

Infrared observations of the 2006 outburst of the recurrent nova RS Ophiuchi: the early phase

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ABSTRACT

We present infrared spectroscopy of the recurrent nova RS Ophiuchi, obtained 11.81, 20.75 and 55.71 d following its 2006 eruption. The spectra are dominated by hydrogen recombination lines, together with He I, O I and O II lines; the electron temperature of $\sim 10^4$ K implied by the recombination spectrum suggests that we are seeing primarily the wind of the red giant, ionized by the ultraviolet flash when RS Oph erupted. However, strong coronal emission lines (i.e. emission from fine structure transitions in ions having high ionization potential) are present in the last spectrum. These imply a temperature of 930 000 K for the coronal gas; this is in line with X-ray observations of the 2006 eruption. The emission linewidths decrease with time in a way that is consistent with the shock model for the X-ray emission.

Key words: binaries: symbiotic – stars: individual: RS Ophiuchi – novae, cataclysmic variables – infrared: stars.

1 INTRODUCTION

RS Ophiuchi is a recurrent nova that has undergone nova eruptions in 1898, 1933, 1958, 1967, 1985 and possibly (Schaeffer 2004) 1907. As in the case of a classical nova, the eruption follows a thermonuclear runaway on the surface of the white dwarf (Starrfield et al. 1996).

The key differences between classical and recurrent novae, in terms of both system properties and outburst behaviour, are reviewed

by Anupama (2002). The recurrenents are a heterogeneous class of objects but the RS Oph type is characterized by a semi-detached binary consisting of a roche-lobe-filling M giant mass donor (M8III in the case of RS Oph; Fekel et al. 2000) and a massive (close to the Chandrasekhar limit) white dwarf (*classical novae* almost exclusively have cool *dwarf* mass donors).

The 1985 eruption of RS Oph was the first to have been observed over the entire electromagnetic spectrum, from the radio to the X-ray (see Bode 1987). What distinguishes the evolution of the eruption in the case of RS Oph is the fact that the ejected material runs into the dense red giant wind, which is shocked (Bode & Kahn 1985). Observations of the 1985 eruption provided indirect evidence for

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the shocking of the wind and the ejecta: RS Oph was a strong and rapidly evolving X-ray (Mason et al. 1987) and radio source (Padin, Davis & Bode 1985), and there was coronal emission over a wide range of wavelengths (Snijders 1987; Evans et al. 1988; Shore et al. 1996).

Infrared (IR) observations of the 1985 eruption are presented in Evans et al. (1988), starting on day 23 of the outburst. These authors found that the 1–2.5 μm spectrum was dominated by hydrogen recombination lines, and He I λ 1.083 μm . Coronal lines ([Si VI] λ 1.965 μm and [Si VII] λ 2.481 μm) were present on day 143 of the eruption. They also tentatively noted the presence of first overtone CO emission, although this was based on low resolution circular variable filter data.

RS Oph was discovered in eruption (Hirosawa 2006) on 2006 February 12.83, which we take to be day zero for this outburst. The discovery of the 2006 eruption triggered a multiwavelength campaign of observations (Bode et al. 2006a,b; Das, Ashok & Banerjee 2006; Evans et al. 2006; Eyres et al. 2006; Ness et al. 2006a,b,c; Gonzalez-Riestra, Orio & Leibowitz 2006; O’Brien et al. 2006a,b,c; Eyres et al., in preparation) and yielded for the first time direct evidence, from very long baseline interferometry (VLBI) imaging, for an expanding shock (O’Brien et al. 2006c).

In this paper we present IR spectroscopy of RS Oph, obtained in the first 55 d of the 2006 eruption, covering a much earlier phase than that observed in 1985.

2 OBSERVATIONS

The observations were obtained with the UIST instrument on the United Kingdom Infrared Telescope (UKIRT), on 2006 February 24, March 5 and April 9. The data were obtained in the *IJK* bands, covering the wavelength range 0.87–2.51 μm . First-order sky subtraction was achieved by nodding along the slit; HR6493 was used to remove telluric features and for flux calibration. Wavelength calibration used an argon arc, and is accurate to $\pm 0.0005 \mu\text{m}$ in the *IJ* bands, and to $\pm 0.0003 \mu\text{m}$ in the *HK* bands.

We note that the precipitable water vapour on March 5 was high (~ 5 mm, cf. ~ 1.3 mm for February 24 and ~ 1.8 mm for April 9). As the March 5.58 data were taken through clouds, and the April 9.54 data were taken through thin cirrus, the telluric cancellation around 1.85 μm (and to a lesser extent the 1.4 μm region) is rather poor, especially for March 5.58. We estimate that the flux calibration for the February and April observations is accurate to ± 20 per cent, that for the March observation is accurate only to ± 60 per cent.

The observing log is given in Table 1, in which the UT times are times of mid-observation. The data for February 24 and April 9 are shown in Fig. 1; the data for March 5 are omitted in view of the greater uncertainty in flux calibration.

3 THE SPECTRA

On all dates the spectra are dominated by hydrogen recombination lines, with He I, O I and O II also present (see Table 2). In particu-

Table 1. Observing log.

2006 UTC Date	Day	Exp (s)		Resolution				Comment
		<i>IJ</i>	<i>HK</i>	<i>I</i>	<i>J</i>	<i>H</i>	<i>K</i>	
February 24.64	11.81	80	80	350	350	1000	1000	
March 5.58	20.75	80	80	350	350	1500	1500	Cloud
April 9.54	55.71	80	80	350	350	1500	1500	Thin cirrus

lar the higher members of the hydrogen Pfund ($n \rightarrow 5$) series are clearly resolved, and there is no evidence for the presence of first overtone CO in either emission or absorption. Thus the identification of CO in the 1985 eruption, reported by Evans et al. (1988) remains problematic. By April 9 (day 55) we also see strong emission in silicon ([Si VI], [Si VII], [Si X]) and sulphur ([S VIII], [S IX]) lines (see Table 3); the first two of these were also reported in the 1985 eruption (Evans et al. 1988).

We have measured the full-width at half-maximum (FWHM) and full-width at zero intensity (FWZI) of several emission lines for each of the three dates (see Figs 2 and 3). While the FWHM of the emission lines indicates an expansion velocity ~ 500 – 600 km s^{-1} , the emission line wings extend to $\gtrsim 2500 \text{ km s}^{-1}$. Swift observations (Bode et al. 2006b) indicate that shock velocities $\sim 3000 \text{ km s}^{-1}$ are present, comparable with the IR line FWZI. After deconvolving the instrumental linewidth, we have converted the FWHM to an expansion velocity (cf. Tables 2 and 3) and, from a variety of lines, derived a mean value for each date.

We find that the mean expansion velocity declines with time, i.e. the emission lines tend to get narrower as the eruption progresses (Figs 2 and 3a); furthermore, the velocity implied by the broad wings also declines (see Fig. 3b). This effect, which arises as the ejected material decelerates as it ploughs into the giant wind, mirrors the behaviour reported by Shore et al. (1996) for optical emission lines and by Snijders (1987) for ultraviolet emission lines during the 1985 eruption. We note that the velocities determined from the line wings are comparable with, but somewhat greater than, the shock velocities deduced from the X-ray emission (see Fig. 3).

We also note that the FWHM of the coronal lines in 2006 April (day 55) is greater than that of the nebular lines. This is clearly seen in Fig. 1(b), which includes the [Si VII] λ 2.483 μm line.

4 DISCUSSION

The spectra have been dereddened for $E(B - V) = 0.73$ (Snijders 1987) and the dereddened fluxes are reported in Table 2 for the He and O lines and in Table 3 for the coronal lines.

4.1 The hydrogen recombination lines

Assuming that the continuum that is clearly visible in Fig. 1 is optically thin free–free and free–bound emission, we estimate the electron temperature to be $\sim 10^4 \text{ K}$ for all three of our observations, but note that the flux calibration for the March observation is not reliable as the data were taken through cloud. This temperature is constrained primarily by the magnitude of the Brackett and Pfund discontinuities at 1.45 and 2.28 μm , respectively (Fig. 4). The electron temperature derived from the optically thin emission is considerably less than that implied by the presence of IR coronal lines in the spectra (see below), or inferred from radio (O’Brien et al. 2006c) and X-ray (Bode et al. 2006b) observations. There remains an excess at wavelengths $\lesssim 1.5 \mu\text{m}$, some (but not all) of which may be due to a contribution from the shocked gas.

Using flux ratios for the hydrogen recombination lines, and assuming Case B (Ferland 2003), we find that the electron density for day 55.71 is $\sim 10^7 \text{ cm}^{-3}$. Assuming the mass loss value given by O’Brien, Bode & Kahn (1992), wind velocity 20 km s^{-1} and shock velocity $\sim 2000 \text{ km s}^{-1}$ (cf. Fig. 3), the corresponding wind column, integrated from the base of the unshocked wind to infinity, is $\sim 2.0 \times 10^{21} \text{ cm}^{-2}$, in good agreement with that obtained from the X-ray data (e.g. fig. 3 of Bode et al. 2006b).

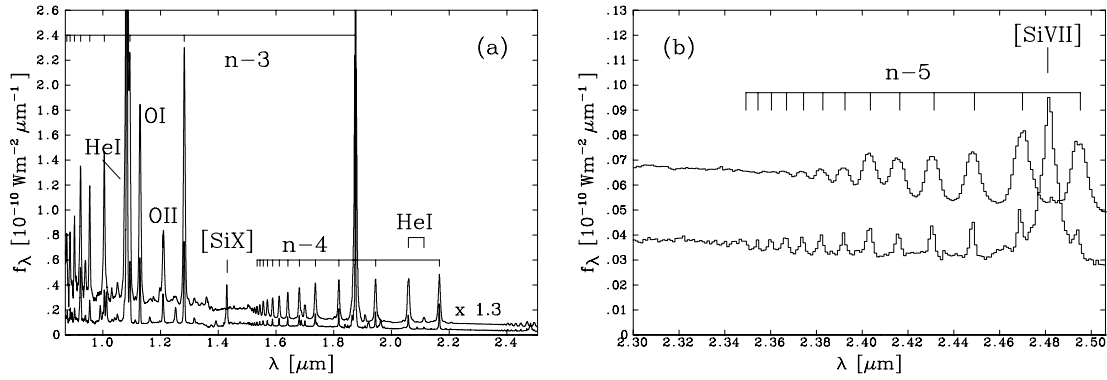


Figure 1. (a) 0.87–2.51 μm spectra for February 24.64 (upper spectrum, data shifted upwards by 30 per cent, for clarity) and April 9.54 (lower spectrum). (b) Detail around 2.4 μm for Feb 24.64 (upper spectrum) and April 9.54 (lower spectrum). In both figures the H recombination lines are identified by ‘ $n - m$ ’.

Table 2. Selected nebular lines in RS Oph; the line fluxes are dereddened for $E(B - V) = 0.73$. Instrumental resolution deconvolved from FWHM values.

Date	λ (μm)	Identification	Dereddened line flux ($10^{-14} \text{ W m}^{-2}$)	FWHM (km s^{-1})
February 24.64	1.0833	He I $^3\text{S}-^3\text{P}^{\circ}$	1131 ± 7	949
	1.12895	O I $^3\text{P}-^3\text{D}^{\circ}$	195 ± 6.2	720
	1.2084	O II $^2\text{D}^{\circ}-^2\text{D}$	74.0 ± 2.0	918
	1.7002	He I $^3\text{P}^{\circ}-^3\text{D}$	9.4 ± 0.5	611
	2.05869	He I $^1\text{S}-^1\text{P}^{\circ}$	33.7 ± 2.3	659
March 5.58	1.0833	He I $^3\text{S}-^3\text{P}^{\circ}$	649 ± 3.1	710
	1.12895	O I $^3\text{P}-^3\text{D}^{\circ}$	71.8 ± 2.6	620
	1.2084	O II $^2\text{D}^{\circ}-^2\text{D}$	30.3 ± 3.0	755
	2.05869	He I $^1\text{S}-^1\text{P}^{\circ}$	13.47 ± 0.96	488
April 9.54	1.0833	He I $^3\text{S}-^3\text{P}^{\circ}$	405.8 ± 2.8	457
	1.12895	O I $^3\text{P}-^3\text{D}^{\circ}$	41.9 ± 2.5	266
	1.2084	O II $^2\text{D}^{\circ}-^2\text{D}$	21.21 ± 0.33	420
	2.05869	He I $^1\text{S}-^1\text{P}^{\circ}$	5.8 ± 0.2	318

Table 3. Coronal lines in RS Oph on 2006 April 9; the line fluxes are dereddened for $E(B - V) = 0.73$. Instrumental resolution deconvolved from FWHM values.

λ (μm)	Identification	Dereddened line flux ($10^{-14} \text{ W m}^{-2}$)	FWHM (km s^{-1})
0.991	0.911 [S VIII] $^2\text{P}^{\circ}-^2\text{P}^{\circ}$	14.21 ± 0.56	531
1.252	1.252 [S IX] $^3\text{P}-^3\text{P}$	14.97 ± 0.39	646
1.431	1.430 [Si X] $^2\text{P}^{\circ}-^2\text{P}^{\circ}$	27.82 ± 0.64	355
	1.653 [Si X] $^4\text{P}-^4\text{P}$	<0.15	—
	1.936 [Si XI] $^3\text{P}^{\circ}-^3\text{P}^{\circ}$	<0.08	—
1.962	1.965 [Si VI] $^2\text{P}^{\circ}-^2\text{P}^{\circ}$	5.96 ± 2.77	550
2.481	2.483 [Si VII] $^3\text{P}-^3\text{P}$	6.42 ± 0.13	554

4.2 The coronal lines

We can use the dereddened fluxes of the silicon coronal lines for 2006 April 9 to estimate the temperature in the coronal region. The relative fluxes for lines in a coronal gas are discussed by Greenhouse et al. (1990) and we follow their analysis here, using collisional strengths from Osterbrock (1989) and Blaha (1969), and ionization fractions as a function of temperature from Shull & van

Steenberg (1982). We find that the temperature of the coronal gas is $\sim 930\,000 \text{ K}$ ($\sim 0.08 \text{ keV}$). We note that Ness et al. (2006c) deduced a temperature of a few $\times 10^6 \text{ K}$ from the coronal X-ray lines in a *Chandra* observation on June 4.5; the temperature for the coronal gas obtained here is broadly consistent with the X-ray data.

4.3 Origin of the IR emission

The deduced electron temperature, $\sim 10^4 \text{ K}$, implies that the hydrogen IR emission on all three dates is primarily due to emission by the red giant wind, ionized by the ultraviolet flash when RS Oph erupted. Emission by the shocked wind must also contribute to the total emission; however, IR observational evidence for this is apparent only on day 55.71 with the clear development of the S and Si coronal lines. As the shock propagates into, and eventually breaks out of, the wind (which is predicted to occur around $t \sim 70 \text{ d}$; see O’Brien et al. 1992) we expect that the contribution of the coronal gas will become dominant, and that of the cooler gas to decline and eventually disappear.

While there exist at least two regions with greatly differing temperatures in the environment of RS Oph, the determination of abundances is problematic. However, we anticipate that this will change when the shock breaks out of the giant wind. This next phase will be discussed in a forthcoming paper.

5 CONCLUSIONS

We have reported the early IR spectroscopy of the 2006 eruption of the recurrent nova RS Oph, covering the first 55 d. We find a spectrum dominated by hydrogen recombination lines arising from a gas at $\sim 10^4 \text{ K}$; silicon coronal lines prominent on day 55, implying a temperature for the coronal gas of $930\,000 \text{ K}$.

IR (and other) observations of this remarkable object are continuing and in subsequent papers we will present contemporaneous observations carried out with UKIRT and the *Spitzer* Space Observatory.

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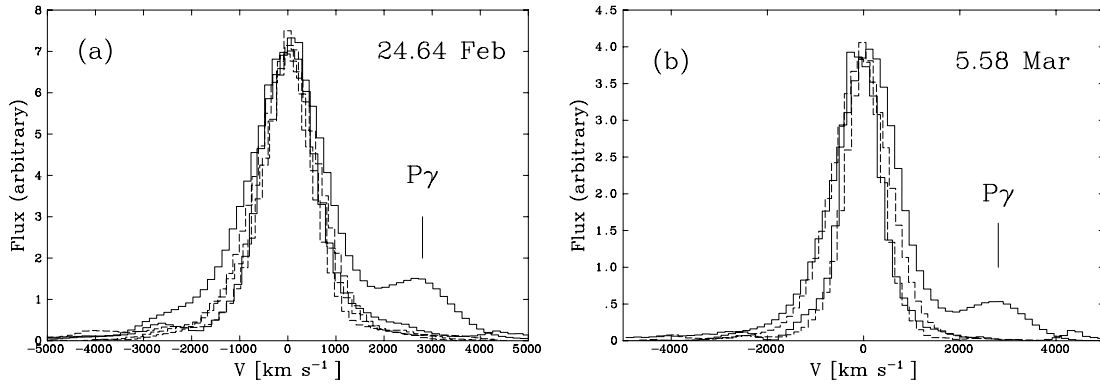


Figure 2. (a) Velocity of selected H I ($P\alpha$, $P\beta$, $Br\gamma$; broken lines) and He I (1.083, 2.058; solid lines) features on 2006 February 24.64 UT; (b) as (a), but for 2006 March 5.58 UT. Note in both cases the wings extend out to ~ 2500 km s $^{-1}$. The feature marked $P\gamma$ is the hydrogen recombination line in the wing of the He I $\lambda 1.083$ line.

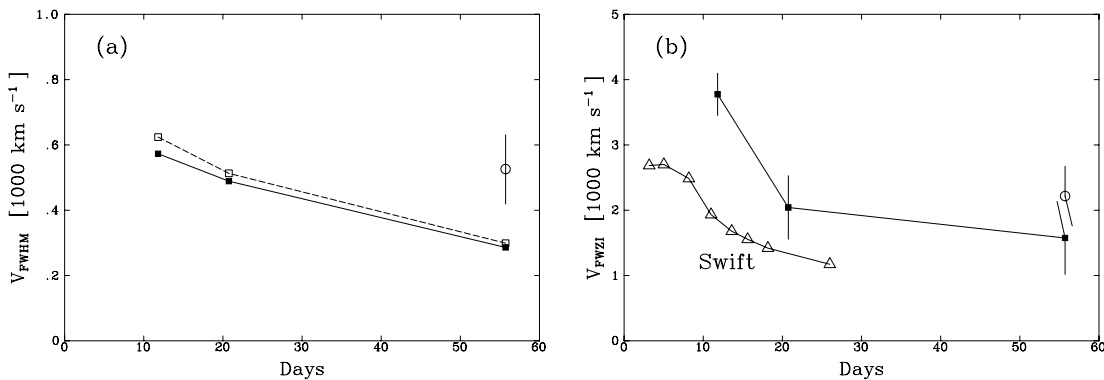


Figure 3. (a) Time-dependence of mean velocity, as determined from deconvolved FWHM of emission lines. Filled squares and continuous line, H I recombination lines only, open squares and broken line, all nebular lines; dispersion is typically 180 km s $^{-1}$ (day 11.81), 130 km s $^{-1}$ (day 20.75), 140 km s $^{-1}$ (day 55.71). Open circle is mean value for coronal lines in Table 3; error bar is dispersion. (b) As (a), but for mean velocity as determined from FWZI; open circle is mean FWZI for coronal lines. Error bars are dispersions. Open triangles show decline of shock velocity as deduced from Swift observations (Bode et al. 2006b).

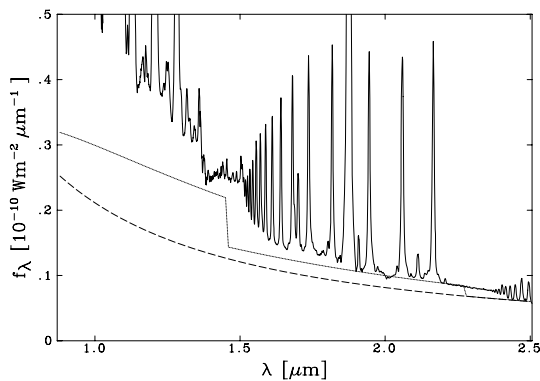


Figure 4. Spectrum for 2006 February 24 with nebular continuum at 10^4 K (dotted line) and 10^6 K (broken line).

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