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# Emission line variability of RS Ophiuchi*

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**ABSTRACT**

We report that the H$\alpha$ emission line of RS Oph was strongly variable during our 2004 observations on a time-scale of one month. The line consisted of both a double-peaked central narrow component [full width at half-maximum (FWHM) $\sim$ 220 km s$^{-1}$] and a strongly variable broad one (FWHM $>$ 2000 km s$^{-1}$). The base of the H$\alpha$ line was very broad, with full width at zero intensity $\approx$ 4600 km s$^{-1}$ on all spectra from 1986 to 2004. The variability of the broad component extends from $-2000$ to $+2000$ km s$^{-1}$. Most probably this is due either to blobs ejected from the white dwarf (with a typical blob mass estimated to be $\sim 10^{-10}$ M$_\odot$) or to a variable accretion disc wind. We also detected variability of the He II $\lambda$4686 line on a time-scale shorter than 1 d. The possible origin is discussed.

**Key words:** binaries: symbiotic – stars: individual: RS Oph – novae, cataclysmic variables.

## 1 INTRODUCTION

RS Ophiuchi (HD 162214) is a recurrent nova which underwent its last major outburst in 1985 (see Bode 1987 and references therein). Following Dobrzycka & Kenyon (1994), RS Oph has a binary period of 460 d with orbital inclination to the line of sight of 30°–40°, and spectroscopic ephemeris $T_0$ = JD 244 4999.9±29.3+460±10$E$. The mass donor is a red giant of spectral type K4–M0 (Mürset & Schmid 1999). The nature of the hot component is unclear. Most probably it is a massive white dwarf with $M_{\rm WD} \approx 1.4$ M$_\odot$, accreting at $\dot{M} \geqslant 10^{-8}$ M$_\odot$ yr$^{-1}$ (Hachisu & Kato 2000). Alternatively, it has been proposed to be a B-type shell star with highly variable luminosity, which occasionally displays blueshifted absorption features (Dobrzycka et al. 1996).

Broad, variable emission components of the hydrogen lines were detected by Iijima et al. (1994), Anupama & Mikołajewska (1999), and Tomov (2003). Variability of the He lines on a time-scale of hours was detected by Sokoloski (2003). The origin of these changes is a mystery. Here we report that similar variability is also evident in our 2004 observations and discuss its possible origin.

## 2 OBSERVATIONS

We secured eight spectra in 2004 using the European Southern Observatory (ESO), La Silla, 2.2-m telescope and the Fibre-fed Extended Range Optical Spectrograph (FEROS). FEROS is a fibre-fed echelle spectrograph, providing a resolution of $\lambda/\Delta\lambda = 48000$, wide wavelength coverage from about 4000 to 8000 Å in one exposure and a high detector efficiency (Kaufer et al. 1999).

Additionally, we retrieved four spectra covering the region of the H$\alpha$ line from the archive of the Isaac Newton Group of telescopes (ING). A journal of observations and the measured quantities are given in Table 1.

## 3 SPECTRAL VARIABILITY

### 3.1 H$\alpha$ emission line

The variability of the H$\alpha$ line is immediately apparent (see Fig. 1 and Table 1). There are changes in the blue and red peaks, as well as in the wings of the line. On all spectra the base of the H$\alpha$ line is very wide, the mean full width at zero intensity $\overline{\rm FWZI} = 4650 \pm 300$ km s$^{-1}$ and the mean equivalent width of the H$\alpha$ emission line $\overline{W} = 112 \pm 11$ Å, which is about $1 \times 10^{-11}$ erg cm$^{-2}$ s$^{-1}$. The ratio of the intensity of the blue and red peaks (V/R) varies from 0.51 to 0.87. Our data suggest that the H$\alpha$ profile of RS Oph is purely in emission and consists of both a double-peaked central narrow component [$W \sim$ 90 Å, full width at half-maximum (FWHM) $\sim$ 200–250 km s$^{-1}$] and a strongly variable broad one ($W \sim 20$ Å, FWHM $>$ 2000 km s$^{-1}$).

When the spectra are obtained in the same night or in consecutive nights, the H$\alpha$ profiles are effectively identical. However, changes are visible when the time difference is $\sim$1 month. To explore in more detail the velocity structure of the variability of the wings, assuming that the variability arises purely from changes in emission, we subtracted at each epoch a minimum spectrum (artificially generated by taking the minimum value from all normalized spectra at a given wavelength). The residuals are plotted in Fig. 2(b).

*This work is based on data from the European Southern Observatory (programme 073.D-0724) and the Isaac Newton Group Archive.
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**Table 1.** Hα and He II λ4686 observations of RS Oph. In the table are given (1) number, (2) date of observation, (3) Julian Day, (4) orbital phase, radial velocity of the (5) blue peak, (6) central dip and (7) red peak, (8) full width at zero intensity (FWZI) of Hα, (9) equivalent width of Hα, (10) equivalent width of He II λ4686, (11) the ratio between intensities of the blue and red peaks, (12) the radial velocity of the additional emission ($V_{\rm emm}$), and (13) the origin of the spectrum. The typical errors are $\pm1$ km s$^{-1}$ for $V_{\rm blue}$, $V_{\rm dip}$ and $V_{\rm red}$, $\pm250$ km s$^{-1}$ for FWZI, $\pm5$ per cent for $W_{\rm H\alpha}$, $\pm20$ per cent for $W_{4686}$, $\pm3$ per cent for the V/R ratio, and $\pm150$ km s$^{-1}$ for $V_{\rm emm}$. The last column indicates the origin of the observations.

| N: | Date | JD 240 0000+ | $\phi$ | $V_{\rm blue}$ km s$^{-1}$ | $V_{\rm dip}$ km s$^{-1}$ | $V_{\rm red}$ km s$^{-1}$ | FWZI km s$^{-1}$ | $W_{\rm H\alpha}$ [Å] | $W_{4686}$ [Å] | V/R | $V_{\rm emm}$ [km s$^{-1}$] | origin |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) | (10) | (11) | (12) | (13) |
| 1 | 1986-07-12 | 46624.4250 | 0.53 | | | | 4750 | 106 | – | 0.51 | +560: | ING |
| 2 | 1986-07-13 | 46625.4868 | 0.53 | | | | 4940 | 102 | – | – | +740: | ING |
| 3 | 1997-08-06 | 50667.3916 | 0.32 | | | | 4390 | – | – | – | −1270 | ING |
| 4 | 1997-08-06 | 50667.3986 | 0.32 | | | | 4660 | – | – | – | −1130 | ING |
| 5 | 2004-04-11 | 53106.3849 | 0.62 | −87.4 | −48.9 | +3.3 | 4940 | 102 | <0.1 | 0.74 | −1440, +2065 | ESO |
| 6 | 2004-04-11 | 53106.3922 | 0.62 | −86.4 | −47.9 | +2.9 | 4980 | 104 | <0.1 | 0.76 | −1420, +2060 | ESO |
| 7 | 2004-06-05 | 53161.2236 | 0.74 | −92.8 | −55.8 | +0.7 | 4160 | 125 | 1.9 | 0.53 | +1110 | ESO |
| 8 | 2004-06-05 | 53161.2311 | 0.74 | −92.8 | −55.9 | +2.0 | 4210 | 125 | 3.2 | 0.54 | +1120 | ESO |
| 9 | 2004-06-06 | 53162.2840 | 0.74 | −90.7 | −54.4 | +2.4 | 4530 | 127 | 0.7 | 0.60 | +1150 | ESO |
| 10 | 2004-06-06 | 53162.2916 | 0.74 | −89.8 | −54.9 | +2.9 | 4300 | 120 | 0.6 | 0.59 | +1100 | ESO |
| 11 | 2004-08-31 | 53248.0434 | 0.93 | −91.0 | −46.8 | +2.9 | 4890 | 110 | 0.2 | 0.86 | −1180, +1750 | ESO |
| 12 | 2004-08-31 | 53248.0510 | 0.93 | −91.2 | −45.6 | +4.7 | 4850 | 102 | 0.3 | 0.87 | −1225, +1740 | ESO |

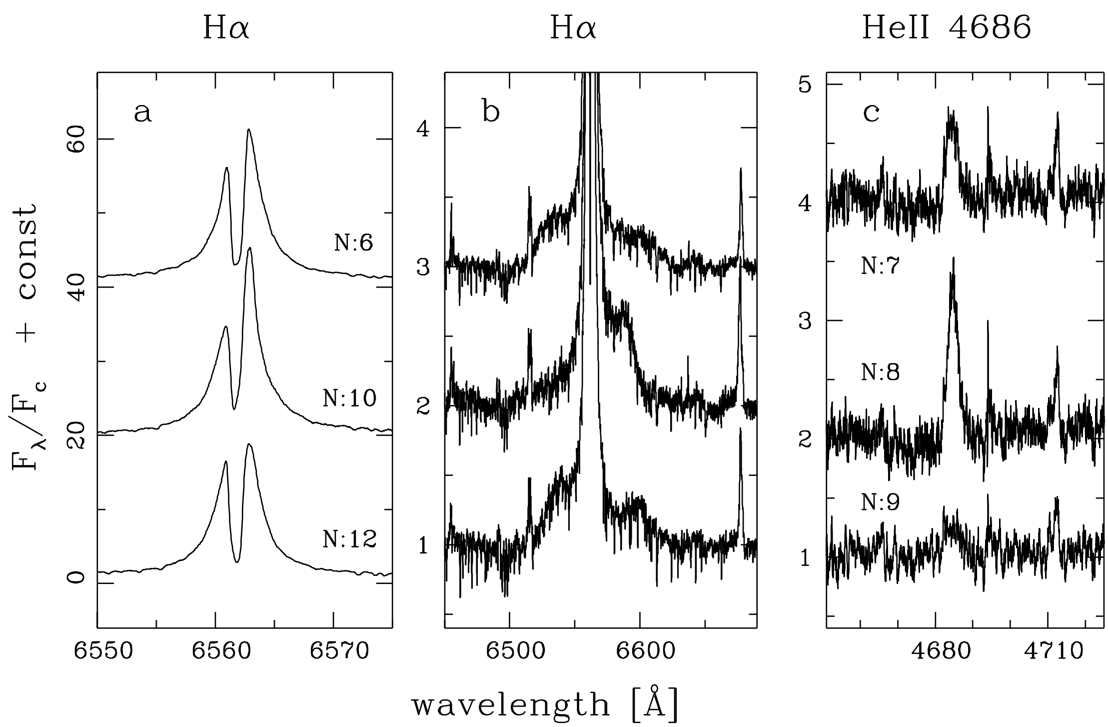


**Figure 1.** The Hα and the He II λ4686 emission lines of RS Oph (FEROS observations). The number against each spectrum refers to the epoch of observation as given in Table 1. All spectra are normalized to the local continuum. (a) The Hα central double-peaked component with FWHM ∼ 5 Å (220 km s$^{-1}$). (b) The same spectra as in (a) but on different scales, so that the Hα broad component is visible. (c) The He II λ4686 line. The spectrum N:8 was obtained 10 min after N:7, the spectrum N:9 was obtained 24 h later. These data demonstrate that the line is variable on a time-scale ⩽1 d.

As can be seen, the variability of the wings extends from −2000 to +2000 km s$^{-1}$, with the most prominent additional emission around −1200 and +1200 km s$^{-1}$. On each spectrum we measured the radial velocity of the additional emission, which has an equivalent width $W \leqslant 7$ Å. The data are given in Table 1 along with other parameters.

A variable broad component was not detected in RS Oph's sister system T CrB (see Stanishev et al. 2004; Zamanov et al. 2005). A similar component appeared, however, in the 1994 observations of CH Cyg (Tomov et al. 1996) and the velocity range of ±2000 km s$^{-1}$ was close to that of RS Oph. However, the time-scale of appearance/disappearance was considerably shorter (∼2 h).

### 3.2 Time-scale of He II λ4686 variability

Our spectra numbered 7, 8 and 9 (Fig. 1c and Table 1) show that the He II λ4686 line is also variable. The spectrum N:8 was obtained

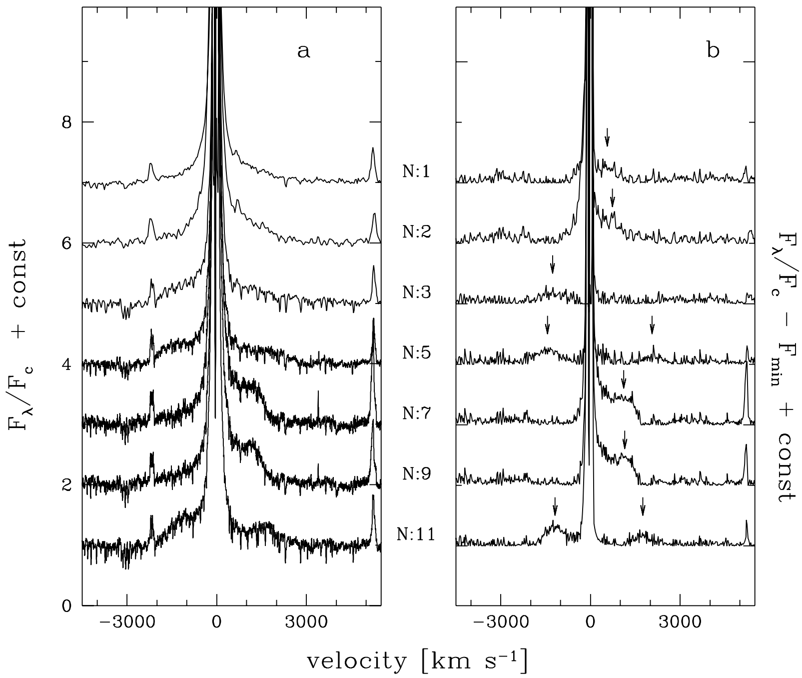


**Figure 2.** (a) The RS Oph H$\alpha$ profiles (normalized to the local continuum) for seven different nights. The numbers again correspond to those in Table 1. (b) After subtraction of the minimum spectrum, the additional emissions are visible as bumps with $W \leqslant 7$ Å. The arrows indicate their measured radial velocities as given in Table 1.

10 min after N:7, and N:9 was obtained 24 h later. This suggests that the intensity of He II $\lambda$4686 changes on a time-scale of minutes to hours (note that we did not detect H$\alpha$ variability on such a short time-scale).

The He II $\lambda$4686 line indicates high excitation conditions in the gas. In the case of RS Oph (see the next section) this can be related to a region located close to the boundary layer between the accretion disc and the white dwarf (Sokoloski 2003). The changes of the intensity of this line indicate changes in the region of its appearance which, in turn, is determined most probably by variable luminosity and/or the temperature of the boundary layer.

## 4 DISCUSSION

Our data suggest that the H$\alpha$ profile of RS Oph is purely in emission and consists of both a double-peaked central narrow component and a strongly variable broad one. The Balmer emission lines appearing in the extended envelopes of symbiotic stars usually have an ordinary nebular profile with typical FWHM $\sim$ 100–150 km s$^{-1}$, for example AG Dra (Tomova & Tomov 1999). FWHM increases to 200 km s$^{-1}$ only during the active phases. The basic mechanism determining the width of the Balmer lines is turbulence in the gas. The central narrow emission of RS Oph is very similar to the double-peaked H$\alpha$ line of T CrB and the two stars have practically the same FWHM of about 200–250 km s$^{-1}$. The H$\alpha$ line of T CrB is supposed to be formed in the outer part of an accretion disc around the hot compact object (Stanishev et al. 2004). By analogy with this star we could assume that the narrow H$\alpha$ component of RS Oph is also formed around its compact object. This assumption, however, is not consistent with the fact that the peak of this component exceeds the level of the continuum by a factor of 20–25, like purely nebular lines of the symbiotic stars. This peak height differs from that of T CrB, which exceeds the level of the continuum by a factor of 2–6 only.

While the appearance and the variability of the narrow component is relatively common in symbiotic stars (see also Ikeda & Tamura 2004 and references therein), appearance and variability of the broad component has been detected in about 10 objects to date. Fast ($\sim$1000 km s$^{-1}$) bipolar winds/jets were detected in Hen 3-1341 and StH$\alpha$ 190 (Tomov 2003). The jets in both systems appeared as satellite emission components on both sides of the strong H I Balmer and He I emission lines, and they looked similar to the additional emission bumps in RS Oph (Fig. 2b). Similar profiles have been observed in the symbiotic nova RX Pup (Mikołajewska et al. 2002) and AR Pav (Quiroga et al. 2002).

At quiescence, the hot components of RS Oph and RX Pup show activity (high states) characterized by the appearance of B/A/F shell-type features and variable 'false atmosphere' together with the broad and complex emission lines, and are related to the accretion flow/accretion-driven phenomena in these binaries. Other systems that show similar behaviour are CH Cyg and MWC 560 (Mikołajewska et al. 2002; Mikołajewska 2003).

Here, we will consider three possible origins for the broad component in RS Oph.

(1) The first possible origin is related to the ejection of blobs of matter. These blobs could be expelled by a rotating white dwarf magnetosphere (Tomov 2003 and references therein) or by a jet mechanism. The de-projected velocity of the ejection is $\sim$1500–4000 km s$^{-1}$, having in mind $V_{\rm emm}$ from Table 1 and assuming it is realized normal to the orbital plane, and also that the orbital inclination is 30°–40°. This velocity is practically the same as ejection velocities of up to 3800 km s$^{-1}$ seen during the 1985 nova outburst (Bode 1987 and references therein).

(2) Variable disc winds with similar (to RS Oph and CH Cyg) velocities were detected in a few cataclysmic variables and the whole wind can even turn on and off. The terminal velocity of the wind in the BZ Cam system is $v_{\rm t} \sim$ 3000 km s$^{-1}$ and the time-scale of the

variability is 30–40 min (Ringwald & Naylor 1998). Indeed, their profiles bear a noticeable similarity to those in RS Oph at some epochs. For Q Cyg the terminal velocity is $v_t \sim 1500$ km s$^{-1}$ and the events last about 1.5 h (Kafka et al. 2003). These time-scales are similar to those of the Balmer-line variability of CH Cyg but not to those of RS Oph. It is possible that the disc wind of RS Oph varies on longer time-scales.

(3) If the variable broad component of RS Oph originates in an asymmetric disc, then a Keplerian velocity of 1000 km s$^{-1}$ requires a distance from a 1.4-M$_{\odot}$ WD of about $2 \times 10^{10}$ cm. At that distance the Keplerian period is 20 min, which is considerably different from the observed time-scale of the H$\alpha$ variability of RS Oph.

All of the mechanisms considered are related to the loss of mass by the system. Whenever such mass-loss occurs, a question about its quantitative estimate arises. A quantitative estimate, however, is possible in those cases where the phenomenon can be related to some geometrical model. However, we have no geometrical model of loss of mass which can be related to the irregular form of the profile of the broad component. The velocity distribution of this line proposes movement of discrete regions (blobs of matter) in the emitting environment (Fig. 2). That is why we tried to obtain a rough estimate of the mass of one 'average' blob on the basis of its emission and supposing that it is optically thin and also has a constant density within some limits. From Fig. 1(b) and Fig. 2, the luminous flux in H$\alpha$ of such a blob is about $3 \times 10^{-13}$ erg cm$^{-2}$ s$^{-1}$ ($W \approx 3$ Å). This flux was corrected for interstellar reddening using $E(B-V) = 0.73$ (Snijders 1987; Hachisu & Kato 2000, 2001) and the extinction law by Seaton (1979). A corrected flux of $1.602 \times 10^{-12}$ erg cm$^{-2}$ s$^{-1}$ was obtained.

To calculate the emission measure of this blob, data about the distance to the RS Oph system, the H$\alpha$ recombination coefficient and the helium abundance are needed. For the distance to the system we adopted 0.6 kpc according to Hachisu & Kato (2000, 2001). It is not possible to obtain from observation the electron temperature and the electron density in the region where the H$\alpha$ broad component is emitted, as we have no indication about the appearance in this region of certain lines giving information for those parameters. We will suppose that the electron temperature is 20 000 K and the electron density is comparatively high (being in the range $10^8$–$10^{10}$ cm$^{-3}$). Then we used recombination coefficients of 5.956 $\times 10^{-14}$ cm$^3$ s$^{-1}$ and $6.336 \times 10^{-14}$ cm$^3$ s$^{-1}$ for case B, corresponding to these temperature and densities (Storey & Hummer 1995). We also adopted a helium abundance of 0.1 which is thought to be typical of symbiotic nebulae (Vogel 1993; Vogel & Nussbaumer 1994).

To calculate the emission measure we need to know the state of ionization of helium in the emitting region. The He II $\lambda$4686 line is absent in the spectrum (Dobrzycka et al. 1996) or is weak (Fig. 1) during the quiescent state of the system. This means that singly ionized helium is dominant in the circumbinary nebula during this state. According to the suppositions presented, however, the broad H$\alpha$ component is emitted in a region in the close vicinity of the hot object in this system, where helium is probably (for the most part) doubly ionized. That is why here we will assume the state of ionization to be He$^{++}$ in the emitting region.

Using a flux of $1.602 \times 10^{-12}$ erg cm$^{-2}$ s$^{-1}$ and density of $10^8$–$10^{10}$ cm$^{-3}$, we obtain the emission measure of one 'average' blob of matter (with a constant density) of $3.19 \times 10^{56}$–$3.00 \times 10^{56}$ cm$^{-3}$. We can also calculate the mass of the blob, adopting the parameter $\mu$ of 1.4 (Nussbaumer & Vogel 1987), determining the mean molecular weight $\mu m_{\rm H}$ in the nebula. The mass is therefore obtained as $3.8 \times 10^{-9}$–$3.5 \times 10^{-11}$ M$_{\odot}$. [Note that Bode (1987) gives $d = 1.6 \pm 0.3$ kpc from a variety of measures. If we adopt this longer distance, we obtain mass of the blob $2.7 \times 10^{-8}$–$2.5 \times 10^{-10}$ M$_{\odot}$].

## 5 CONCLUSIONS

We report that the H$\alpha$ emission of RS Oph was strongly variable during our 2004 observations on time-scales of ∼1 month. No variability was detected on time-scales of $\leqslant$1 d. The line was always very wide at its base (FWZI $\approx$ 4600 km s$^{-1}$) on all spectra from 1986 to 2004, consisting of narrow and broad emission components. Variable emission is detected at velocities up to $\pm$2000 km s$^{-1}$. Most probably this variable emission is due either to blobs ejected from the white dwarf or to a variable accretion-disc wind. The approximate mass of one 'average' ejected blob of matter, suggested by the variability of the broad emission component is $3.8 \times 10^{-9}$–$3.5 \times 10^{-11}$ M$_{\odot}$. We also detected variability of the He II $\lambda$4686 line on time-scales <1 d. To understand more fully the nature of the emission-line variability of RS Oph, we need to acquire a set of spectra with time resolution from minutes to days.

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