Mon. Not. R. Astron. Soc. **398,** 375–384 (2009) doi:10.1111/j.1365-2966.2009.15141.x

Detection and evolution of the CO ($\Delta v = 2$) emission in Nova V2615 Ophiuchi (2007)

R. K. Das,★ D. P. K. Banerjee and N. M. Ashok

Astronomy & Astrophysics Division, Physical Research Laboratory, Navrangpura, Ahmedabad 380009, India

Accepted 2009 May 27. Received 2009 May 13; in original form 2009 March 24

ABSTRACT

We present near-infrared (1–2.5 μm) spectroscopic and photometric results of Nova V2615 Ophiuchi which was discovered in outburst in 2007 March. Our observations span a period of ∼80 d starting from 2007 March 28 when the nova was at its maximum light. The evolution of the spectra is shown from the initial P Cygni phase to an emission-line phase and finally to a dust formation stage. The characteristics of the *JHK* spectra are very similar to those observed in a nova outburst occurring on a carbon–oxygen white dwarf. We analyse an observed line at 2.088 μm and suggest that it could be due to Fe II excited by Lyman α fluorescence. The highlight of the observations is the detection of the first overtone bands of carbon monoxide (CO) in the 2.29–2.40 μm region. The CO bands are modelled to estimate the temperature and mass of the emitting CO gas and also to place limits on the $^{12}C/^{13}C$ ratio. The CO bands are recorded over several epochs, thereby allowing a rare opportunity to study the evolution from a phase of constant strength through a stage when the CO is destroyed fairly rapidly. We compare the observed time-scales involved in the evolution of the CO emission and find a good agreement with model predictions that investigate the chemistry in a nova outflow during the early stages.

Key words: line: identification – techniques: spectroscopic – stars: individual: V2615 Oph – novae, cataclysmic variables.

1 INTRODUCTION

V2615 Ophiuchi (Nova Ophiuchi 2007) was discovered by Nishimura (2007) at a visual magnitude of 10.2 on 2007 March 19.812 UT. No star was visible at the position of the nova on a film taken by Nishimura on 2007 March 17.82 UT and earlier survey films since 2005 (limiting mag 11.5–12). The discovery report was supplemented by several other observers from observations obtained close to and around the time of discovery. These reports, in conjunction with the lack of a detection of the nova in images taken just a few days prior to discovery, imply that the nova was discovered a few days before maximum light which was reached on March 28.

The early low-resolution optical spectra (410–670 nm, resolution 1500) of V2615 Oph by Naito & Narusawa (2007) on March 20.84 UT showed Balmer lines having P Cyg features and Fe II lines (multiplets 42, 49, 74), suggesting that the nova is an 'Fe II'-type nova. The full widths at half-maximum (FWHMs) of the Hα, Hβ and Hγ emissions were 920, 810 and 790 km s^{-1}, and the displacement of the P Cyg absorptions from the Balmer emission peaks was 940, 820 and 830 km s^{-1}, respectively. Early optical spectra were also obtained by Munari et al. (2007, 2008) on March 22.17 and 24.18 UT. On March 22.17 UT, the spectrum was characterized by weak emission lines with P Cygni profiles. The strongest emission lines were due to Fe II multiplets 27, 28, 37, 38, 42, 48, 49, 55 and 74; Si II multiplets 2, 3, 4 and 5; N I multiplet 3; Ca II H & K; Na I D1 and D2; and O I 777.2 nm (the O I line showed the second strongest emission component after Hα). With respect to the peak of the Hα emission, the absorption terminal velocity was −1415 km s^{-1}, and the mean velocity −910 km s^{-1}. In comparison to the March 22.17 UT spectrum, the March 24.18 UT spectra show large changes: mainly a marked reduction in equivalent width of emission lines and reduction in outflow velocity of absorption components of P Cyg profiles.

Infrared (IR) observations of V2615 Oph have been made by Das, Ashok & Banerjee (2007) and Rudy et al. (2007) – some of the findings in Rudy et al. (2007) are subsequently discussed in detail. The highlight of the Das et al. (2007) report was the detection of first overtone CO emission in the nova – similar emission has been recorded previously in only a few novae. In this paper, we present *JHK* spectrophotometry of V2615 Oph between March 28 and June 9. The spectroscopic results are fairly extensive as spectra have been obtained on 15 occasions during this period.

2 OBSERVATIONS

The near-IR *JHK* spectrophotometric data of V2615 Oph presented here were acquired at the Mount Abu 1.2-m telescope. The first

★E-mail: rkdas@prl.res.in (RKD); orion@prl.res.in (DPKB); ashok@prl.res.in (NMA)

Table 1. A log of the spectroscopic observations of V2615 Oph. The date of outburst is taken to be 2007 March 19.812 UT.

Date 2007 (UT)	Days since outburst	Integration time (s) J	H	K
Mar. 28.928	09.116	60	45	45
Mar. 31.917	12.105	60	60	60
Apr. 02.901	14.089	45	40	60
Apr. 03.893	15.082	60	40	45
Apr. 05.904	17.092	60	45	60
Apr. 06.890	18.078	60	60	60
Apr. 07.915	19.103	75	75	75
Apr. 16.942	28.130	90	90	90
Apr. 18.888	30.076	90	75	90
Apr. 27.869	39.057	90	60	90
Apr. 30.830	42.018	90	90	90
May 02.835	44.023	90	90	90
May 06.832	48.020	90	60	60
May 08.840	50.028	90	90	90
Jun. 09.846	82.034	500	120	90

Table 2. A log of the photometric observations of V2615 Oph. The date of outburst is taken to be 2007 March 19.812 UT.

Date 2007 (UT)	Days since outburst	Magnitudes J	H	K
Mar. 28.993	09.181	6.26	5.83	5.39
Mar. 31.961	12.149	6.94	6.51	5.90
Apr. 02.970	14.158	6.49	6.07	5.54
Apr. 05.993	17.181	6.54	6.14	5.64
Apr. 07.956	19.144	6.93	6.57	6.18
Apr. 15.979	27.167	7.36	7.07	6.53
Apr. 16.981	28.169	7.22	6.97	6.46
Apr. 18.940	30.128	7.30	6.96	6.62
Apr. 26.885	38.073	7.76	7.53	7.09
Apr. 30.906	42.094	7.98	7.68	7.18
May 02.932	44.120	8.14	7.84	7.07
May 06.934	48.122	8.13	7.72	6.79
May 08.882	50.070	7.94	7.32	6.26
Jun. 09.887	82.075	9.31	7.62	5.34

observation was recorded on the night of 2007 March 28 while the nova was close to the optical maximum. The nova was then observed regularly until the arrival of the monsoon, when inclement weather brought our monitoring to an end. The instrument used was the Near-Infrared Imager/Spectrometer with a 256 × 256 HgCdTe NICMOS3 array. The observation logs for spectroscopy and photometry are presented in Tables 1 and 2, respectively. Near-IR *JHK* spectra were obtained at similar dispersions of ∼9.75 Å pixel^{-1} in each of the J, H, K bands. In each band, spectra were recorded at different positions along the slit (slitwidth ∼1 arcsec) to provide for the background subtraction. To remove telluric features in the spectra of V2615 Oph, we obtained spectra of a nearby standard star (SAO 184301; spectral type A0V) at a similar airmass to the target.

The spectra were extracted using the APEXTRACT task in IRAF, and were calibrated in wavelength using a combination of OH sky lines and telluric lines in the extracted spectra. Following the standard reduction procedure, the nova spectra were then ratioed with the spectra of the standard star from which the hydrogen Paschen and Brackett absorption lines had been manually removed. These ratioed spectra were multiplied by a blackbody curve corresponding to the effective temperature of the standard star to yield the final spectra.

V2615 Oph was monitored photometrically in the *JHK* bands for 85 d after discovery. Photometric observations were performed under photometric sky conditions using the imaging mode of the NICMOS3 array. In each of the J, H, K filters, several frames at five dithered positions offset typically by 20 arcsec were obtained of both the nova and a selected standard star (2MASS J16232693−2425291; $J = 7.340$, $H = 6.027$, $K = 5.464$). Near-IR *JHK* magnitudes were then derived using the IRAF aperture photometry task APPHOT. The derived *JHK* magnitudes are given in Table 2; the typical errors associated with them lie in the range of 0.02 to 0.04 mag.

3 RESULTS

3.1 Optical and near-IR light curve

The optical light curve of V2615 Oph is presented in Fig. 1. The object was discovered about 9 d before its maximum which was reached on 2007 March 28 at $V = 8.52$. On the whole, the object shows a steady post-maximum decline in brightness of 0.05 mag d^{-1} for the first ∼80 d after maximum. Subsequently, there is a steep decline in the light curve due to dust formation – this aspect is addressed below in the discussion of the near-IR light curve. From the light curve, we estimate t_2 and t_3 – the time for a drop of 2 and 3 mag, respectively, in the visual brightness – to be 33 and 58 d, respectively. The use of these values of t_2 and t_3 in various maximum magnitude versus rate of decline (MMRD) relationships [della Valle & Livio (1995), Capaccioli et al. (1989) and Cohen (1988) for t_2; Schmidt (1957) for t_3] leads to closely similar values for the absolute visual magnitude and we obtained a mean value of $M_v = 7.16 \pm 0.12$. The extinction towards the object can be estimated in two ways. Rudy et al. (2007), using the strength of the O I lines, have determined the reddening prior to dust formation to be $E(B - V) = 1.0$ (or $A_v = 3.1$ mag). This leads to a distance estimate of $D = 3.25$ kpc to the object. To show that this value

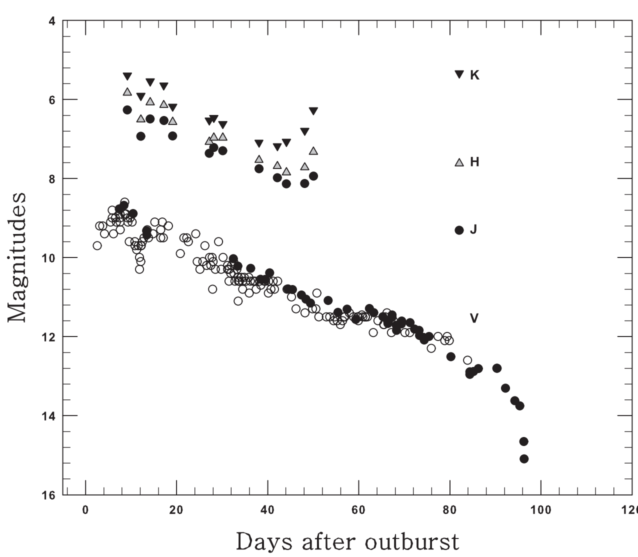

Figure 1. The V-band light curve is shown at the bottom (photoelectric/CCD measurements shown by filled circles; visual estimates by open circles) based on data from IAU circulars, AAVSO and AFOEV data bases. At the top are shown the near-IR J-, H- and K-band light curves based on the present observations (J: filled circles, H: grey triangles – up; K: black triangles – down.)

of A_v is reasonable, we use the extinction data of Marshall et al. (2006) which show that A_{Ks} is constant at $= 0.34$–0.36 beyond 3 and up to 12 kpc in the direction of V2615 Oph. Thus, assuming $A_v/A_{Ks} \sim 11$ (Koornneef 1983), a maximum value of $A_v = 3.85$ is suggested towards V2615 Oph, thereby leading to a lower limit on the distance of $D = 2.3$ kpc. For the present work, we adopt the distance estimate derived from the Rudy et al. (2007) findings, namely $D = 3.2$ kpc.

Our IR observations, begun close to optical maximum, show a steady decline for the first 42 days. After this, each of the J, H, K magnitudes show an increasing trend possibly indicating the onset of dust formation. However, no corresponding sharp decline in the optical light curve is seen at this stage, implying that any dust that may have formed is likely to be optically thin. Rudy et al. (2007) have reported 0.4 to 2.5 μm spectroscopy of V2615 Oph on 2007 May 7 and 0.8 to 5.5 μm spectroscopy on 2007 May 31. They find that the nova evolved dramatically between the two observations (i.e. between May 7 and 31) due to the formation of dust. The reddening derived from the O I lines increased from $E(B - V) = 1.0$ to 1.3 in their data. Our last observations on 2007 June 9 show a significant IR excess due to emission by the newly formed dust.

3.2 General characteristics of the *JHK* spectra

The lines in the earliest spectrum of March 28, when the nova was at maximum light, show P Cygni structure with a prominent absorption component. By following the Paβ line, for example, it is seen that the P Cygni absorption component persists for at least 10 d (up to April 7), indicating that mass loss extends over a prolonged period. The minimum of the absorption component is found to be displaced from the emission peak by $\sim$950 km s^{-1} on March 28, but this value changes closer to $\sim$1400–1500 km s^{-1} for March 31 and other subsequent dates up to April 7. Variations of a similar nature in the outflow velocities were also noted by Munari et al. (2007) on March 22 and 24 – when the nova was on its rise to maximum light. Clearly, the mass-loss process and its kinematics during the early stages are not uniform.

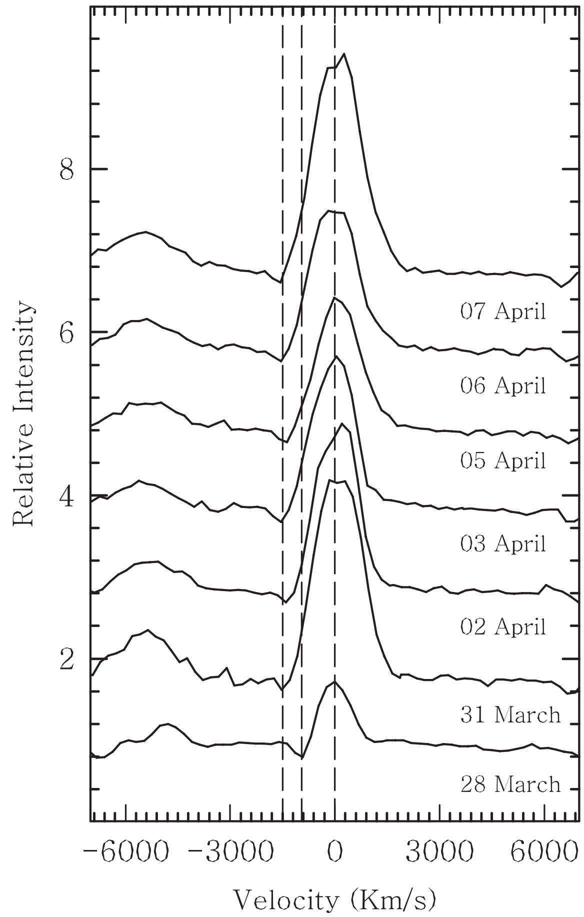

Figure 2. The Paschen β 1.2818 μm line is presented on different days to show the evolution of the profile. The two dotted lines, at left of the line centre, are positioned at -950 and -1500 km s^{-1}, respectively, to indicate the change in position of the P Cygni absorption minimum with respect to the emission peak [further details are in given in the text (Section 3.2)].

Mosaics of the J-, H- and K-band spectra are presented in Figs 2, 3 and 4, respectively. The early spectrum of V2615 Oph is typical of a carbon–oxygen nova (CO nova) – examples of which are V2274 Cyg (Rudy et al. 2003), V1419 Aql (Lynch et al. 1995) and V1280 Sco (Das, Banerjee & Ashok 2008). In addition to lines of H, He, N and O, these novae show strong lines of carbon, for example, in the wavelength region 1.16 to 1.18 μm in the J band. In contrast, such carbon lines are weak in the spectra of ONeMg novae, for example, in the novae V597 Pup and V2491 Cyg (Naik, Banerjee & Ashok 2009). The IR-based classification of V2615 Oph is consistent with its optical classification as an Fe II-type nova (Naito & Narusawa 2007). Fe II novae are believed to be associated with explosions on CO white dwarfs (Williams 1992). We have presented the line identification in Table 3 but do not show them marked on the spectra as a separate figure. However, since the lines are very similar to those seen in V1280 Sco, the line-identification figure for V1280 Sco could be referred to, which contains greater detail (Das et al. 2008). The most prominent lines in the *JHK* spectra of V2615 Oph are the Paschen and Brackett hydrogen recombination lines; the Lyman β and continuum fluoresced O I lines at 1.1287 and 1.3164 μm; the He I lines at 1.0830 and 2.0585 μm. Strong carbon lines are seen in the J band and also in the H band redwards of the Brackett 11 line. Among subtle features, the presence of a C I line at 1.6 μm, which could be mistaken as just another member of the H-band Brackett series lines, should not be missed. The region between 1.2 and 1.275 μm contains the complex blend of a large number of N I and C I lines that are often seen in the early spectra of CO novae. The presence of several lines of Na I and Mg I (the prominent ones being at 1.1404, 1.5040, 1.5749, 2.2056 and 2.2084 μm) is worth noting as it may be inferred, from their presence, that dust will form in a nova. During the analysis of V1280 Sco, one of the conclusions that emerged was that the lines of Na I in particular, and also of Mg I, are associated with low excitation and ionization conditions (Das et al. 2008). Such conditions necessarily imply the existence of a cool zone which is conducive for dust formation. This was observationally corroborated in the case of several novae, in which these lines were detected, and which proceeded to form dust [e.g. V2274 Cyg (Rudy et al. 2003), V1419 Aql (Lynch et al. 1995), NQ Vul (Ferland et al. 1979), V705 Cas (Evans et al. 1996), V842 Cen (Wichmann et al. 1991), V1280 Sco (Das et al. 2008); for a more detailed discussion see Das et al. (2008)]. The presence of these lines in V2615 Oph, and the dust formation witnessed subsequently, is consistent with this scenario. The formation of dust is clearly reflected in the last spectrum of June 9. Each of the spectra in the individual J, H and K bands shows the continuum level increasing to longer wavelengths showing the development of an IR excess associated with dust.

The most interesting spectral features in V2615 Oph are the first overtone CO bands in the K band which is discussed in the following

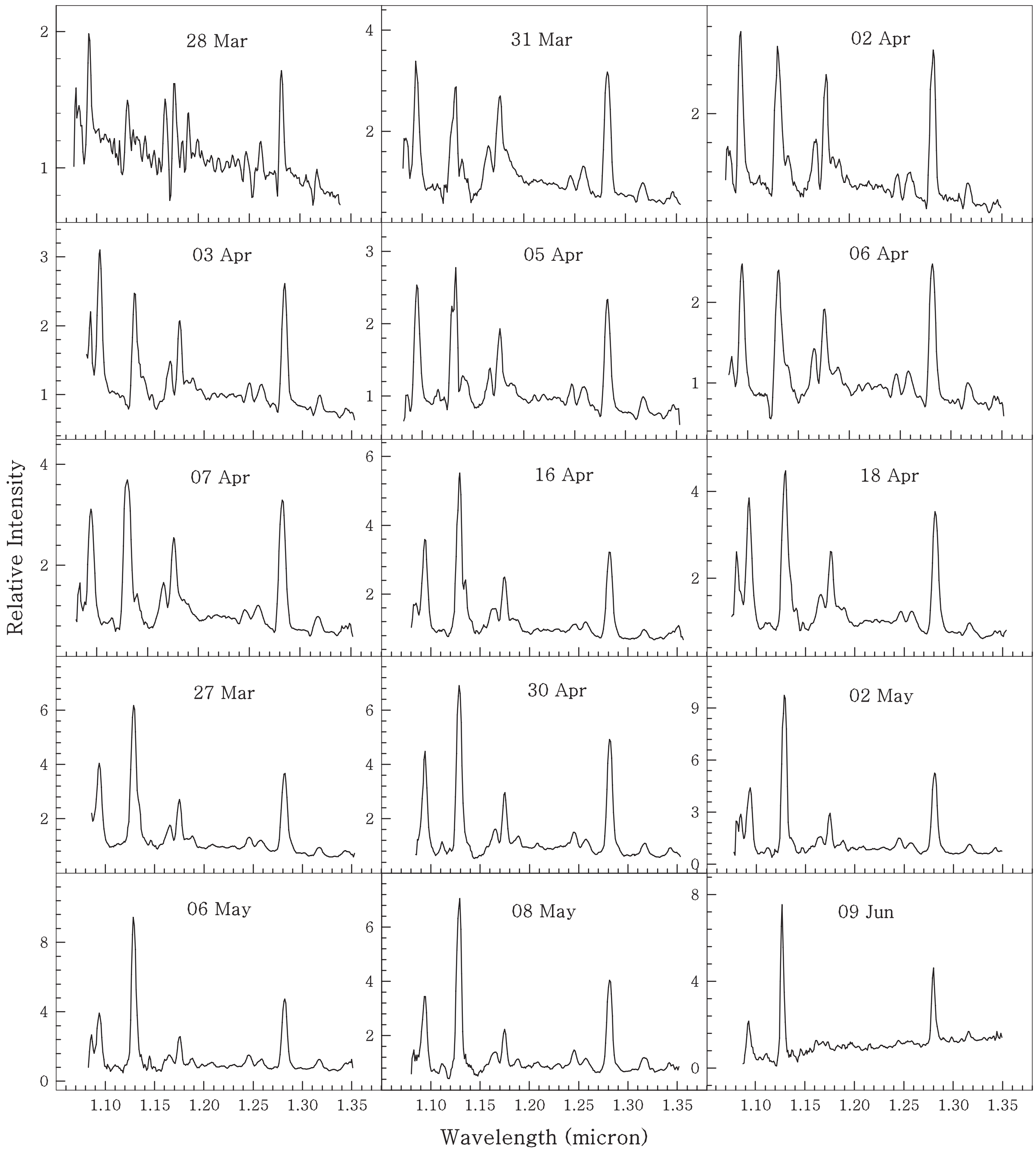

Figure 3. The *J*-band spectra of V2615 Oph on different days with the flux normalized to unity at 1.25 μm.

sections. The other atomic lines in V2615 Oph are similar to those seen in carbon–oxygen novae and which were discussed in our earlier work on V1280 Sco – hence they are not discussed further here. There is, however, an unidentified line at 2.088 μm which is discussed below.

3.3 An unidentified line at 2.0888 μm: possibly an Fe II line excited by Lyman α fluorescence?

We note the presence of an emission line at ~2.0890 μm in the *K* band that is seen fairly prominently in the spectra from April 27 onwards. We propose that this is an Fe II line and additionally investigate whether this line could be excited by Lyman α (Lyα) fluorescence. In the near-IR, there are a few Fe II lines seen in the spectra of novae, which are believed to be primarily excited by Lyman α and Lyman continuum (Lyc) fluorescence. Among these are the so-called '1 μm Fe II lines' at 0.9997, 1.0171, 1.0490, 1.0501, 1.0863 and 1.1126 μm seen in several novae (Rudy et al. 1991, 2000). In addition, two other Fe II lines at 1.6872 and 1.7414 μm in the *H* band are also proposed to be pumped by the same mechanism (Banerjee, Das & Ashok 2009). The *H*-band lines are prominently detected in the 2006 outburst of recurrent nova RS Oph (Banerjee et al. 2009), in the slow nova V2540 Ophiuchi (Rudy et al. 2002), and possibly also in the recurrent nova CI Aquila (Lynch et al. 2004). These *H*-band lines could be present in the spectra of other novae too, but have evaded detection because of blending

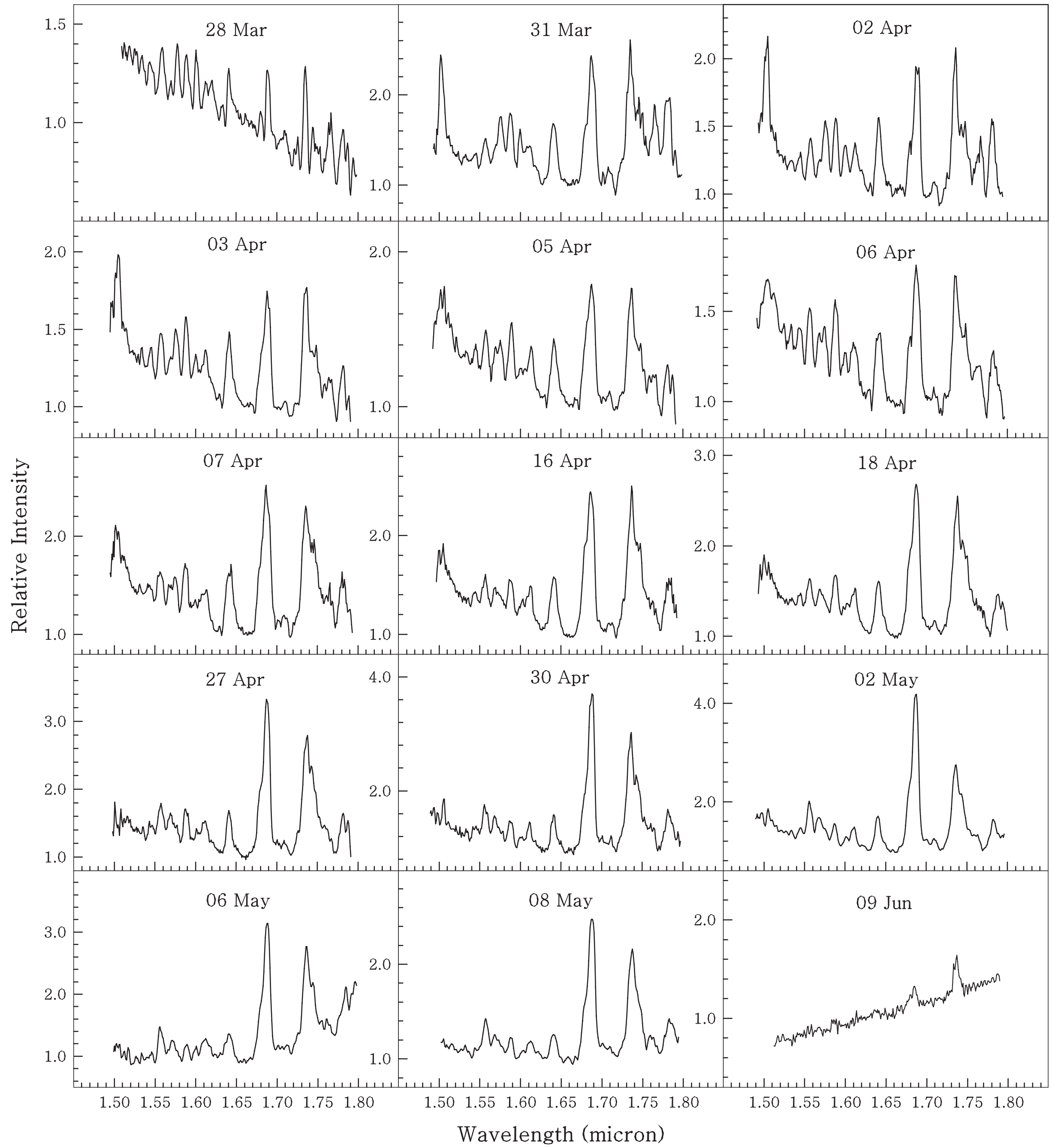

Figure 4. The *H*-band spectra of V2615 Oph on different days with the flux normalized to unity at 1.65 μm.

with the Br 11 (1.6806 μm) and C I lines at 1.6890 and 1.7449 μm which lie close by. However, these lines are well resolved in RS Ophiuchi (Banerjee et al. 2009), especially during the later stages of its outburst when all linewidths in RS Oph become small – due to deceleration of the shocked, emitting gas – and blending effects are thereby minimal.

The excitation mechanism of the Fe II lines appears to be a three-step process (Johansson & Jordan 1984; Bautista, Rudy & Venturini 2004 and references therein; Banerjee et al. 2009). Fe II is first excited from low-lying levels by Lyα or Lyc to a high energy level (typically 11 to 13 eV above ground state) which decays, in the second step, to feed the upper level associated with the observed Fe II line (the decay of this upper level, in the third step, leads to the line proper). The 2.0888 μm line results from the decay of the $3d^6(^3_2F)4sc^4F$ term at ~6.209 eV above the ground state. It so happens that this term can be fed by not just one but, in fact, several high lying levels – each of these high lying levels capable of being pumped by Lyα photons. As illustrative examples, it is noted that photons at 1213.738, 1214.067, 1216.239, 1216.272 and 1217.152 Å, which are reasonably coincident with the Lyα line centre at 1215.671 Å, can excite transitions from the low lying (5D) 4s a^4D term in Fe II (at 1.076 eV above ground state) to the higher excited levels [(5D) 4p 4F, (5D) 4p 4D and (3P) 4p 4P, respectively, at around 11.3 eV]. Since H I lines in novae (Lyα included) are broad with widths extending up to a few thousands of km s^{-1} (1 Å corresponds to about 250 km s^{-1} at the Lyα wavelength), these

Table 3. List of observed lines in the *JHK* spectra.

Wavelength (μm)	Species	Other contributing lines & remarks
1.0830	He I	
1.0938	Paγ	
1.1116	u.i.	
1.1126	Fe II	
1.1287	O I	
1.1330	C I	
1.1381, 1.1404	Na I	
1.1600–1.1674	C I	Strongest lines at 1.1653, 1.1659, 1.16696
1.1748–1.1800	C I	Strongest lines at 1.1748, 1.1753, 1.1755
1.1828	Mg I	
1.1880	C I	Blended with C I at 1.1896
1.2074, 1.2095	N I	Blended with C I at 1.2088
1.2187, 1.2204	N I	
1.2249, 1.2264	C I	
1.2329	N I	
1.2382	N I	
1.2461, 1.2469	N I	
1.2562, 1.2569	C I	
1.2818	Paβ	
1.3164	O I	
1.3465	N I	
1.5040	Mg I	
1.5184	Br 20	
1.5256	Br 19	
1.5341	Br 18	
1.5439	Br 17	
1.5557	Br 16	
1.5685	Br 15	
1.5749	Mg I	
1.5881	Br 14	
1.6005	C I	
1.6109	Br 13	
1.6407	Br 12	
1.6806	Br 11	
1.6890	C I	
1.7109	Mg I	
1.7200–1.7900	C I	Several C I lines
1.7362	Br 10	
2.0585	He I	Blended with u.i. 2.0620
2.0888	u.i.	Fe II ? (see Section 3.3)
2.1023	C I	
2.1156–2.1295	C I	Blend of several C I lines
2.1452	Na I	
2.1655	Br γ	
2.2056, 2.2084	Na I	
2.2156–2.2167	C I	
2.29–2.40	CO	$\Delta v = 2$ bands
2.2906	C I	
2.3130	C I	
2.3348, 2.3379	Na I	

photons could contribute to the fluorescence process, even though they are not coincident with the Lyα line centre. These higher levels at 11.3 eV can then decay via ultraviolet photons to the upper level of the 2.0888 μm transition. The Kurucz atomic data,[1] on which the present analysis is based, indicate that there are additional Lyα fluorescing candidate lines (apart from the five discussed here), all within a few angstroms of the Lyα line centre, that could also contribute to the Lyα fluorescence process. Therefore, the 2.0888 μm line could be excited by Lyα fluorescence, if its identification with Fe II is correct.

A few cautionary words regarding the identification of the 2.0888 μm with Fe II would be appropriate. In case the Fe II identification is correct, then a few other Fe II lines – as mentioned earlier – could also be expected, namely lines at 0.9997, 1.0171, 1.0490, 1.0501, 1.0863, 1.1126, 1.6872 and 1.7414 μm. Unfortunately, the first four of these lines are not covered in our spectra while it is difficult to make any definitive conclusion about the 1.0863 μm line which is in a region of low signal since it is at the edge of our spectral window. However, the 1.1126 μm line is seen. It is also difficult to draw a firm conclusion whether the 1.6872 and 1.7414 μm lines are present. Unfortunately, both these lines occur at positions close to strong C I and H I lines (Table 3) which could lead to line blending. In essence, further detections of the 2.0888 μm line in other novae are desirable to enable a secure identification.

3.4 Modelling the CO emission

The CO emission is modelled by assuming the gas to be in thermal equilibrium characterized by the same rotational and vibrational temperature. The populations of the different levels can then be determined from the Boltzmann distribution since the energy of individual rovibrational levels is known (we adopt a similar model to Spyromilio et al. 1988). In our calculations, we have used values for the rotational and vibrational constants of $^{12}C^{16}O$ and $^{13}C^{16}O$ from the National Institute of Standards and Technology (NIST) data base[2] except for the vibrational constants for ^{13}CO which are adopted from Benedict et al. (1962). We have not considered other isotopic species like $^{12}C^{17}O$, $^{14}C^{16}O$, etc. since they are expected to have low abundances.

The line luminosity E of each rovibrational transition can be calculated from knowing the population of the upper level involved in the transition, the associated transition probability for the line (Goorvitch 1994) and the photon energy ($h\nu$) associated with the transition. To enable a comparison of the model value with the observed data, the line luminosity E calculated above, which is in units of erg s^{-1}, needs to be converted into units of the observed flux (we use units of erg s^{-1} cm^{-2} μm^{-1}). This conversion is achieved by first dividing E by $4\pi D^2$ (where D is the distance to the source) and subsequently scaling E to a unit of wavelength. In implementing the last step, it is assumed that each rotational line is Gaussian in shape. Then, the peak intensity of such a Gaussian (plotted with its ordinate units in erg s^{-1} cm^{-2} μm^{-1}; abscissa in units of μm) can be determined analytically by ensuring that the integrated area under this Gaussian matches the known quantity $E/4\pi D^2$. The Gaussian line profiles of all the rotational lines are thus generated and co-added together to generate the resulting envelope of the CO emission. To this envelope, we add the appropriate continuum, the level of which is determined from broad-band photometry of Table 2, to provide a model CO emission spectrum for a particular day. Such model spectra matching the observed data of March 28 and 31 and April 2 and 3 are shown in Fig. 5. The parameters that are fed as inputs for the modelling are the total mass of the CO gas (M_{CO}), the $^{12}C/^{13}C$ ratio (designated as α) and the gas temperature (T_{CO}). Once M_{CO} and α are chosen, the total number of ^{12}CO and ^{13}CO molecules is fixed – thus the level populations in thermal equilibrium at a temperature T_{CO} can be calculated and the emerging spectrum determined. The estimated model CO flux is therefore an absolute quantity but it

[1] http://cfa-www.harvard.edu/amp/ampdata/kurucz23/sekur.html

[2] http://physics.nist.gov/PhysRefData/MolSpec

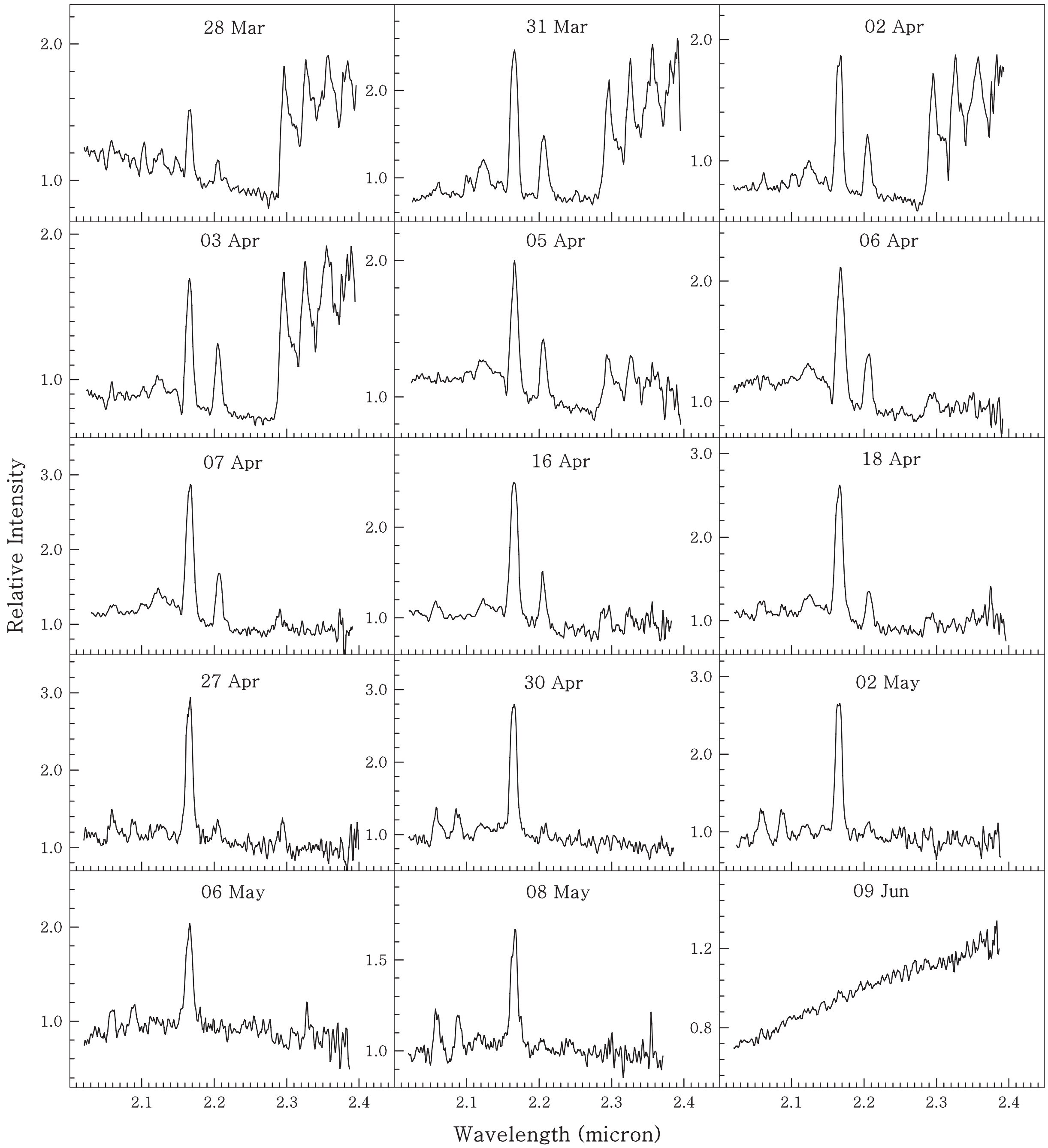

Figure 5. The *K*-band spectra of V2615 Oph on different days with the flux normalized to unity at 2.2 μm.

could, however, be subject to certain errors. One of these is the value of the distance D to the source – the model CO flux scales as D^2.

Different combinations of the parameters M_{CO}, α and T_{CO} were tried to find the best fit between model spectra and the observed data. The characteristics of the CO emission remain fairly constant between March 28 and April 3. The profiles of Fig. 6 are reasonably well modelled with closely similar values of T_{CO} and M_{CO} in the range 4000–4300 K and 2.75×10^{-8} to $3.25 \times 10^{-8}\,\mathrm{M}_{\odot}$, respectively. Some of the difficulties encountered in the modelling, and also possible sources of errors involved therein, are as follows. It is noted that changes brought about in the spectra by either changing T_{CO} or changing M_{CO} can be similar in the following respect. Increasing either of these quantities enhances the absolute level of the CO emission. However, the contributions of these two parameters can be distinguished by the fact that increasing M_{CO} just scales up the overall level of the CO emission level. On the other hand, increasing T_{CO} not only increases the CO flux but also changes the intensities of the different vibrational bands, relative to each other, within the first overtone. Therefore, vibrational bands from $\upsilon \geq 5$ would help the analysis, but they are located in regions of poor atmospheric transmission, beyond the spectral coverage, and the $\upsilon =$ 5–3 band is barely covered.

While making the fits, we note that the CO bands are likely contaminated by C I lines at 2.2906 and 2.2310 μm and from Na I lines at 2.3348 and 2.3379 μm. The position of these lines is marked

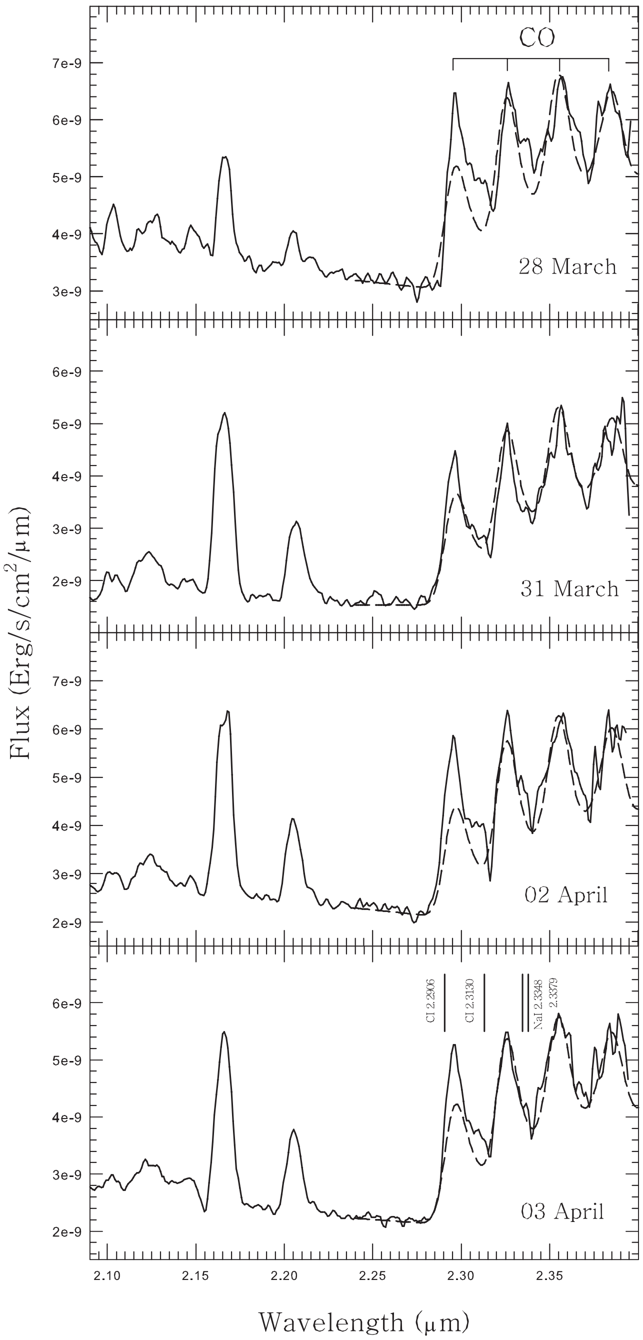

Figure 6. Model fits (dashed lines) to the observed first overtone CO bands in V2615 Oph. The fits are made for a constant CO mass of 3.0×10^{-8} M$_\odot$ on all days while the temperature of the gas T_{CO} is estimated to be 4100, 4000, 4100 and 4300 K (with an error of ±400 K) for March 28 and 31 and April 2 and 3, respectively. The bottom panel shows the position of certain C I and Na I lines that complicate the modelling. The other prominent lines seen in the spectra are Br γ at 2.1655 μm; Na I 2.2056, 2.2084 μm blended with weaker emission from C I 2.2156, 2.2167 μm lines and other C I lines between 2.1 and 2.14 μm. The position of the $^{12}C^{16}O$ bandheads is shown in the top panel.

in the bottom panel of Fig. 6 and there are discernible structures at these positions in most of the profiles, indicating these lines are present. The 2.29 μm (v = 2–0) band would appear to be affected, especially by the C I 2.2906 line which can be significant in strength in carbon–oxygen novae (Rudy et al. 2003; Das et al. 2008) and whose presence is possibly responsible for the lack of agreement between model and observed data in this region. In view of the above, we have relied more on the fits to the higher bands (the v = 3–1 and 4–2 bands) while estimating the CO parameters. We have also assumed the CO emission to be optically thin. For the assumptions and constraints outlined above, the formal fits of Fig. 6 yield estimates of T_{CO} of 4100, 4000, 4100 and 4300 K (with an error of ±400 K) for March 28, March 31, April 2 and April 3. We find that a constant CO mass of 3.0×10^{-8} M$_\odot$, or at the most a marginal variation of M_{CO} between 2.75×10^{-8} and 3.25×10^{-8} M$_\odot$, can account for the observed profiles on the four days. The fits shown in all panels of Fig. 6 are made for the same mass of 3.0×10^{-8} M$_\odot$, and the implications of a fairly constant mass are discussed below.

As in earlier studies on the $^{12}C/^{13}C$ ratio in a few novae, discussed in the following section, we are also able to place only a lower limit on this ratio, namely $^{12}C/^{13}C$ is greater than 2. If this ratio is decreased below 2, the ^{13}CO contribution becomes rather prominent, i.e. the ^{13}CO bandheads begin to appear prominently in the synthetic spectra resulting in poor model fits. The determined lower limit for the $^{12}C/^{13}C$ ratio may be compared with that expected from theoretical calculations. For carbon–oxygen novae like V2615 Oph, the expected $^{12}C/^{13}C$ ratio in the ejecta has been computed (e.g. Jose & Hernanz 1998; Starrfield, Gehrz & Truran 1997) and shown to be dependent on the white dwarf mass among other parameters. Different models by Jose & Hernanz (1998) show that this ratio is approximately constrained between 0.3 and 0.65 for a white dwarf mass between 0.8 and 1.15 M$_\odot$; Starrfield et al. (1997) find the $^{12}C/^{13}C$ ratio to decrease from 2.4 to 0.84 as the white dwarf mass increases from 0.6 to 1.25 M$_\odot$. However, our observations and modelling seem to indicate that ^{13}C is possibly not synthesized to the high levels predicted by the theoretical models.

To calculate the CO column density, we assume that the CO is uniformly spread in a shell of thickness ΔR and volume $4\pi R^2 \Delta R$. The radius R of the shell is estimated kinematically knowing the time elapsed since outburst and the velocity of the shell. A value of ∼1450 km s^{-1} is adopted for the shell velocity based on the P Cygni terminal velocity reported by Munari et al. (2007) and similar values of the FWHM of the near-IR lines as found in this work. The column density, which is proportional to $(M_{CO}\Delta R)/(4\pi R^2 \Delta R)$, is then independent of the thickness of the shell. In this manner, we determine the CO column densities to be 7.5×10^{18}, 4.1×10^{18}, 3.8×10^{18} and 2.9×10^{18} cm^{-2} on March 28, March 31, April 2 and April 3, respectively.

It may be useful to present similar results in other known novae in which the first overtone of CO has been detected. These are V2274 Cyg (Rudy et al. 2003), NQ Vul (Ferland et al. 1979), V842 Cen (Hyland & McGregor 1989; Wichmann et al. 1990, 1991), V705 Cas (Evans et al. 1996) and V1419 Aql (Lynch et al. 1995). The CO mass M_{CO} was determined to be $10^{25.5\pm0.5}$ g (i.e. 1.6×10^{-8} M$_\odot$) in NQ Vul by Ferland et al. (1979) from observations 19 d after the outburst or 20 d before the large visual fading associated with dust formation. A limit of $^{12}C/^{13}C$ greater than 3.0 and a temperature $T_{CO} = 3500 \pm 750$ K were determined for the object. In V2274 Cyg, Rudy et al. (2003), from observations 17 d after discovery, determined $M_{CO} = 8 \times 10^{-9}$ M$_\odot$, $^{13}C/^{12}C \geq 0.83 \pm 0.3$ and $T_{CO} = 2500$ K. In Nova V705 Cas, observations by Evans et al. (1996) taken at two epochs, i.e. 1 d before maximum light and 26.5 d after maximum light, yielded estimates for M_{CO} of $(2.8 \pm 0.2) \times 10^{-10}$ M$_\odot$ and $(3.8 \pm 0.2) \times 10^{-10}$ M$_\odot$, respectively, and T_{CO} equal to 4300 ± 300 and 4500 ± 300 K, respectively. They estimate the $^{12}C/^{13}C$ ratio to be ≥5 and the CO column density to be 2×10^{17} cm^{-2} for M_{CO} equal to 1.0×10^{-10} M$_\odot$. Apart from the above sources, the $^{12}C/^{13}C$ ratio has also been estimated in two other novae. In DQ Her, this ratio was found to be $\geq$1.5 by Sneden & Lambert (1975); in V842 Cen, observations between days 29 and 45 after outburst by Wichmann et al. (1991) show the $^{12}C/^{13}C$ ratio to be 2.9 $\pm$ 0.4.

3.5 Evolution of the CO emission

The detection of CO over a significant duration of time in the present observations presents an opportunity – not available before – to study the formation and destruction of CO during a nova outburst. The earliest theoretical studies of the chemistry of novae were done by Rawlings (1988) in the form of pseudo-equilibrium chemical models of the pre-dust-formation epoch. These models, which were developed with the main aim of explaining the observed presence of CO in novae, found that the outer parts of the ejecta have to be substantially more dense and less ionized than the bulk of the wind for substantial molecule formation to occur. For this to occur, carbon has to be neutral. In a neutral carbon region, the carbon ionization continuum, which extends to less than 1102 Å, shields several molecular species against the dissociative UV flux from the central star. A more refined model for molecule formation in the nova outflow in the early stages is presented in Pontefract & Rawlings (2004, hereafter PR) – we try to correlate the present observational findings with the results in this work. The PR studies are a major extension of their earlier models with only one major qualitative point of departure, namely neutral–neutral reactions are now shown to be more important than photoreactions in determining the nova chemistry.

A significant result in PR is the prediction of the evolution of the fractional CO abundance with time. Two models are considered – Model A considers oxygen-rich ejecta and Model B considers carbon-rich ejecta. Figs 1 and 2 of PR show the evolution of the fractional abundance of different molecules and radicals, including CO, with time. It is seen that in both models, the CO abundance remains constant up to about 2 weeks after outburst ($\sim$12 d in Case A and $\sim$15 d in Case B). This behaviour, and the length of its duration, seems to be generic to the models. During this phase, the CO is saturated – that is to say, all the available oxygen or carbon, whichever has the lower abundance, is completely incorporated into forming CO. After this, there is a sharp decline in the CO abundance as CO is destroyed mostly by reactions with N and N^+. During this stage, from figs 1 and 2 of PR, we estimate an approximate decrease in CO by a factor of 1000 in $\sim$27 d for Model A and a decrease by a factor of 100 in $\sim$16 d for Model B. The present data allow us to check these two vital aspects of the model predictions, namely the existence of a short-lived saturated phase followed by a phase involving rapid destruction of CO.

The present observations and modelling show that the CO mass was constant between March 28 and April 3 , i.e. for a period of 7 d. This puts a lower limit on the duration of the saturated phase since our observations commenced on March 28, nearly 8–9 d after the beginning of the outburst on March 19.812 UT. It is possible that the CO emission was present, and at similar levels, between March 19 and March 28 also. After all, CO has been seen very early after the commencement of the eruption as in the case of V705 Cas (Evans et al. 1996). If that is the case, then the upper limit on the saturated-phase time-scale would be around 15 d. Thus, the evidence indicates that a phase does exist when the CO mass is constant and whose duration t_s is constrained within $7 \leq t_s \leq 16$ d. This observational finding conforms well with the predicted time-scales of $\sim$12–15 d from the PR model calculations.

Between April 3 and 5, there is a sudden decrease in the CO strength. It is difficult to meaningfully model the April 5 data, and hence derive the CO parameters, because the relative contribution of the C I 2.2906 μm line is considerable at this stage. Also, the signal-to-noise ratio in the region around the CO emission region begins to get low now. However, if we assume that $T_{\rm CO}$ has not changed drastically between April 3 and 5, then from the diminished CO flux on the latter date, we estimate that $M_{\rm CO}$ has decreased by a factor of 3. Beyond this date, the decrease in the CO emission continues to take place, with a possible restrengthening again on April 16, to finally drop below measurable limits by April 27–30. But the data beyond April 5 are of inadequate quality to make a quantitative assessment of the strength of the CO emission beyond this stage (or indeed whether CO is even present on some of the days; the presence of the C I lines complicates the assessment further). However, a quantitative assessment can certainly be made with a good degree of surety – there is a phase of rapid reduction in the CO emission after April 3. The initial decrease is indeed rapid – the spectra over a 4 d gap, between April 3 and 7, have only to be compared to establish this. This quantitative behaviour, i.e. the rapid destruction of CO following the saturated phase, is again largely consistent with the predictions of the theoretical model (PR).

It is also possible to estimate the CO:C ratio, though with substantial uncertainties, at different stages of the CO evolution and compare it with model predictions. We assume the entire ejecta mass to be in the range 10^{-5} to 10^{-6} $M_{\odot}$ which is fairly representative of the mass of novae ejecta. Carbon can be assumed to comprise about 10 per cent of this mass as indicated by model calculations for elemental abundances (Jose & Hernanz 1998) in CO novae like V2615 Oph. Thus, in the initial saturated phase when $M_{\rm CO}$ is found to be 3×10^{-8} $M_{\odot}$, the CO:C ratio is determined to lie in the range between 10^{-1} and 10^{-2}. This would clearly rule out the PR models in which the initial abundances of carbon are less than that of oxygen (Model A) and are consistent with Model B (carbon rich) where a CO:C ratio of $\sim 10^{-1}$ is expected. At later stages, after the destruction of CO, $M_{\rm CO}$ is difficult to estimate precisely but it is certainly lower than one-tenth of its value during saturation. This suggests that CO:C is in the range 10^{-2} to 10^{-3} and likely to be even lower. This is again reasonably consistent with the PR results which find that in most models, regardless of whether the ejecta is O- or C-rich, the CO:C ratio decreases with time and is less than 10^{-3} at a time greater than 50 d.

4 SUMMARY

Near-IR spectroscopy and photometry of the dust-forming nova V2615 Oph are presented. The key observational result is the detection of first overtone CO emission in this nova. Modelling of the data indicates an initial phase when the CO is saturated and whose duration t_s is constrained in the range $7 \leq t_s \leq 16$ d. During this phase, the gas temperature and mass are found to be fairly constant in the range 4000–4300 K and 2.75×10^{-8} to 3.25×10^{-8} $M_{\odot}$, respectively. A ratio of $^{12}C/^{13}C \geq 2$ is inferred. Following the saturated phase, the CO is found to be destroyed fairly fast. The observed time-scales involved in the evolution of the CO emission and the estimated CO:C ratio are compared with model predictions and found to be in good agreement.

ACKNOWLEDGMENTS

The research work at Physical Research Laboratory is funded by the Department of Space, Government of India. We are grateful for the online availability of the Kurucz and NIST atomic linelists and also the optical photometric data from the American Association of Variable Star Observers (AAVSO) and Association Française des Observateurs d'Etoiles Variables (AFOEV), France, data bases. We wish to thank the anonymous referee for his suggestions and comments which greatly helped in improving the presentation of the paper.

REFERENCES

Banerjee D. P. K., Das R. K., Ashok N. M., 2009, MNRAS, in press (arXiv.0903.3794)
Bautista M. A., Rudy R. J., Venturini C. C., 2004, ApJ, 604, L129
Benedict W. S., Herman R., Moore G. E., Silverman S., 1962, ApJ, 135, 277
Capaccioli M., della Valle M., Rosino L., D'Onofrio M., 1989, AJ, 97, 1622
Cohen J. G., 1988, in van den Bergh S., Pritchet C. J., eds, ASP Conf. Ser. Vol. 4. The Extragalactic Distance Scale. Astron. Soc. Pac., San Francisco, p. 114
Das R. K., Ashok N. M., Banerjee D. P. K., 2007, Cent. Bur. Electron. Telegrams, 925
Das R. K., Banerjee D. P. K., Ashok N. M., 2008, MNRAS, 391, 1874
della Valle M., Livio M., 1995, ApJ, 452, 704
Evans A., Geballe T. R., Rawlings J. M. C., Scott A. D., 1996, MNRAS, 282, 1049
Ferland G. J., Lambert D. L., Netzer H., Hall D. N. B., Ridgway S. T., 1979, ApJ, 227, 489
Goorvitch D., 1994, ApJS, 95, 535
Hyland A. R., McGregor P. J., 1989, in Allamandola L. J., Tielens A. G. G. M. eds, IAU Symp. Vol. 135. Interstellar Dust. NASA CP-3036. NASA, Washington, p. 495
Johansson S., Jordan C., 1984, MNRAS, 210, 239
Jose J., Hernanz M., 1998, ApJ, 494, 680
Koornneef J., 1983, A&A, 128, 84
Lynch D. K., Rossano G. S., Rudy R. J., Puetter R. C., 1995, AJ, 110, 2274
Lynch D. K., Wilson J. C., Rudy R. J., Venturini C., Mazuk S., Miller N. A., Puetter R. C., 2004, AJ, 127, 1089
Marshall D. J., Robin A. C., Reyle C., Schultheis M., Picaud S., 2006, A&A, 453, 635
Munari U., Siviero A., Valentini M., Ochner P., Dallaporta S., 2007, Cent. Bur. Electron. Telegrams, 906
Munari U., Henden A., Valentini M., Siviero A., Dallaporta S. O. P., Tomasoni S., 2008, MNRAS, 387, 344
Naik S., Banerjee D. P. K., Ashok N. M., 2009, MNRAS, 394, 1551
Naito H., Narusawa S., 2007, IAU Circ. 8824
Nishimura H., 2007, IAU Circ. 8824
Pontefract M., Rawlings J. M. C., 2004, MNRAS, 347, 1294 (PR)
Rawlings J. M. C., 1988, MNRAS, 232, 507
Rudy R. J., Erwin P., Rossano G. S., Puetter R. C., 1991, ApJ, 383, 344
Rudy R. J., Mazuk S., Puetter R. C., Hamann F., 2000, ApJ, 539, 166
Rudy R. J., Lynch D. K., Mazuk S., Venturini C. C., Puetter R. C., Perry R. B., 2002, BAAS, 34, 1162
Rudy R. J., Dimpel W. L., Lynch D. K., Mazuk S., Venturini C. C., Wilson J. C., Puetter R. C., Perry R. B., 2003, ApJ, 596, 1229
Rudy R. J., Russell W., Lynch D. K., Mazuk S., Pearson R. L., Woodward C. E., Puetter R. C., Perry R. B., 2007, IAU Circ. 8846
Schmidt Th., 1957, Zeitschrift fur Astrophysik, 41, 182
Sneden C., Lambert D. L., 1975, MNRAS, 170, 533
Spyromilio J., Meikle W. P. S., Learner R. C. M., Allen D. A., 1988, Nat, 334, 327
Starrfield S., Gehrz R. D., Truran J. W., 1997, in Bernatowicz T. J., Zinner E., eds, AIP Conf. Proc. 402, Astrophysical Implications of the Laboratory Study of Presolar Materials. Am. Inst. Phys., New York, p. 203
Wichmann R., Krautter J., Kawara K., Williams R. E., 1990, Astron. Gesellschaft Abstr. Ser., 5, 17
Wichmann R., Krautter J., Kawara K., Williams R. E., 1991, in Jaschek C., Andrillat Y., eds, The Infrared Spectral Region of Stars. Proceedings of the International Colloquium Held in Montpellier, France 1990. Cambridge Univ. Press, Cambridge, p. 353
Williams R. E., 1992, AJ, 104, 725

This paper has been typeset from a TEX/LATEX file prepared by the author.