SPITZER AND GROUND-BASED INFRARED OBSERVATIONS OF THE 2006 ERUPTION OF RS OPHIUCHI

A. EVANS,¹ C. E. WOODWARD,² L. A. HELTON,² R. D. GEHRZ,² D. K. LYNCH,³ R. J. RUDY,³ R. W. RUSSELL,³ T. KERR,⁴
 M. F. BODE,⁵ M. J. DARNLEY,⁵ S. P. S. EYRES,⁶ T. R. GEBALLE,⁷ T. J. O'BRIEN,⁸ R. J. DAVIS,⁸ S. STARRFIELD,⁹
 J.-U. NESS,⁹ J. DRAKE,¹⁰ J. P. OSBORNE,¹¹ K. L. PAGE,¹¹ G. SCHWARZ,¹² AND J. KRAUTTER¹³

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ABSTRACT

We present *Spitzer Space Telescope* and complementary ground-based infrared observations of the recurrent nova RS Ophiuchi, obtained over the period 64–111 days after the 2006 eruption. The *Spitzer* IRS data show a rich emission-line spectrum superimposed on a free-free continuum. The presence of fine-structure and coronal infrared lines lead us to deduce that there are at least two temperatures (1.5×10^5 and 9×10^5 K) in the ejecta/wind environment and that the electron density in the “cooler” region is $2.2 \times 10^5 \text{ cm}^{-3}$. The determination of elemental abundances is not straightforward, but on the assumption that the Ne and O fine-structure lines arise in the same volume of the ejecta, the O/Ne ratio is ≥ 0.6 by number.

Subject headings: binaries: close — binaries: symbiotic — infrared: stars — novae, cataclysmic variables — stars: individual (RS Ophiuchi)

1. INTRODUCTION

RS Oph is a recurrent nova (RN) that erupted in 1898, 1933, 1958, 1967, 1985, and possibly 1907 and 1945. The system consists of a semidetached binary system comprised of a Roche lobe–filling giant (RG) and a massive ($\sim 1.2 M_{\odot}$) white dwarf (WD; Shore et al. 1996; Fekel et al. 2000). As in classical novae, the eruption follows a thermonuclear runaway on the surface of the WD (Starrfield et al. 1988). In the case of the RS Oph class of RNe, however, the ejected material runs into, and shocks, a dense RG wind (Bode & Kahn 1985).

The 1985 eruption of RS Oph was, for the first time, the subject of a multiwavelength observational campaign, from the radio to the X-ray (Bode 1987). The most recent eruption, on 2006 February 12.83 (Hirose 2006; we take this to define the origin of time: $t = 0$), triggered an even more intensive campaign. Infrared (IR) observations by Das et al. (2006) and Evans et al. (2007, hereafter Paper I) show evidence for the shock, seen also at radio (O’Brien et al. 2006) and X-ray (Bode et al. 2006; Sokoloski et al. 2006; Ness et al. 2007; J. P. Osborne et al. 2007, in preparation)

wavelengths, as the ejecta interact with the RG wind. *Hubble Space Telescope* (HST) observations of the ejecta from the 2006 eruption (Bode et al. 2007) showed that emission in [O III] 5007 Å consists of two “rings” consistent with constant velocity expansion of the radio lobes seen earlier in the eruption (O’Brien et al. 2006). In contrast, the [Ne V] 3426 Å lines possibly arise from two “polar caps” at the extremities of the rings.

We present here further IR observations, obtained with the Infrared Spectrometer (IRS; Houck et al. 2004) on the *Spitzer Space Telescope* (Werner et al. 2004; Gehrz et al. 2007) and from ground-based facilities.

2. OBSERVATIONS

2.1. *Spitzer*

RS Oph was observed on 2006 April 16 ($t = 62.51$ days) and 2006 April 26 ($t = 72.54$ days) with *Spitzer* IRS as part of the Director’s Discretionary Time program ID 270. Observations were performed using all IRS modules, with IRS blue (13.3–18.6 μm) peak-up on RS Oph. The spectroscopy consisted of five cycles of 14 s ramps in Short-Low (SL) mode, five cycles of 30 s ramps in both Short-High (SH) and Long-Low (LL) modes, and five cycles of 60 s ramps in Long-High (LH) mode. IRS Basic Calibrated Data (BCD) products were processed with version 14.0.0 of the IRS pipeline. Details of the calibration and raw data processing are specified in the IRS Pipeline Description Document,¹⁴ version 1.0.

Bad pixels were interpolated in individual BCD products using bad-pixel masks provided by the *Spitzer* Science Center (SSC). For the low-resolution data, multiple data collection events were obtained at two different positions on the slit using *Spitzer*’s nod function. The low-resolution two-dimensional BCD products were differenced to remove the background flux contribution, and the data were extracted with SPICE¹⁵ using the default point-source extraction widths. For the high-resolution data, the point-spread function nearly fills the high-resolution slit length, so it is not possible to perform background subtraction using nod pairs. Instead, separate sky observations were used to construct

¹ Astrophysics Group, Keele University, Keele, Staffordshire ST5 5BG, UK; ae@astro.keele.ac.uk.

² Department of Astronomy, School of Physics and Astronomy, University of Minnesota, Minneapolis, MN 55455; chelsea@astro.umn.edu, ahelton@astro.umn.edu, gehrz@astro.umn.edu.

³ Aerospace Corporation, Los Angeles, CA 90009-2957; david.k.lynch@aero.org, richard.j.rudy@aero.org, ray.russell@aero.org.

⁴ Joint Astronomy Centre, Hilo, HI 96720; t.kerr@jach.hawaii.edu.

⁵ Astrophysics Research Institute, Liverpool John Moores University, Twelve Quays House, Birkenhead CH41 1LD, UK; mfb@astro.livjm.ac.uk, mjd@astro.livjm.ac.uk.

⁶ Centre for Astrophysics, University of Central Lancashire, Preston PR1 2HE, UK; spseyres@uclan.ac.uk.

⁷ Gemini Observatory, Hilo, HI 96720; tgeballe@gemini.edu.

⁸ Department of Physics and Astronomy, University of Manchester, Manchester, UK; tob@jb.man.ac.uk, rjd@jb.man.ac.uk.

⁹ School of Earth and Space Exploration, Arizona State University, Tempe, AZ 85287-1404; sumner.starrfield@asu.edu, ness@susie.la.asu.edu.

¹⁰ Harvard-Smithsonian Center for Astrophysics, Cambridge, MA 02138; jdrake@cfa.harvard.edu.

¹¹ Department of Physics and Astronomy, University of Leicester, Leicester LE1 7RH, UK; julio@star.le.ac.uk, kpa@star.le.ac.uk.

¹² Steward Observatory, University of Arizona, Tucson, AZ 85721; gschwarz@as.arizona.edu.

¹³ Landessternwarte, Königstuhl, D-69117 Heidelberg, Germany; j.krautter@lsw.uni-heidelberg.de.

¹⁴ See <http://ssc.spitzer.caltech.edu/irs/dh/PDD.pdf>.

¹⁵ See SPICE User’s Guide, version 1.3-beta1; <http://ssc.spitzer.caltech.edu/postbcd/spice.html>.

FIG. 1.—*Spitzer* spectrum of RS Oph for 2006 April 16 UT. Principal H recombination (n – m) and fine-structure lines are identified; many of the lines without identification are also H recombination lines originating in high ($n \geq 15$) levels.

a master sky that was subtracted from the individual BCD products to remove the background contribution. Extraction was performed in the same manner as for the low-resolution modules. For both resolution regimes, the extracted, background-corrected data were combined, using a weighted linear mean, into a single output data file. The point-to-point errors were estimated from the standard deviation of the flux at each wavelength bin except when there were fewer than three data points, in which case the errors generated by the SSC pipeline were added in quadrature to determine the final error. For the high-resolution modules, in the order overlap regions, the long-wavelength edge of the orders were much less reliable than the short-wavelength edges, and so only the short-wavelength regions of overlap were retained, i.e., the data from the lower order. As suggested by the SSC, data outside the ranges 5.2–14.5 μm for the SL module, 9.9–19.6 μm for the SH module, and 14.0–38.0 and 18.7–37.0 μm for the LL and LH modules, respectively, were discarded as unreliable. The spectral lines were fit using a least-squares Gaussian routine that fit the line center, line amplitude, continuum amplitude, and slope of the continuum. Individual segments of the IRS spectrum were shifted upward or downward by $\leq 10\%$ to ensure that segments adjoined smoothly. The spectrum for 2006 April 16 is shown in Figure 1; the spectrum for 2006 April 26 is not substantially different.

2.2. Ground-based Observations

The SpeX/IRTF data were obtained on 2006 May 1 ($t = 77.61$ days) and June 3 ($t = 110.72$ days), UT, using a $0.8'' \times 15''$ slit and a $10''$ north-south nod for background cancellation. No chopping was performed, and extinction corrections were not necessary because of the proximity of the calibrator star. Data reduction was done using SpeXTools (Cushing et al. 2004) with HD 164716 (B9 V) as the calibrator star. The flux of HD 164716 was obtained by using the Kurucz (1991, 1994) model of α Lyr scaled to the V magnitude of HD 164716. SpeXTools makes an automatic, and in this case small, correction for extinction based on the measured $(B - V)$ colors. United Kingdom Infrared Telescope (UKIRT) observations were performed on 2006 April 16 and 24 ($t =$ days 62.72 and 70.66, respectively) using the UIST instrument; details of the observations and data reduction are given in Paper I. The spectra from both telescopes, in the 1–2.6 and 2.8–4.0 μm ranges, are shown in Figure 2.

FIG. 2.—*Top*: Ground-based (UKIRT and IRTF) observations of RS Oph, obtained on 2006 April 24 (UKIRT) and May 1 (IRTF); the UKIRT spectrum has been displaced upward by $0.1 \times 10^{-12} \text{ W m}^{-2} \mu\text{m}^{-1}$. Coronal lines are identified. *Bottom*: Ground-based (UKIRT1, UKIRT2, and IRTF) observations of RS Oph, obtained on 2006 April 16 (UKIRT1), April 24 (UKIRT2), and May 1 (IRTF); spectra UKIRT2 and IRTF have been displaced downward by 0.1×10^{-12} and $0.2 \times 10^{-12} \text{ W m}^{-2} \mu\text{m}^{-1}$, respectively. Coronal lines are identified. Many of the narrow lines without identification are H recombination lines. All dates UT.

Optical ($BVr'iz'$) photometry was obtained by the robotic 2 m Liverpool Telescope (Steele et al. 2004), sited on the island of La Palma, Canaries. Observations commenced as soon as RS Oph had declined to a level that would not saturate the detectors; standard photometric reduction techniques were used.

3. DISCUSSION

The IR spectrum contains numerous emission lines. In the *Spitzer* wavelength range, these lines are superimposed on a continuum that declines with increasing wavelength as $f_\lambda \propto \lambda^{-2}$, consistent with free-free emission. The emission lines include hydrogen recombination lines, together with fine-structure lines, many of which are coronal; the hydrogen lines and free-free emission will be discussed elsewhere. We use flux ratios for lines from the same atomic species and within the same wavelength band to estimate the electron temperature in the region in which they originate; the line pairs are listed in Table 1. In Paper I, the $[\text{Si VI}]/[\text{Si X}]$ flux ratio enabled us to estimate the temperature of the shocked, IR-emitting gas to be $\approx 9.3 \times 10^5 \text{ K}$.

In this Letter, we have a wide range of ionic species and ionization stages at our disposal from which to estimate the electron temperature. Table 1 summarizes the collision strengths (Ω) at

TABLE 1
ESTIMATED TEMPERATURES FROM CORONAL LINES

Line ratio (1)	Flux Ratio (2)	Ω at 10^5 K ^a (3)	$\log T$ (K) (4)
[Si vi] 1.96 μm /[Si x] 1.43 μm	0.26	0.43, 0.13	5.96
[Mg vii] 5.50 μm /[Mg v] 5.61 μm	3.25	1.36, 1.06	5.85
[Ne iii] 15.55 μm /[Ne v] 14.32 μm	1.18	0.79, 2.16	5.18
[Ne iii] 15.55 μm /[Ne v] 24.32 μm	4.53	0.79, 0.75	5.15
[Ne vi] 7.65 μm /[Ne iii] 15.55 μm	7.29	1.70, 0.79	5.34
[Ne ii] 12.81 μm /[Ne v] 14.32 μm	0.99	0.40, 2.16	5.08

^a From Berrington et al. (1998) ([Si vi]), Butler & Zeppen (1994) ([Mg vi], [Ne iii]), Griffin et al. (2001) ([Ne ii]), Griffin & Badnell (2000) ([Ne v]), Lennon & Blair (1994) ([Mg vii]), Mitnik et al. (2001) ([Ne vi]), and Zhang et al. (1994) ([Si x]).

10^5 K (Paper I) for the species and ionization stages observed in the IR spectra. This temperature is the highest in these sources available in common to all species and stages of ionization, and the temperature dependence of Ω is relatively weak. The ionization fractions are from Sutherland & Dopita (1993). The [Mg vii] 5.50 μm feature is blended with the H16–7 recombination line ($\lambda = 5.52 \mu\text{m}$) at the resolution of the *Spitzer* SL mode. To correct for this, we assume case B (Osterbrock & Ferland 2006), to estimate the expected flux ratio $f(\text{H16–7})/f(\text{H9–7}) \approx 0.19$ at electron density $2 \times 10^5 \text{ cm}^{-3}$ (see below); we use the measured flux in the H9–7 line ($\lambda = 11.31 \mu\text{m}$) to correct the [Mg vii] line for the blend with H16–7. In view of the uncertainties (particularly in the applicability of case B), we should give the temperature derived from the Mg lines lower weight than that derived from other species.

The derived temperatures are given in Table 1 (col. [4]). The uncertainties in $\log T(\text{K})$ arising from uncertainties in the line fluxes are ± 0.2 . We note that the temperatures in Table 1, derived from the Ne lines (mean $\approx 1.5 \times 10^5$ K), are lower than those derived from Si and Mg lines. The temperature derived from the Si lines in this Letter is not significantly different from that given in Paper I during the early ($t = 55.7$ days) phase. Apparently there is a range of T -values present in the shocked region. This result, derived from analysis of the IR emission lines, is also suggested by X-ray data obtained on 2006 April 16 (Osborne et al. 2006) and follows naturally from models of the shock in RS Oph (O’Brien et al. 1992).

We assume that the electron temperature in the region in which the various Ne and [O iv] lines originate is 1.5×10^5 K, while that in the Si/Mg line emitting region is 9×10^5 K. The resulting critical densities n_c , below which radiative de-excitation begins to dominate over collisional de-excitation at the assumed temperatures, are given in Table 2.

We use the fluxes in the [Ne v] 14.3, 24.3 μm lines to estimate the electron density in the “cooler” line-emitting region. Denoting the 2P_2 , 2P_1 , and 1P_0 levels as levels “2,” “1,” and “0,” respectively, the fluxes f in the 14.32 and 24.3 μm lines are

$$f = n_u \frac{hc}{\lambda} A \frac{V}{4\pi D^2}, \quad (1)$$

where n_u (in cm^{-3} , $u = 2, 1$) is the population of the upper level, λ is the wavelength, A (s^{-1}) is the appropriate Einstein coefficient, V is the emitting volume, and D ($= 1.6$ kpc; Bode 1987) is the distance. Assuming that the [Ne v] 14.2, 24.3 μm lines arise in the same region, the flux ratio gives $n_2/n_1 \approx 0.6$. Detailed balance between radiative de-excitation, and electron collisional excitation and de-excitation among the three levels, together with the above values for n_2/n_1 and the electron

TABLE 2
CRITICAL DENSITIES

Identification	Term	λ (μm)	n_c^a (cm^{-3})
[Si x]	$^2P_{3/2}^o - ^2P_{1/2}^o$	1.4290	1.0×10^{10}
[Si vi]	$^2P_{1/2}^o - ^2P_{3/2}^o$	1.9625	1.7×10^9
[Si vii]	$^3P_{1/2}^o - ^3P_2^o$	2.4822	7.0×10^8
[Mg viii]	$^2P_{3/2}^o - ^2P_{1/2}^o$	3.0269	2.6×10^8
[S ix]	$^3P_{0-3} - ^3P_1$	3.7495	4.5×10^8
[Ne ii]	$^2P_{1/2} - ^2P_{1/3}$	12.808	2.8×10^6
[Ne v]	$^3P_{2-3} - ^3P_1$	14.311	1.4×10^5
[Ne iii]	$^3P_{1-3} - ^3P_2$	15.550	8.1×10^5
[Ne v]	$^3P_{1-3} - ^3P_0$	24.300	2.4×10^4
[O iv]	$^2P_{3/2} - ^2P_{1/2}$	25.871	2.0×10^4

^a At 1.5×10^5 K for Ne/O lines; at 9×10^5 K for Si/Mg lines; see text.

temperature, provide a value for the electron density n_e . We find $n_e \approx 2.2 \times 10^5 \text{ cm}^{-3}$ in the [Ne v] emitting region.

On the basis of radio imaging of the ejecta, O’Brien et al. (2006) estimate that the density in the radio-emitting shell was $\sim 10^{-17} \text{ g cm}^{-3}$ at $t \approx 14$ days. The wind/ejecta geometry is known to be complex (Bode et al. 2007); however, assuming that the density declines as t^{-2} (appropriate for a uniformly expanding shell of constant thickness), we expect the electron density would be $\sim 3 \times 10^5 \text{ cm}^{-3}$ at $t \approx 63$ days, consistent with our estimate from the Ne lines. From Table 2, we see that this is generally below the critical density for all Ne lines with the exception of [Ne v] 24.3 μm , the weakness of which compared with the other Ne lines may be consistent with a degree of collisional de-excitation.

We estimate the mass of emitting Ne, assuming that $n_0 + n_1 + n_2 = n(\text{[Ne v]})$, and using the [Ne v] fluxes from Table 2 and equation (1). We find $n(\text{[Ne v]}) \approx 8.4 \times 10^{-9} M_\odot$ for a distance of $D = 1.6$ kpc and, using the fractional abundance of [Ne v] at 1.5×10^5 K from Sutherland & Dopita (1993), we get $M(\text{Ne}) \approx 2 \times 10^{-7} (D/\text{kpc})^2 M_\odot$. In principle, we could also determine the mass of O; however, it is clear from Table 2 that the deduced n_e in the Ne/O region exceeds the n_c for the $^2P_{3/2}$ state of [O iv]. Consequently, we conclude only that $M(\text{O}) \gtrsim 1 \times 10^{-7} (D/\text{kpc})^2 M_\odot$.

In principle, it would be straightforward to use the fluxes in the IR Ne (and other species) lines, together with the fluxes in the H lines, to estimate the Ne : H ratio in the ejecta/wind mix. However, given the complex geometry of the ejecta as evidenced by the radio (O’Brien et al. 2006) and *HST* (Bode et al. 2007) observations we do not consider that this is justified until we have a better understanding of the environment of RS Oph. However, assuming that the emitting volumes of Ne and O coincide, we find $n(\text{O})/n(\text{Ne}) \gtrsim 0.6$, compared with a $\{n(\text{O})/n(\text{Ne})\}_\odot$ of 6.6 (Asplund et al. 2005).

In Figure 3, we plot the time dependence of the coronal line fluxes for which we have the longest time base, namely, S and Si; line fluxes for earlier data are taken from Paper I. It is curious that the S line fluxes decline monotonically over the first ~ 80 days of the eruption, whereas there is a distinct minimum in the line fluxes around $t \approx 70$ days for the Si lines (the errors in the measured fluxes are typically $\approx 5\%$). We consider that this result is real, because (1) there is a consistent pattern in the behavior of the Si and S lines and (2) it coincides (within the time resolution) with a distinct “kink” in the $BVr'i'z'$ light curves. There is no corresponding break in either the X-ray light curve (which coincides with the decline of the supersoft phase; Ness et al. 2007) or in the variation of the hardness ratio (J. P. Osborne et al. 2007, in preparation; see Fig. 3, which shows only the V and B light curves for clarity).

FIG. 3.—Decline in coronal line fluxes (filled circles: [Si VI]; open circles: [Si IX]; open squares: [Si VIII]; filled triangles: [Si X]; filled squares: [S VIII]); ordinate (left axis) is line flux in $10^{-13} \text{ W m}^{-2}$. Swift fluxes in the 0.3–10 keV channel are shown as filled circles; ordinate (left axis) is in counts s^{-1} . Liverpool Telescope (BV) light curves are shown as open triangles (right axis); B data have been displaced upward by 1.5 mag for clarity. Straight lines are least-squares fits to light curves for the $40 < t(d) < 75$, $75 < t(d) < 120$ ranges, illustrating a break in the light curve around $t \approx 70$ days. See text for discussion.

In *classical novae*, fluctuations in the visual light curve are often related to fluctuations in the mass loss from the WD and the behavior of the pseudophotosphere; however, it is difficult to see how this can also lead to changes in the coronal line fluxes. Accordingly, we consider it unlikely that this behavior is directly related to the mass loss.

For the 1985 eruption of RS Oph, O'Brien et al. (1992) estimated that breakout of the shock from the edge of the RG wind occurred ~ 60 –70 days after the eruption, corresponding to 70–80 days after the 2006 eruption, allowing for the greater inter-eruption interval. While this is close to the day 70 event in the 2006 eruption, it is unlikely that the behavior seen in Figure 3 is related to any simple breakout phenomenon, which will be far more complex than the spherically symmetric model of O'Brien et al. (1992). Furthermore, while the electron density we determine is for the Ne/O region, it is likely that this value is not atypical and the disparity between the n_e (Table 2) and n_e values suggest that the behavior depicted in Figure 3 is not a collisional de-excitation effect. Figure 3 suggests we may be

seeing the combined effects of recombination, abundance gradients, and element segregation, but a detailed discussion is beyond the scope of this Letter.

4. CONCLUDING REMARKS

We have presented the *Spitzer* IRS spectrum of RS Oph during its 2006 eruption, the first mid-IR observations of a RN in outburst. The IR spectrum, from 1 to $30 \mu\text{m}$, shows the rich fine-structure (including) coronal and H recombination line spectrum of the shocked RG wind. There are at least two temperature regimes in the shocked wind, and the deduced electron density is consistent with extrapolation from radio observations earlier in the eruption.

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Facilities: Spitzer(IRS), UKIRT, IRTF, Liverpool:2m

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