K_2 km s^{-1}	Eccentricity	Range km s^{-1}	Reference
ϕ Per	B2pe	4.09	450	126.673	9.97	81.3		± 120	Gies et al. (1993, 1998)
FY CMa	B0.5 IVe:	5.56	340	37.253	17.4 (14.4)	128.2		± 185:	Peters et al. (2008)
59 Cyg	B1-1.5Ve	4.74	450	28.192	24.77	120.1	0.11	± 200	Maintz et al. (2005)
o Pup	B1 IVne	4.50	435	28.9	10:			± 135	Chauville et al. (2001) (rot. vel.)

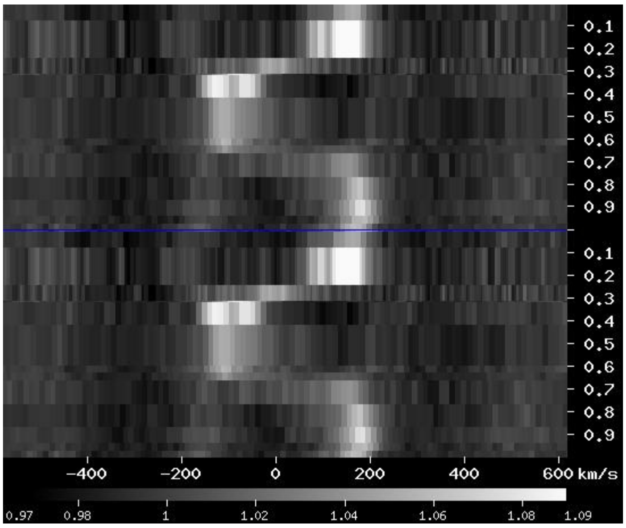

Fig. 2. Trailed spectra of *o* Pup arranged according to the phase of the period 28.903^{d} in a grey-scale representation. The spectral image for the orbital cycle is reproduced twice to improve the sense of phase continuity.

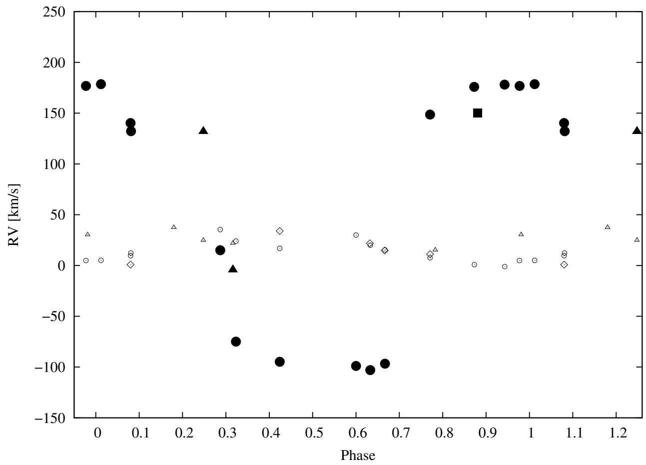

Fig. 3. Radial velocity of the prominent emission peak in the profile of He I 6678 Å folded with the 28.9-day period represented by solid symbols: dots Ondřejov, triangles BeSS, square Hanuschik (1987). The open symbols indicate the emission velocities of Hα and Paschen lines: circles Hα Ondřejov, diamonds Paschen Ondřejov, triangles BeSS Hα.

within the 73-d interval – the minimum was rather shallow. The PDM search indicated the best period $P = 28.271$ days with $\theta = 0.058$. The period was found to be significant ($p < 0.01$) using the test described by Linnell Nemec & Nemec (1985). We used the value of 28.3 d as an input parameter to the code SPEL (written by Dr. J. Horn and never published) designed for orbital solutions of spectroscopic binaries to derive RV curves based both on Hα and Paschen emission lines (component 1) and maximum helium emission peak (component 2).

We allowed for circular orbit and converged period, time of maximum radial-velocity, the amplitudes, and the value of γ velocity. We found a period $P = 28.903^{d} \pm 0.004^{d}$. The period was then used in all phase diagrams presented in this study. The phase 0.0 corresponds to the time of RV_{max} – JD = 2 456 012.93. Table 2 summarizes the elements of the solution with code SPEL and the errors. The aim of the calculation was not to determine elements of a binary but primarily to check the value of the period using more data in one task than was possible with the PDM search. Figure 2 shows a montage of all He I 6678 Å line profiles as a grey-scale image and Fig. 3 displays velocities from Table 1.

4. Discussion

Our work demonstrates that the spectroscopic variability of *o* Pup is dominated by a period of 28.9^{d}. The phase variation of the principal emission component of He I 6678 Å with this period is presented in Fig. 2, while in Fig. 3 we show RV curves for helium emission component and for Hα and Paschen emissions folded with the same period. It seems that the strength of the helium He I 6678 Å emission feature depends on phase, because the emission component is strongest at velocity extremes, and weaker when at zero velocity. Similar features to those presented in Figs. 2 and 3 were obtained for ϕ Per (Gies et al. 1993, 1998; Štefl et al. 2000; Hummel & Štefl 2001), 59 Cyg (Maintz et al. 2005), and FY CMa (Peters et al. 2008). These authors used the results to imply that a hot subdwarf in local heating of Be star's disk is responsible for the described effects. These systems, called ϕ Per-type binaries, contain a Be star and a hot subdwarf companion in an interesting stage of close binary evolution. The sdO star represents the remains of an intense binary interaction that stripped down the mass donor to a small fraction of its original mass and left the mass gainer spinning rapidly. Both observations and theoretical models show that a rapidly rotating massive star is the source of a Be-star disk. It is still unresolved, however, what fraction of Be population was formed by binary processes (rapid rotation of the gainer caused by mass transfer from the donor) and what fraction was born by rapid rotation.

The systems with hot faint companions are hard to detect, and no reliable estimates are presently available to tell their numbers (see Gies 2000). In Table 3 we give a comparison of basic properties of ϕ Per-type binaries with those of *o* Pup. Very good agreement is found for spectral type, rotational velocity, and range of RV curve for the helium He I 6678 Å emission feature. Though we lack any direct evidence for lines of the hot subdwarf, and also the RV curve for the primary star in *o* Pup is very noisy, we suggest that *o Puppis is a Be+sdO binary, the* *fourth case of a Be star of this type.* New phase-resolved observations of o Puppis covering broader spectral interval are needed, as is a search for other ϕ Per-type binaries (all stars listed in Table 3 are very bright objects!), which would offer us unique opportunity to study the outcome of close binary processes at a critical point of evolutionary sequence.

Acknowledgements. This research was conducted in part from funding by the ESA PECS 98058 contract to the Astronomical Institute of the Academy of Sciences of the Czech Republic. Š.D. aknowledges financial support from MUNI/A/0968/2009 grant. We would like to express gratitude to Drs. P. Harmanec and M. Oksala, whose suggestions led to several important improvements in the paper. The authors thank the anonymous referee, whose comments helped to strenghten the arguments that o Pup belongs to the group of ϕ Per-type binaries. Some spectra used in this study were downloaded from the BeSS database. Particularly, we appreciate the effort of C. Buil and S. Ubaud. We thank Drs. P. Harmanec, D. Korčáková, M. Oksala, M. Wolf, and P. Zasche, who at our request obtained some of the Ondřejov spectra used in this study.

References

Baade, D. 1992, in Evolutionary Processes in Interacting Binary Stars, eds. Y. Kondo, R. F. Sistero, & R. S. Polidan, IAU Symp., 151, 147
Božić, H., Harmanec, P., Horn, J., et al. 1996, A&A, 304, 235
Buscombe, W., & Kennedy, P. M. 1965 MNRAS, 130, 281
Cannon, A. J., & Pickering, E. C. 1901, Annals of Harvard College Observatory, 28, 129
Chauville, J., Zorec, J., Ballereau, D., et al. 2001, A&A, 378, 80
Dachs, J., Eichendorf, W., Schleicher, H., et al. 1981, A&A, 43, 427
Dachs, J., Hanuschik, R. W., Kaiser, D., et al. 1986, A&A, 63, 87
Dachs, J., Hummel, W., & Hanuschik, R. W. 1992, A&AS, 95, 437
Doazan, V., Grady, C. A., Snow, T. P., et al. 1985, A&A, 152, 182
Feinstein, A. 1968, ZAp, 68, 29
Gies, D. R. 2000, in The Be Phenomenon in Early-Type Stars, eds. M. A. Smith, H. F. Henrichs, & J. Fabregat, IAU Coll., 175
Gies, D. R., Willis, C. Y., Penny, L. R., & McDavid, D. 1993, PASP, 105, 281
Gies, D. R., Bagnuolo, Jr., W. G., Ferrara, E. C., et al. 1998, ApJ, 493, 440
Hanuschik, R. W. 1986, A&A, 166, 185
Hanuschik, R. W. 1987, A&A, 190, 187
Hanuschik, R. W., Hummel, W., Sutorius, E., et al. 1996, A&AS, 116, 309
Harmanec, P., Božić, H., Percy, J. R., et al. 2002, A&A, 387, 580
Horn, J., Kubát, J., Harmanec, P., et al. 1996, A&A, 309, 521
Hummel, W., & Štefl, S. 2001, A&A, 368, 471
Koubský, P., Hummel, C. A., Harmanec, P., et al. 2010, A&A, 517, A24
Linnell Nemec, A. F., & Nemec, J. M. 1985, AJ, 90, 2317
Maintz, M., Rivinius, T., Stahl, O., et al. 2005, Publ. Astron. Inst. Czechosl. Acad. Sci., 93, 21
Merrill, P. W. 1913, Lick Obs. Bull., 7, 162
Merrill, P. W., & Burwell, C. G. 1933 ApJ, 78, 87
Nemravová, J., Harmanec, P., & Koubský, P., et al. 2012, A&A, 537, A59
Okazaki, A. T. 1997, A&A, 318, 548
Peters, G. J., Gies, D. R., Grundstrom, E. D., & McSwain, M. V. 2008, ApJ, 686, 128
Ruždjak, D., & Božić, H., Harmanec, P., et al. 2009, A&A, 506, 1319
Silaj, J., Jones, C. E., Tycner, C., et al. 2010, ApJS, 187, 228
Slettebak, A., Collins, G. W., II., & Truax, R. 1992, ApJS, 81, 335
Stift, M. J. 1979, Inf. Bull. Var. Stars, 1541
Stellingwerf, R. F. 1978, AJ, 83, 118
Škoda, P. 1996, in Astronomical Data Analysis Software and Systems V, eds. G. H. Jacoby, & J. Barnes, ASP Conf. Ser., 101, 187
Štefl, S., Hummel, W., & Rivinius, T. 2000, A&A, 358, 208