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Wolf–Rayet features observed in the spectrum of the symbiotic nova PU Vulpeculae

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SUMMARY

Observations from 1990 July to 1991 January show a strong Balmer continuum and Balmer emission lines in the spectrum of PU Vul. The presence of Wolf–Rayet features in the spectrum corresponding to those of a star of spectral class WN8 is noted. At the end of 1990 December and the beginning of 1991 January changes in the profiles of the H I lines and an increase of the emissions of He I and nebular lines [Ne III] and [O III] are observed.

1 INTRODUCTION

Discovered as a nova-like object independently by Kuwano & Honda (Kozai 1979a,b) in 1979, PU Vul has been a subject of intensive investigations over a wide spectral range. From the database obtained from the numerous observations (Kenyon 1986a,b; Iijima 1989; Belyakina *et al.* 1989, and references therein), the evolution of the star after the outburst is rather well known. The system consists of a white dwarf and a normal red giant, whose spectral class is given by Kenyon (1986b) as M4.5. Changes in the brightness and the spectrum of the star give reason for many authors to suppose that PU Vul is a symbiotic nova (Belyakina *et al.* 1984; Kenyon 1986a,b).

According to Kenyon & Truran (1983) and Kenyon (1988) two processes – degenerate and non-degenerate flashes on the surface of a white dwarf, cause the outbursts of the symbiotic novae. The comparison of theory with the previous observations of PU Vul shows that its evolution is similar to that of AG Peg, RR Tel and RT Ser, which have undergone degenerate flashes (Kenyon 1988; Viotti 1988).

Before the deep minimum in 1980, and quite a long time after that, when the brightness of PU Vul was maximal, the spectrum looked like the spectrum of an A–F supergiant (Kenyon 1986a,b; Belyakina *et al.* 1989, and references therein). In the second half of 1987 the spectrum of the star changed remarkably and permitted numerous observations of forbidden emission lines (Iijima 1989).

In this paper we discuss the results from our spectral observations, which show that now, in the optical spectrum of PU Vul, emission lines are present similar to those observed in WR stars of spectral class WN8. This fact confirms, once again, that PU Vul is a symbiotic nova whose evolution rather precisely follows the theoretical scenario (Kenyon 1988).

2 OBSERVATIONS

Seven high-resolution spectra of PU Vul (~0.35 Å) were obtained on 1990 July 11, 12, 15 and 17, October 6, December 30 and 1991 January 1, with the coudé-spectrograph of the 2-m telescope of NAO Rozhen. 103aO emulsion sensitized by hydrogen was used to cover the spectral interval 3600–4900 Å. The exposure times of our spectra were in the range 2–4 hr and their signal-to-noise (S/N) ~ 10–15. The plates were digitized using a Joyce–Loebl MDM6 microdensitometer and were processed using the ReWiA software system (Borkowski 1988). The spectra obtained on 1990 July 12 and December 30 were not used for measuring the radial velocities.

One spectrum with low resolution (~2 Å) was obtained on July 17 with emulsion IIaO in the spectral interval 3425–5225 Å with the Canadian Copernicus Spectrograph mounted at the Cassegrain focus of the 90-cm telescope of the Torun Observatory. It was also processed with the ReWiA software system and reduced to the Hayes & Latham (1975) flux scale using standard methods with an accuracy of about 5 per cent.

Table 1. Three estimates for the brightness of PU Vul.

Date	V	B − V	U − B
17 July	$10^{m}.76$	$0^{m}.20$	$-0^{m}.76$
18 July	10.71	0.26	−0.73
8 Aug.	10.76	0.18	−0.72

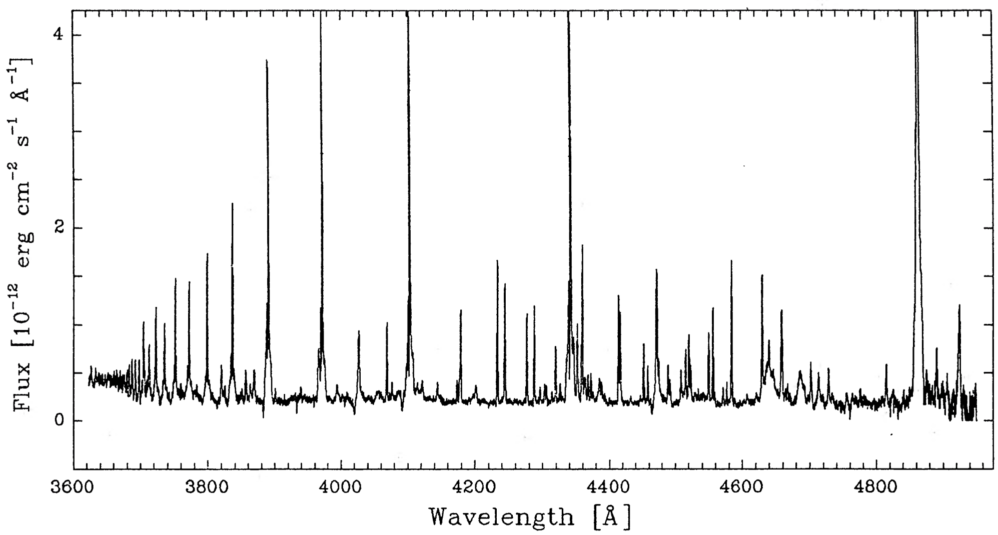

Figure 1. The spectrum of PU Vul on 1990 July 17. The most intensive Balmer emissions from Hβ to Hε are truncated on this scale.

Table 2. Emission-line fluxes (in units of 10^{-12} erg cm^{-2} s^{-1}), measured in the spectrum of PU Vul obtained on 1990 July 17.

Line	λ [Å]	Flux	Line	λ [Å]	Flux	Line	λ [Å]	Flux
H_β		59.0	NIV	4058	1.0	[FeII]	4287	1.1
H_γ		20.0	FeII	4629	1.9	[FeII]	4276	1.1
H_δ		12.0	FeII	4583	2.3	[FeII]	4243	1.9
H_8		9.3	FeII	4555	1.3	[SII]	4076	0.2
H_9		4.7	FeII	4549	1.0	[SII]	4068	1.1
H_{10}		3.4	FeII	4233	2.1	HeI	4471	5.7:
H_{11}		2.7	[FeIII]	4701	1.0	HeI	4026	2.4:
H_{12}		2.1	[FeIII]	4658	1.8	HeI	3819	0.8
H_{13}		1.7	[FeII]	4457	0.6	[OIII]	4363	0.6:
HeII	4685	2.6	[FeII]	4452	0.9	[NIII]	3868	0.9
NIII	4634÷42	5.6	[FeII]	4319	0.8			

During 1990, we made three estimates of the brightness of PU Vul with a single-channel *UBV* photometer and a 60-cm telescope of NAO Rozhen. HD 194011 ($V = 8.31$ mag, $B-V = 1.26$ mag, $U-B = 1.4$ mag, Sp K0) was used as a comparison star. The brightness of the star in the filter V and the colours B − V and $U-B$ on these dates are in Table 1.

3 RESULTS

Fig. 1 shows the spectrum of PU Vul in the range 3600–4900 Å obtained on July 17, with resolution 0.35 Å. It is reduced to an absolute energy scale using the low-resolution spectrum obtained in the same night. Very strong Balmer emission lines, visible up to about $H_{20}-H_{21}$ and a reverse Balmer jump dominate the spectrum. All other emission lines which are present in the spectrum are considerably fainter. If we compare this spectrum to previous observations (Kenyon 1986b; Belyakina *et al.* 1989; Iijima 1989) it is apparent that the changes are remarkable.

The Balmer emission on our spectra is well visible in comparison to Kenyon's observations (see figs 1 and 2 in Kenyon 1986b). The presently observed continuum flux shows a diminution, between 1984 and 1990, of about four. In the same period the Hβ flux increases about 10 times (Table 2 and Kenyon 1986b).

Relatively weak, wide emission wings of the Balmer lines are well visible on Fig. 1. A better presentation of the profiles of the hydrogen lines is shown on Fig. 2, where the profiles of H_8 in the spectra from 1990 July 11 and 1991 January 1, are presented. On all of the spectra obtained before 1990 December 30, two emission peaks, divided by an absorption component and wide emission wings, are well visible in the profiles of the Balmer lines from Hβ to $H_{11}-H_{12}$. The higher members of the series show only one emission peak and the broad emission wings are very weak. The absorption component which is present in the violet wing of H_8 on the spectrum from July 11 (Fig. 2) is rather faint and is confidently seen in H_8 and, in some cases, in Hδ and Hβ only. The two emission peaks and the sharp absorption component do not show remarkable changes of the radial velocities during the time of our observations. Their average heliocentric radial velocities for the whole period between 1990 July and 1991 January, are respectively, $+71\pm5$ km s^{-1}, -72 ± 6 km s^{-1} and -20 ± 4 km s^{-1}.

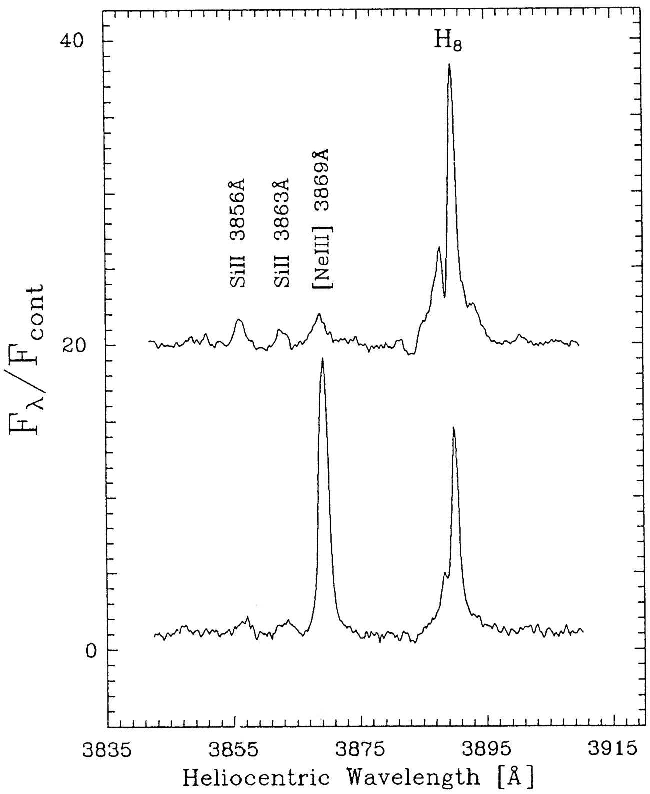

Figure 2. Changes of the H_8 and [Ne III] profiles obtained on 1990 July 11 (up) and 1991 January 1 (down).

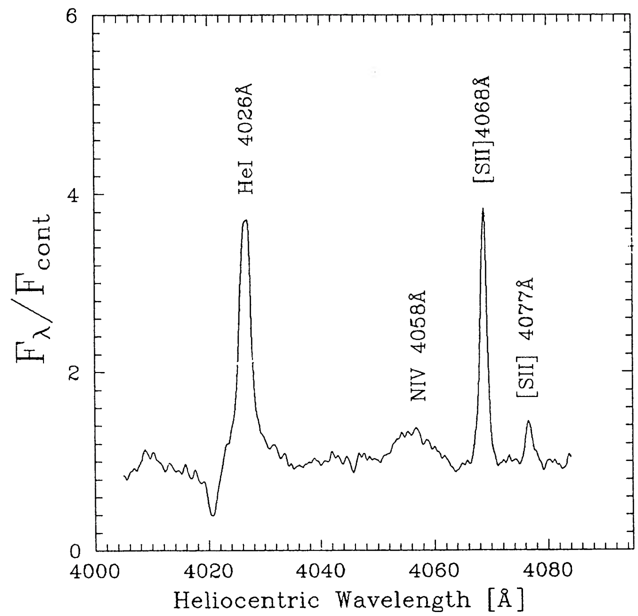

Figure 3. Intensity tracing around the N IV emission line, averaged from the 1990 July 11, 12, 15 and 17 plates.

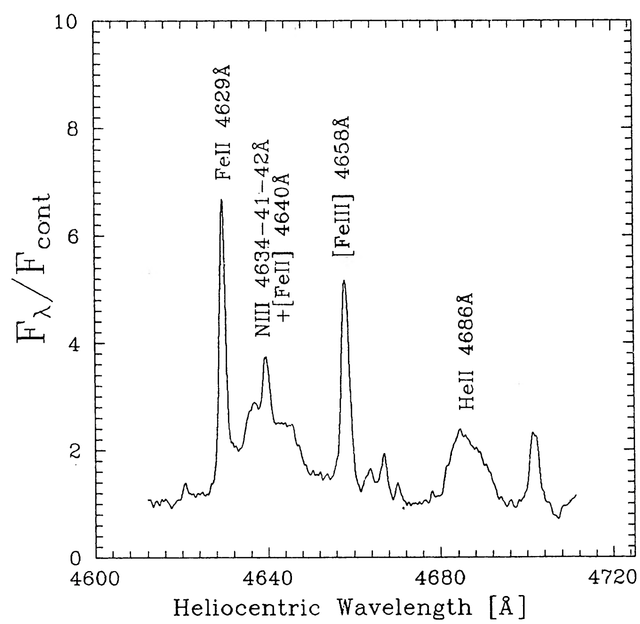

Figure 4. Intensity tracing around the N III and He II emission lines, averaged as on Fig. 3.

Profiles with an emission peak, wide emission wings, and violet shifted P Cyg type absorption, are shown by He I 4026 (Fig. 3) and 4471 Å. Apart from that, the spectrum shows fainter emission lines of He I 3820 and 4713 Å.

The most important change in the spectrum of PU Vul, in comparison to the observations of Iijima (1989) and Belyakina *et al.* (1989), is the appearance of emission lines, typical of the spectra of Wolf–Rayet (WR) stars. On all our spectra wide emissions of He II 4686 Å, the blend N III 4634–41–42 Å (Fig. 4) and a very faint emission N IV 4058 Å (Fig. 3) are present. In comparison to the Balmer lines these emissions are much fainter, but they are comparable by intensity to their wide emission wings (Fig. 1). During our observations the emission lines of He II, N III and N IV are of practically constant intensity. The fluxes measured in the spectrum from July 17, for the WR-type lines, Balmer emission lines and some other permitted and forbidden emission lines are shown in Table 2.

In Figs 3 and 4 an asymmetry in the profiles of the emission lines He II 4686 Å and N IV 4058 Å is easily seen. Compared to their violet emission wing, the red ones are more smooth and more extended. The full widths, at zero intensity of the emission wings, averaged by the measurements of the lines of H I, He I, He II and N IV, are about 1100–1200 km s^{-1}. This is less than half the width of the Balmer emission wings (~ 2600 km s^{-1}) measured by Iijima (1989) at the end of 1987 and the beginning of 1988. The radial velocity of the P Cyg-type absorption in the violet end of the wide emission wings is practically constant on all our spectra and the mean value measured for the profile centres, in the lines of He I 4026 and 4471 Å (where it is better seen), is about -420 ± 12 km s^{-1}.

Taking into account only the broad structures in the spectrum of PU Vul – the profile shapes of the Balmer lines and the lines of He I, the intensities of the emission lines He II 4686 Å, N III 4634–41–42 Å and N IV 4058 Å, and using the criteria of van der Hucht *et al.* (1981) for the classification of the Wolf–Rayet stars, it is possible to classify the companion. So, our rough estimation of the spectral class of the hot component of PU Vul during the period 1990 July to 1991 January, is WN8.

Table 3. Heliocentric radial velocities of sharp emission lines in the spectrum of PU Vul in km s^{-1}. The numbers in parentheses indicate the number of measured lines.

Date	11 Jul 90	15 Jul 90	17 Jul 90	6 Oct 90	1 Jan 91
JD	2448083.5	...8087.5	...8089.5	...8171.3	...8258.2
[FeII]	+27±1.5 (10)	+24±1.0 (12)	+25±1.0 (6)	+25±1.0 (10)	+24±1.5 (8)
FeII	+27±1.0 (13)	+25±1.0 (12)	+26±1.0 (10)	+23±1.0 (10)	+25±1.0 (12)
HeI	+28±1.0 (3)	+29±1.5 (4)	+25±3.0 (2)	+25±4.0 (4)	+24±1.0 (4)
[OIII]	+32 (1)	+28 (1)	+28 (1)	+33 (1)	+31±1.0 (3)
[NeIII]	+26 (1)	+33 (1)	+20 (1)	+25 (1)	+23 (1)
[SII]	+23 (1)	+26 (1)	+18: (1)	+17: (1)	+23 (1)

In comparison to the previous observations of Kenyon (1986b), Iijima (1989) and Belyakina *et al.* (1989), there are some other interesting changes in the spectrum of PU Vul during 1990. Spectral lines of Ti II, Cr II and Mg II are completely absent on our spectra. The emissions of Fe II and [Fe II] are the most numerous and intense. There are emission lines of [O III] 5007, 4959 and 4363 Å, [Ne III] 3869 Å (Fig. 2), [S II] 4068 and 4077 Å (Fig. 3), Si II 3856 and 3963 A (Fig. 2). All these lines are relatively sharp with FWHM of about 100 km s^{-1}. Their radial velocities are shown in Table 3. For the first time in the spectrum of PU Vul, emission lines of [Fe III] appear and the most intense among them is 4658 Å (Fig. 4). The mean heliocentric radial velocity, measured for that line on all spectra, is about $+23 \pm 3$ km s^{-1}.

For our photographic observations PU Vul is relatively faint, and that is why, on most of the spectra, the continuum is underexposed. Despite that, the only absorption lines in its spectrum are the P Cyg components of He I and of some Balmer lines and weak, relatively sharp absorptions of Ca II H and K. The mean heliocentric radial velocity, measured on Ca II K is about -27 ± 2 km s^{-1}.

The last observations on 1990 December 30 and 1991 January 1 show strong changes in the Balmer lines, the lines of He I and nebular emissions [Ne III] and [O III], in comparison to the spectra obtained before. The intensity of the absorption component, dividing the emission peaks in the profiles of the hydrogen lines, strongly decreased (Fig. 2). The sharp emission component of the He I lines is about two times more intense. Nebular emission lines [Ne III] 3869 A, [O III] 5007, 4959 and 4363 Å, which are weak and with a constant intensity on all the previous spectra, are very strong on the last two spectra. The relative intensity of the line [O III] 4363 Å increases about five times, and of [Ne III] 3869 Å (Fig. 2) – about 10 times. All the other lines in the spectrum did not show remarkable changes.

4 DISCUSSION

The spectral and photometric observations of PU Vul in the last few years, once again, confirm its belonging to the group of symbiotic novae stars. In agreement with the theoretical scenario and the observations of other symbiotic novae that have undergone degenerate flashes, Wolf–Rayet features appear in the spectrum of PU Vul, which shows the development of a rather intense, high-velocity stellar wind. In the spectra of AG Peg, RR Tel and RT Ser (Kenyon 1986a,b; Biotti 1988) these WR-type emission lines appeared after the visual maximum, during the brightness decreases.

The observations of Belyakina *et al.* (1989) and Kolotilov (1989) show that in the last two to three years the brightness of the star in *UBV* systematically decreased. Our estimates in 1990 July–August, confirm that this decrease continued during 1990 as well. The presence of wide emission lines, typical of Wolf–Rayet stars, in the spectrum of PU Vul during the second half of 1990 is a very good observational confirmation for the theoretical scenario. Unfortunately, our spectral observations started in 1990 July, and we can not say when Wolf–Rayet features appeared for the first time.

Recently, Baratta & Viotti (1990) published a binary model of the symbiotic nova V1329 Cyg based on observations in a similar phase of its evolution. According to them 'there exist three separate line emitting regions, which can be identified with (i) the M-star wind partially ionized by the hot star radiation, (ii) cloudlets of low-density, high-velocity gas well probably ejected by the hot star, and (iii) the transient WR-type atmosphere surrounding the hot star'.

Our results show that in the presently observed spectrum of PU Vul only two emission line systems, originating in two different regions, are present. The broad emissions of He II, N III and N IV, the wide emission wings of the Balmer lines, and the lines of He I, as well as the violet-shifted P Cyg-type absorption components, are formed in the stellar wind of its hot companion, similar to a WN8 star. The wind velocity is about 500 km s^{-1}. Having in mind the data published earlier (Iijima & Ortolani 1984; Iijima 1989; Belyakina *et al.* 1989) and the radial velocities measured by us, as well as the profile shapes, we suppose that all the remaining lines originate in another region, in different physical conditions. It is very difficult to understand whether this is an earlier ejected envelope, or a region in which the wind of the M giant interacts with the high-temperature radiation and/or with the fast wind of the hot component. The expansion velocity of such an envelope seems to be of the order of several tens of km s^{-1} (Belyakina *et al.* 1989). It is possible for this envelope to look like a bubble as a result of the sweeping of matter from its internal parts by the fast wind of the hot component. The symmetric, single-component profiles of the emission lines of [Ne III] and [O III], as well as their radial velocities, show that they can not originate in a region with low density and cloudy structure, similar to that suggested by Baratta & Viotti (1990) for V1329 Cyg.

By analogy with the observations of the above cited symbiotic novae, we can expect a gradual increase of the ionization potential of the emission lines in the spectrum of PU Vul. The presence of emission lines of [Fe III] on our spectra shows that this process possibly has already begun. What is more, the latest changes of the sharp absorption components of the Balmer lines and of the nebular emission lines of [Ne III] and [O III] show a decrease of the density in the region where they originate.

The present state of PU Vul is one of the few candidates for the investigation of a symbiotic nova when its hot component is in a Wolf–Rayet stage. Further observations from X-rays to radio wavelengths could help in solving some of the problems connected with the nature of the few symbiotic novae stars.

REFERENCES

Baratta, G. B. & Viotti, R., 1990. *Astr. Astrophys.*, **229**, 104.
Belyakina, T. S. *et al.* 1984. *Astr. Astrophys.*, **132**, L12.
Belyakina, T. S. *et al.*, 1989. *Astr. Astrophys.*, **223**, 119.
Borkowski, J., 1988. *ReWiA – Instrukcja Obslugi*, Torun Observatory (in Polish).
Hayes, D. S. & Latham, D. W., 1975. *Astrophys. J.*, **197**, 593.
Iijima, T., 1989. *Astr. Astrophys.*, **215**, 57.
Iijima, T. & Ortolani, S., 1984. *Astr. Astrophys.*, **136**, 1.
Kenyon, S. J., 1986a. *The Symbiotic Stars*, Cambridge University Press, Cambridge.
Kenyon, S. J., 1986b. *Astr. J.*, **91**, 563.
Kenyon, S. J., 1988. In: *The Symbiotic Phenomenon, IAU Coll. No. 103*, p. 161, eds Mikolajewska, J. *et al.*, Kluwer, Dordrecht.
Kenyon, S. J. & Truran, J. W., 1983. *Astrophys. J.*, **273**, 280.
Kolotilov, E. A., 1989. *Pisma Astron. Zh.*, **15**, 519.
Kozai, Y., 1979a. *IAU Circ. No. 3344.*
Kozai, Y., 1979b. *IAU Circ. No. 3348.*
van der Hucht, K. A., Conti, P. S., Lundstrom, I. & Stenholm, B., 1981. *Space Sci. Rev.*, **28**, 227.
Viotti, R., 1988. In: *The Symbiotic Phenomenon, IAU Coll. No. 103*, p. 269, eds Mikolajewska, J. *et al.*, Kluwer, Dordrecht.