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

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ABSTRACT

We present near-infrared (1 - 2.5 $\mu$m) spectroscopic and photometric results of Nova V2615 Ophiuchi which was discovered in outburst in 2007 March. Our observations span a period of $\sim$ 80 days starting from 2007 March 28 when the nova was at its maximum light. The evolution of the spectra are 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 $\mu$m and suggest it could be due to FeII excited by Lyman $\alpha$ fluorescence. The highlight of the observations is the detection of the first overtone bands of carbon monoxide (CO) in the 2.29 - 2.40 $\mu$m region. The CO bands are modeled 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 its evolution from a phase of constant strength through a stage when the CO is destroyed fairly rapidly. We compare the observed timescales 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: infrared: spectra - line : identification - stars : novae, cataclysmic variables - stars : individual (V2615 Oph) - techniques : spectroscopic

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 28 March.

The early low-resolution optical spectra (410-670 nm, resolution 1500) of V2615 Oph by Naito and 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 a Fe II- type nova. The FWHMs of the $H\alpha$, $H\beta$, and $H\gamma$ emissions were 920, 810, and 790 km/s, and the displacement of the P-Cyg absorptions from the Balmer emission peaks were 940, 820, and 830 km/s, respectively. Early optical spectra were also obtained by Munari et al. (2007, 2008) on Mar. 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, 42, 48, 49, 55, and 74; Si II multiplets 2, 3, 4 and 5; N I multiplet 3; Ca II H and K; Na I D1 and D2; and O I 777.2-nm (the O I line showed the second strongest emission component after $H\alpha$). With respect to the peak of the $H\alpha$ emission, the absorption terminal velocity was -1415 km/s, and the mean velocity -910km/s. In comparison to the March 22.17 UT spectrum, the Mar. 24.18 UT spectra show large changes: mainly a marked reduction in equivalent width of emission lines with P-Cygni profiles. The strongest emission lines were due to Fe II multiplets 27, 28, 37, 42, 48, 49, 55, and 74; Si II multiplets 2, 3, 4 and 5; N I multiplet 3; Ca II H and K; Na I D1 and D2; and O I 777.2-nm (the O I line showed the second strongest emission component after $H\alpha$). With respect to the peak of the $H\alpha$ emission, the absorption terminal velocity was -1415 km/s, and the mean velocity -910km/s. In comparison to the March 22.17 UT spectrum, the Mar. 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-Cygni profiles.

Infrared observations of V2615 Oph have been made by Das et al. (2007) and Rudy et al. (2007) - some of the findings in Rudy et al. (2007) are discussed in details subsequently. 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-Infrared $JHK$ spectrophotometric data of V2615 Oph presented here were acquired at the Mount Abu 1.2m telescope. The first 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 $256 \times 256$ HgCdTe NICMOS3 array. The observation logs for spectroscopy and photometry are presented in Tables 1 and 2 respectively. Near-IR photometry were presented in Tables 1 and 2 respectively. Near-IR $JHK$ spectra were obtained at similar dispersions of $\sim 9.75$ Å/pixel in each of the $J$, $H$, $K$ bands. In each band, spectra were recorded at different positions along the slit (slit width $\sim 1$ 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 as the target.

The spectra were extracted using the APEXTRACT task in IRAF and the spectra 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 JHIK bands for 85 days 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 5 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 APHOT. 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 magnitudes.

3 RESULTS

3.1 Optical and near-infrared lightcurve

The optical lightcurve of V2615 Oph is presented in Figure 1. The object was discovered about 9 days 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/day for the first $\sim 80$ days after maximum. Subsequently there is a steep decline in the lightcurve due to dust formation - this aspect is addressed shortly while discussing the near-IR light curve. From the lightcurve we estimate $t_2$ and $t_3$ - the time for a drop of 2 and 3 magnitudes respectively in the visual brightness - to be 33 and 58 days respectively. The use of these values of $t_2$ and $t_3$ in various MMRD relationships (della Valle et al. (1990), Capaccioli et al. (1989) Cohen (1988) for $t_2$; Schmidt (1957) for $t_3$) leads to closely similar values for the absolute visual magnitude - a mean value of $M_v = 7.16 \pm 0.12$ is obtained. The extinction toward the object can be estimated in two ways. Rudy et al. (2007), using the strength of the OI lines, have determined the reddening prior to dust formation to be $E(B-V) = 1.0$ (or $A_v = 3.1$ magnitudes). This leads to an distance estimate of $D = 3.25$ kpc to the object. To show that this value of $A_v$ is reasonable, we use the extinction data of Marshall et al. (2006) which shows that $A_K$ is constant at $= 0.34-0.36$ beyond 3 and upto 12 kpc in the direction of V2615 Oph. Thus, assuming $A_v/A_K \sim 11$ (Koornneef 1983), a maximum value of $A_v = 3.85$ is suggested toward V2615 Oph thereby leading to a lower limit on the distance of $D = 2.3$ kpc. For the present work we

| Date (UT) | Days since Outburst | Integration time (sec) |
|-----------|---------------------|------------------------|
| 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 | 120 |

| Date (UT) | Days since Outburst | Magnitudes |
|-----------|---------------------|------------|
| 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 |

Table 1. A log of the spectroscopic observations of V2615 Oph. The date of outburst is taken to be 2007 March 19.812 UT
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3.2 General characteristics of the \(JHK\) spectra

The lines in the earliest spectrum of 28 March, when the nova was at maximum light, show P-Cygni structure with a prominent absorption component. By following the Pa $\beta$ line for example, it is seen that the P-Cygni absorption component persists for at least 10 days (upto 7 April) 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 on 28 March but this value changes closer to $\sim 1400$-$1500$ km/s for 31 March and other subsequent dates upto 7 April. Variations, of a similar nature, in the outflow velocities were also noted by Munari et al. (2007) on 22 and 24 March - when the nova was on its rise to maximum light. Clearly, the mass loss process and its kinematics during the early stages is not uniform.

Mosaics of the the \(J\), \(H\) and \(K\) band spectra are presented in Figures 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 et al. 2008). In addition to lines of H, He, N and O, these novae show strong lines of carbon e.g. in the \(J\) band in the 1.16 to 1.18 $\mu$m wavelength region. In contrast, such carbon lines are weak in the spectra of ONeMg novae e.g. in the novae V597 Pup and V2491 Cyg (Naik et al. 2009). The IR-based classification of V2615 Oph is consistent with its optical classification as an FeII 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 details (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 $\beta$ and continuum fluoresced OI lines at 1.1287 and 1.3164 $\mu$m; the HeI lines at 1.0830 $\mu$m and 2.0585. Strong carbon lines are seen in the $J$ band also in the $H$ band redwards of Br 11. Among subtle features, the presence of a C I line at 1.6 $\mu$m, which could be mistaken as just another member of the $H$ band Brackett series lines, should not be missed. The region between 1.2 to 1.275 $\mu$m contains the complex blend of a large number of NI and C I lines that are often seen in the early spectra of CO novae. The presence of several lines of NaI and MgI (the prominent ones being at 1.1404, 1.5040, 1.5749, 2.2056 and 2.2084 $\mu$m ) are 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 NaI particularly, and also of MgI, 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), QV 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 9 June. 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 infrared 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 coming 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 $\mu$m which is discussed below.

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

| Wavelength ($\mu$m) | Species | Other contributing lines & remarks |
|--------------------|---------|-----------------------------------|
| 1.0830             | He I    |                                   |
| 1.0938             | Pa $\gamma$ |                                   |
| 1.1116             | u.i.    |                                   |
| 1.1126             | Fe I    |                                   |
| 1.1287             | O I     |                                   |
| 1.1330             | C I     |                                   |
| 1.1381, 1.1404     | Na I    | strongest lines at 1.1653, 1.1659, 1.16696 |
| 1.1600-1.1674      | C I     | strongest lines at 1.1748, 1.1753, 1.1755 |
| 1.1748-1.1800      | C I     |                                   |
| 1.1828             | Mg I    | blended with C I at 1.1896        |
| 1.1880             | C I     | blended with C I at 1.2088        |
| 1.2074, 1.2095     | N I     |                                   |
| 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             | Pa $\beta$ |                                  |
| 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    | Several C I lines               |
| 1.7200-1.7900      | C I     | blended with u.i. 2.0620         |
| 1.7362             | Br 10   |                                   |
| 2.0585             | He I    |                                   |
| 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 $\gamma$ |                                |
| 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    |                                   |

3.3 An unidentified line at 2.0888 $\mu$m: possibly a FeII line excited by Lyman $\alpha$ fluorescence?

We note the presence of an emission line at $\sim 2.0890$ $\mu$m in the $K$ band that is seen fairly prominently in the spectra from 27 April onwards. We propose that this is a FeII line and additionally investigate whether this line could be excited by Lyman $\alpha$ (Lyco) fluorescence. In the near-infrared, there are a few FeII lines seen in the spectra of novae, which are believed to be primarily excited by Lyman $\alpha$ and Lyman continuum fluorescence. Among these are the so-called "one micron Fe II lines" at 0.9997, 1.0171, 1.0490, 1.0501, 1.0863, and 1.1126 $\mu$m seen in several novae (Rudy et al. 1991, 2000). In addition, two other Fe II lines at 1.6872 and 1.7414 $\mu$m in the $H$ band, are also proposed to be pumped by the same mechanism (Banerjee et al. 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 with the Br 11 (1.6806 $\mu$m) and CI lines at 1.6890 and 1.7449 $\mu$m 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 line widths in RS Oph become small - due to deceleration of the shocked, emitting gas - and blending effects are thereby minimal.
Figure 3. The J band spectra of V2615 Oph on different days with the flux normalized to unity at 1.25 μm.

The excitation mechanism of the Fe II lines appears to be a three step process (Johansson & Jordan 1984; Bautista et al. 2004 and references therein, Banerjee et al. 2009). FeII 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 FeII 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(4F)4s^2^F 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 by several high lying levels - each of these high lying levels capable of being pumped by Ly α photons. As illustrative examples, it is noted that photons at 1213.738, 1214.067, 1216.239, 1216.272 and 1217.15 ˚A, which are reasonably coincident with the Ly α line center at 1215.671 ˚A, can excite transitions from the low lying (5D) 4s a^D 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...
Figure 4. The $H$ band spectra of V2615 Oph on different days with the flux normalized to unity at 1.65 $\mu$m.

4P respectively at around 11.3 eV. Since HI lines in novae (Ly $\alpha$ included) are broad with widths extending up to a few thousands of km/s (1 Angstrom corresponds to about 250 km/s at the Ly $\alpha$ wavelength), these photons could contribute to the fluorescence process, even though they are not coincident with the Ly $\alpha$ line center. These higher levels at 11.3 eV can then decay via ultraviolet photons to the upper level of the 2.0888 $\mu$m transition. The Kurucz atomic data on which the present analysis is based, indicates there are additional Ly $\alpha$ fluorescing candidate lines (apart from the five discussed here), all within a few Angstroms of the Ly $\alpha$ line center - that could also contribute to the Ly $\alpha$ fluorescence process. Therefore, the 2.0888 $\mu$m line could be

1 http://cfa-www.harvard.edu/amp/ampdata/kurucz23/sekur.html
excited by Ly alpha fluorescence, if its identification with Fe II is correct.

A few cautionary words regarding the identification of the 2.0888 \( \mu \text{m} \) with FeII may be in order. In case the Fe II identification is correct, then a few other Fe II lines - as mentioned earlier - could also be expected viz. lines at 0.9971, 1.0171, 1.0490, 1.0501, 1.0863, 1.1126, 1.6872 and 1.7414 \( \mu \text{m} \). 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 \( \mu \text{m} \) line which is in a region of low signal since it is at the edge of our spectral window. However the 1.1126 \( \mu \text{m} \) line is seen. It is also difficult to draw a firm conclusion whether the 1.6872 and 1.7414 \( \mu \text{m} \) lines are present. Unfortunately both these lines occur at positions close to strong CI and HI lines (Table 3) which could lead to line blending. In essence, further detections of the 2.0888 \( \mu \text{m} \) line in other novae is desirable to enable a secure identification.

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**Figure 5.** The K band spectra of V2615 Oph on different days with the flux normalized to unity at 2.2 \( \mu \text{m} \).
3.4 Modeling the CO emission

The CO emission is modeled 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 as Spyromilio et al. 1988). In our calculations, we have used values for the rotational and vibrational constants of $^{12}$C$^{16}$O, $^{13}$C$^{16}$O from the NIST database 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 (νννν) 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 ergs/sec, needs to be converted into units of the observed flux (we use units of ergs/s/cm²/µm). 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 ergs/s/cm²/µm; 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 profile 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 28 and 31 March; and 2 and 3 April are shown in Figure 5. The parameters that are fed as inputs for the modeling are the total mass of the CO gas ($M_{CO}$), the $^{12}$C/$^{13}$C ratio (designated as $\alpha$) and the gas temperature ($T_{CO}$). Once $M_{CO}$ and $\alpha$ are chosen, the total number of $^{12}$CO and $^{13}$CO molecules are fixed - thus the level the 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 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 $M_{CO}$, $\alpha$ and $T_{CO}$ were tried to find the best fit between model spectra and the observed data. The characteristics of the CO emission remains fairly constant between 28 March and 3 April. The profiles of Figure 6 are reasonably well modeled with closely similar values of $T_{CO}$ and $M_{CO}$ in the range of 4000 - 4300K and 2.75x10⁻⁸ to 3.25x10⁻⁸ $M_\odot$ respectively. Some of the difficulties encountered in the modeling, 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 additionally changes the intensities of the different vibrational bands, relative to each other, within the first overtone. Therefore, vibrational bands from $\nu \geq 5$, would help the analysis, but they are located in regions of poor atmospheric transmission, beyond the spectral coverage and the $\nu=5$-3 band is barely covered.

While making the fits we note that the CO bands are likely contaminated by CI lines at 2.2906 and 2.2310 µm and from NaI lines at 2.3348 and 2.3379 µm. The position of these lines are marked in the bottom panel of Figure 6 and there are discernible structures at these positions, in most of the profiles, indicating these lines are present. The 2.29 µm ($\nu = 2$-0) band would appear to be affected, especially by the CI 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 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 $\nu = 3$-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 Figure 6 yield estimates of $T_{CO}$ of 4100, 4000, 4100 and 4300K (with an error of ≈ 400K) for 28 March, 31 March, 2 April and 3 April. We find that a constant CO mass of 3.0x10⁻⁸ $M_\odot$, or at most a marginal variation of $M_{CO}$ between 2.75x10⁻⁸ to 3.25x10⁻⁸ $M_\odot$, can account for the observed profiles on the four days. The fits shown in all panels of Figure 6 are made for the same mass of 3.0x10⁻⁸ $M_\odot$ and the implications of a fairly constant mass is discussed shortly.

As in earlier studies on the $^{12}$C/$^{13}$C ratio in a few novae, discussed in the following sub-section, we are also able to place only a lower limit on this ratio viz. $^{12}$C/$^{13}$C $>$ 2. If this ratio is decreased below 2, the $^{12}$CO contribution becomes rather prominent i.e. the $^{13}$CO bandheads begin to prominently appear in the synthetic spectrum 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 and Hernanz (1998); Starrfield et al. (1997)) and shown to be dependent on the white dwarf mass among other parameters. Different models by Jose and Hernanz (1998) show that this ratio is approximately constrained between 0.3 to 0.65 for a white dwarf mass between 0.8 to 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 form 0.6 to 1.25 $M_\odot$. However, our observations and modeling 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 $\Delta R$ 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 $\sim 1450$ km/s is adopted for the shell velocity based on the P-Cygni ter-

2 http://physics.nist.gov/PhysRefData/MolSpec
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 and 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 viz. 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

$$\text{CO}$$

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 $3.0 \times 10^{-8} \, M_\odot$ 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 $\pm 400 \, K$) for 28 & 31 March and 2 & 3 April respectively. The bottom panel shows the position of certain CI and NaI lines that complicate the modeling. The other prominent lines seen in the spectra are Br $\gamma$ at 2.1655 $\mu$m; NaI 2.2056, 2.2084 $\mu$m blended with weaker emission from CI 2.2156, 2.2167 $\mu$m lines and other CI lines between 2.1 and 2.14 $\mu$m. The position of the $^{12}\text{C}^{16}\text{O}$ bands are shown in the top panel.
are considered - model A considers oxygen rich ejecta and model B considers carbon rich ejecta. Figures 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 upto about 2 weeks after outburst (~ 12 days in case A and ~ 15 days 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 Figures 1 and 2 of PR, we estimate an approximate decrease in CO by a factor of 1000 in ~ 27 days for model A and a decrease by a factor of 100 in ~ 16 days for model B. The present data allows to check on these two vital aspects of the model predictions viz. the existence of a short-lived saturated phase followed by a phase involving rapid destruction of CO.

The present observations and modeling show that the CO mass was constant between 28 March and 3 April i.e. for a period of 7 days. This puts a lower limit on the duration of the saturated phase since our observations commenced on 28 March, nearly 9 days after the beginning of the outburst on Mar. 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 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 timescale would be around 15 days. Thus the evidence indicates that a phase does exist when the CO is saturated and whose duration \( t_s \) is constrained within \( 7 \leq t_s \leq 16 \) days. This observational finding conforms well with the predicted timescales of ~ 12-15 days from the PR model calculations.

Between 3 April and 5 April there is a sudden decrease in the CO strength. It is difficult to meaningfully model the 5 April data, and hence derive the CO parameters, because the relative contribution of the CI 2.2906 \( \mu m \) 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 \( T_{CO} \) has not changed drastically between 3 and 5 April, then from the diminished CO flux on the latter date, we estimate that \( M_{CO} \) 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 16 April, to finally drop below measurable limits by 27-30 April. But the data beyond 5 April is 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 CI 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 3 April. The initial decrease is indeed rapid - the spectra over a 4 day gap, between 3 April and 7 April, 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; 2004).

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 of \( 10^{-5} \) to \( 10^{-6} M_\odot \), which is fairly representative for the mass of novae ejecta. Carbon can be assumed to comprise about 10 percent of this mass as indicated by model calculations for elemental abundances (Jose and Hernanz, 1998) in CO novae like V2615 Oph. Thus, in the initial saturated phase when \( M_{CO} \) is found to be \( 3 \times 10^{-8} M_\odot \), the CO:C ratio is determined to lie in the range between \( 10^{-2} \) and \( 10^{-3} \). This would clearly rule out the PR models in which the initial abundances of carbon are less than oxygen (model A) and be 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, \( M_{CO} \) 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 days.

4 SUMMARY

Near-infrared 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. Modeling of the data indicates an initial phase when the CO is saturated and whose duration \( t_s \) is constrained in the range \( 7 \leq t_s \leq 16 \) days. During this phase, the gas temperature and mass are found to be fairly constant in the range of \( 4000 - 4300 K \) and \( 2.75 \times 10^{-8} \) to \( 3.25 \times 10^{-8} M_\odot \) 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 timescales 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.

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