IR STUDY OF NOVA V2468 Cyg FROM EARLY DECLINE TO THE CORONAL PHASE

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ABSTRACT

We present infrared spectroscopic and photometric observations of the nova V2468 Cyg covering the period from 2008 March 13 to 2008 November 11. The JHK spectra of the object were taken from the Mt. Abu Infrared Observatory using the Near-Infrared Imager/Spectrometer. Spectra from 0.8 to 5.2 μm that were obtained using the NASA Infrared Telescope Facility and the SPEX instrument are also presented. The spectra are dominated by strong H I lines from the Brackett and Paschen series and Fe II, O I, and C I lines in the initial days, typical of an Fe II type nova. The lines were broader in the period immediately after outburst, with measured FWHMs of 1800–2300 km s⁻¹ for the Paβ and Brγ lines. These values narrowed to 1500–1600 km s⁻¹ by 12 days from the outburst. The spectra showed prominent He I lines at 1.0830 and 2.0581 μm together with H i and O i emission features after 36 days from the outburst. Our IR observations show the comparatively broad emission lines, the rapid development of the spectrum to higher ionization, the early appearance of coronal lines, and the absence of dust emission, all features that indicate the hybrid nature of the nova. This is perhaps the most extensively observed example of a probable FeIIb type nova at infrared wavelengths. We also note a short lived emission line of Fe II at 2.0888 μm, which was present between 2008 April 9 and 2008 May 9. No dust emission is seen from the nova ejecta. We have also estimated the range for the ejecta mass in V2468 Cyg to be 3 × 10⁻³–10⁻⁵M⊙.

Key words: line: identification – novae, cataclysmic variables – stars: individual (V2468 Cyg) – techniques: spectroscopic

1. INTRODUCTION

Nova V2468 Cyg was discovered on 2008 March 7.801 UT by Hiroshi Kaneda on nine 4 s unfiltered CCD frames with a limiting magnitude of 10.7 at V = 8.2 ± 0.3 (Nakano & Kaneda 2008). Nothing was visible at the same position on his three patrol images taken on 2007 October 5, 2008 January 1, and 2008 February 18 with a limiting magnitude of 10.7. A low-resolution optical spectrum obtained on March 8.794 UT with a 1.88 m telescope (+KOOLS) at the Okayama Astrophysical Observatory by Nogami et al. (2008) showed a blue continuum with strong Balmer and Fe II lines with prominent P Cygni profiles. The FWHM of the emission component of Hα was about 1000 km s⁻¹, and the absorption component was blueshifted from the emission peak by about 880 km s⁻¹. They suggested that the object was a classical nova before or around optical maximum. The next spectrum taken by Beaky (2008) on March 11.46 UT showed prominent emission lines of Hα and Hβ and large Fe II emission lines, which confirmed that the nova was of the Fe II class. The near-IR observations reported by Ashok & Banerjee (2008) that were taken on March 14 also showed that the spectra are typical of a classical nova showing prominent H I emission lines of Paβ, Paγ, and Brγ and other Brackett series lines. The other prominent features seen were O I lines at 1.1287 and 1.3164 μm, moderately strong C I lines in the J band, and the Na I 2.2056 and 2.2084 μm lines. The FWHM of the infrared H I lines were in the range 2000–2200 km s⁻¹. Rudy et al. (2008) reported on the IR spectra for the nova in two epochs: 2008 March 13 and 2008 April 12 UT. Among other things, they found that the Ca II infrared triplet, which was strong in March, was almost undetectable in the April spectrum. X-ray emission from V2468 Cyg was also detected in 2009 (Schwarz et al. 2009), 2011 (Schwarz et al. 2011), and 2012 (Page et al. 2012).

2. OBSERVATIONS

Near-IR observations were obtained using the 1.2 m telescope of the Mt. Abu Infrared Observatory and NASA Infrared Telescope Facility from 2008 March 13 to 2008 November 11. The log of the spectroscopic and photometric observations is given in Table 1. The spectra from Mt. Abu at a resolution of ~1000 were obtained using the Near-Infrared Imager/Spectrometer incorporating a 256 × 256 HgCdTe NICMOS3 array. The IRTF data had resolutions from 1000 to 2000 and were acquired with the SPEX instrument, a cross dispersed imaging spectrometer incorporating a 1024 × 1024 InSb detector and covering the wavelength range 0.8–5.5 μm (Rayner et al. 2003). In each of the JHK bands a set of spectra was taken with the nova offset to two different positions along the slit, which were subtracted from each other to remove sky and detector dark current contributions. Spectral calibration was done using the OH sky lines that register with the stellar spectra. The spectra of the comparison star SAO 88071 were taken at an airmass similar to that of V2468 Cyg to ensure that...
3. RESULTS

3.1. General Characteristics of JHK Light Curves

The light curves based on the JHK magnitudes from Mt. Abu (see Table 1) are presented in Figure 1. The spectroscopic observations for the nova are marked in the lowest panel of Figure 1. The optical light curve shows small amplitude outbursts at 110, 180, and 240 days from the date of the outburst (see Figure 1 of Tarasova 2013). There is no indication of dust formation in the nova ejecta at any stage of its evolution. The JHK light curves show a decline in the JHK magnitudes, and the observations taken in 2008 November clearly show the cooling of the nova envelope.

3.2. Line Identification, Evolution, and General Characteristics of the JHKLM Spectra

The JHK spectra from Mt. Abu and the NASA Infrared Telescope Facility are presented in Figures 2 and 3, respectively. The LM spectra from the NASA Infrared Telescope Facility are presented in Figure 4. The line identification is given in Table 2. The infrared observations presented here cover the phase after optical maximum, with the first infrared spectra taken on 2008 March 13.

The JHK bands were obtained in clear sky conditions using the NICMOS3 array in imaging mode. Several frames in four dithered positions offset by ∼30 arcsec were obtained in all bands. The sky frames, which are subtracted from the nova frames, were generated by median combining the dithered frames. The star SAO 68744, located close to the nova, was used for photometric calibration. Further details of the data reduction are described in Banerjee et al. (2014). The data were reduced and analyzed using IRAF.

### Table 1

| Date of Observation | Spectroscopic Observations | J     | H     | K     | Observatory and Instrument |
|---------------------|----------------------------|-------|-------|-------|-----------------------------|
| 2008 Mar 13         | JHK                        | ...   | ...   | ...   | NASA IRTF SPEX              |
| 2008 Mar 14         | JHK                        | ...   | ...   | ...   | Mt. Abu NICMOS3             |
| 2008 Mar 15         | JHK                        | 6.21 ± 0.06 | 6.02 ± 0.05 | 5.55 ± 0.05 | Mt. Abu NICMOS3             |
| 2008 Mar 19         | JHK                        | ...   | ...   | ...   | Mt. Abu NICMOS3             |
| 2008 Apr 08         | ...                        | 7.50 ± 0.01 | 7.50 ± 0.02 | 6.94 ± 0.05 | Mt. Abu NICMOS3             |
| 2008 Apr 09         | JHK                        | ...   | ...   | ...   | Mt. Abu NICMOS3             |
| 2008 Apr 12         | JHK                        | ...   | ...   | ...   | NASA IRTF SPEX              |
| 2008 Apr 22         | JHK                        | 7.73 ± 0.05 | 7.92 ± 0.03 | 7.20 ± 0.03 | Mt. Abu NICMOS3             |
| 2008 May 01         | ...                        | 8.63 ± 0.01 | 8.75 ± 0.02 | 7.92 ± 0.01 | Mt. Abu NICMOS3             |
| 2008 May 09         | JHKLM                      | ...   | ...   | ...   | NASA IRTF SPEX              |
| 2008 May 15         | JHK                        | ...   | ...   | ...   | Mt. Abu NICMOS3             |
| 2008 Aug 21         | JHKLM                      | ...   | ...   | ...   | NASA IRTF SPEX              |
| 2008 Oct 04         | JHKLM                      | ...   | ...   | ...   | NASA IRTF SPEX              |
| 2008 Nov 08         | ...                        | 12.95 ± 0.04 | 12.77 ± 0.11 | 12.73 ± 0.20 | Mt. Abu NICMOS3             |
| 2008 Nov 11         | ...                        | 13.24 ± 0.05 | 13.27 ± 0.18 | 12.75 ± 0.20 | Mt. Abu NICMOS3             |

**Note.** The JHK band magnitudes are listed.
2.0581 μm, a disappearance of the Na I line at 2.2050 μm, and a sudden appearance of the line at 2.0888 μm. In their study on nova V2615 Oph, Das et al. (2009) have predicted that this line could be an Fe II line excited by Lyα fluorescence.

The JHK band spectra obtained on 2008 April 12 are similar to the previous spectra, but the Ca II infrared triplet, which was very strong in March, is nearly undetectable in this spectrum. The He I lines are now quite strong, and He II features are also starting to emerge.

The spectrum taken on 2008 April 22 shows very strong He I line at 1.0830 μm, weak Paγ and an absence of the Fe II line, strong emission of O I at 1.1287 μm, very weak N I lines at 1.2461, 1.2090, and 1.3450 μm, Paβ, and a weak
Table 2
A List of the Lines Identified from the JHKLM Spectra Shown in Figures 2–4

| Wavelength (μm) | Species | Other Contributing Lines and Remarks |
|-----------------|---------|-------------------------------------|
| 0.8446          | O I     |                                     |
| 0.8863          | Pa 11   |                                     |
| 0.9013          | Pa 10   |                                     |
| 0.9226          | Pa 9    |                                     |
| 0.9545          | Pa 8    |                                     |
| 0.9911          | [Si viii] |                                    |
| 1.0043          | Pa 7    |                                     |
| 1.0830          | He i    |                                     |
| 1.0938          | Pa γ    |                                     |
| 1.1126          | u i     | Fe ii ?                             |
| 1.1287          | O i     |                                     |
| 1.1626          | He ii   |                                     |
| 1.1600-1.1674   | C i     | The strongest lines at 1.1653, 1.1659, 1.16696 |
| 1.1746-1.1800   | C i     | The strongest lines at 1.1748, 1.1753, 1.1755 |
| 1.1828          | Mg i    |                                     |
| 1.1819-1.2614   | several C i and N i | The strongest lines at 1.1880, 1.1896 |
| 1.1969          | He i    |                                     |
| 1.2461, 1.2469  | N i     | Blended with O i 1.2464             |
| 1.2528          | He i    |                                     |
| 1.2562, 1.2569  | C i     | Blended with O i 1.2570             |
| 1.2818          | Pa β    |                                     |
| 1.3164          | O i     |                                     |
| 1.3450          | N i     |                                     |
| 1.4760          | He ii   |                                     |
| 1.4882          | He i    |                                     |
| 1.5439          | Br 17   |                                     |
| 1.5557          | Br 16   |                                     |
| 1.5701          | Br 15   |                                     |
| 1.5881          | Br 14   | Blended with C i 1.5853             |
| 1.6109          | Br 13   |                                     |
| 1.6407          | Br 12   |                                     |
| 1.6806          | Br 11   |                                     |
| 1.7002          | He i    |                                     |
| 1.7109          | Mg i    |                                     |
| 1.7362          | Br 10   | Affected by C i 1.7339 line         |
| 1.7769-1.7814   | C i     |                                     |
| 1.9445          | Br 8    |                                     |
| 1.9645          | [Si vii] |                                    |
| 1.9722          | C i     |                                     |
| 2.0449          | [Al ix] |                                     |
| 2.0581          | He i    |                                     |
| 2.0888          | u i     | Fe ii ?                             |
| 2.1120, 2.1132  | He i    |                                     |
| 2.1156-2.1295   | C i     |                                     |
| 2.1655          | Br γ    |                                     |
| 2.1882          | He ii   |                                     |
| 2.2056-2.2084   | Na i    |                                     |
| 2.2906          | C i     |                                     |
| 2.3205          | [Ca viii] |                                   |
| 2.4693          | H i 5–18 |                                    |
| 2.4827          | Si vii  |                                    |
| 2.4946          | H i 5–17 |                                    |
| 2.5254          | H i 5–16 |                                    |
| 3.0384          | H i 5–10 |                                    |
| 3.0908          | He ii 6–7 |                                   |
| 3.2067          | [Ca iv] |                                     |
| 3.2961          | H i 5–9  |                                    |
| 3.6060          | H i 6–20 |                                    |
| 3.6449          | H i 6–19 |                                    |
| 3.6916          | H i 6–18 |                                    |
| 3.7395          | H i 5–8  |                                    |
| 3.8184          | H i 6–16 |                                    |
| 3.9065          | H i 6–15 |                                    |
| 4.0512          | H i 4–5  |                                    |
| 4.6525          | H i 5–7  |                                    |
| 4.6712          | H i 6–11 |                                    |
| 5.1273          | H i 6–10 |                                    |

Note. All lines are seen at any one epoch. The additional lines contributing to the identified lines are listed.
line of O i at 1.3164 μm. The H band spectrum shows most of the Brackett series lines, a He i line at 1.7002 μm, and a Mg i line at 1.7109 μm. The C i line at 1.7808 μm is absent now. The K band spectrum shows the strengthening of the He i line at 2.0581, the absence of the C i line at 1.9722 μm, the Fe ii line at 2.0888 μm, and the appearance of the He i line at 2.1120 μm. The spectra taken on 2008 May 9 are very similar to the previous spectra. The spectra taken on 2008 May 15 are very similar to the previous spectra. However, the disappearance of the Fe ii line at 2.0888 μm is consistent with the rising ionization but is contrary to its observed persistence in the nova V2615 Oph (Das et al. 2009).

The observations presented in Figure 3 are of great importance, as they show the development of the coronal lines. We can see in particular the rise of the [Si vi] line at 1.9645 μm. This feature is barely detectable on the red wing of the Br 8 line on 2008 April 12. But by day 167 it is the larger feature and by day 211 it is completely dominant. The other coronal lines that are present and display a similar development are [Si vii] and [Ca viii] at 0.9911 and 2.3205 μm, respectively.

The LM band spectra taken on three epochs (see Figure 4) show the emission lines of the [Ca vii], [Si vii], and H i lines. We do not find any evidence of thermal emission from dust. The absence of dust formation, together with the relatively rapid appearance of coronal lines, supports the notion that V2615 Cyg was an FeIIb type nova.

### 3.3. The Reddening and Distance of V2468 Cyg

The relative strengths of the fluorescently excited lines of neutral oxygen have been used to determine the reddening in numerous novae and other emission-line objects (Rudy et al. 1991). This makes use of the specific O i lines at 0.8446, 1.1287, and 1.3164 μm. For the first epoch at 2008 March 13, there is a strong Ca ii triplet that is partially blended with 0.8446 μm, and the lines are broad with complex profiles. This contributes to the uncertainty in the determination of reddening. By 2008 April 12, however, the O i lines are dominant and can be measured accurately. The reddening for the four epochs between 2008 April 12 and 2008 October 4 yields a value of $E(B-V) = 0.77 \pm 0.15$ as reported in Rudy et al. (2008). This value is similar to the values derived by Schwarz et al. (2009) and Tarasova (2013) of $\sim 0.80$ from the Balmer decrement, Chochol et al. (2012) of $\sim 0.79$ using B and V band light curves, and Iijima & Naito (2011) of $\sim 0.80$ using the column density of hydrogen atoms. Using the MMRD relation (della Valle & Livio 1995), we estimated the absolute magnitude at maximum $M_V$ and distance $d$ to the nova as $\sim -8.8$ and $\sim 5.6$ kpc, respectively, where we used $t_2 = 7.8$ d from Iijima & Naito (2011) and our estimate of $E(B-V)$ above. We also estimated the mass of the white dwarf, $M_{WD} \sim 1.1 M_\odot$ (Livio 1992). This suggests that nova V2615 Cyg may have originated from a massive WD.

### 3.4. A Possible Case of Hybrid Nova

Williams (1992) has suggested a new class of novae that displays characteristics of both Fe ii and He/N classes, which are referred to as hybrid or Fe ii nova. The observed spectral lines of hybrid novae are broader than the ones typically seen in Fe ii nova and subsequently exhibit characteristics of He/N novae like strong He/N lines. The observed FWHMs of H i lines in V2468 Cyg in the early decline phase range from 1800 to 2300 km s$^{-1}$ (Figure 6), which are larger compared to those seen in typical Fe ii novae. A remarkable and rapid increase in the strength of He i lines starting from day 33 after the outburst (2008 April 9) is seen as observed in He/N novae e.g., KT Eri (Raj et al. 2013). An extension of the optical classification scheme to the near-IR by Banerjee & Ashok (2012) distinguishes these two classes by the presence of strong...
C I lines in Fe II novae and their absence in He/N novae. The spectra of V2468 Cyg displayed in Figures 2–4 clearly show that the strong C I lines seen in the initial spectra quickly fade away. A similar behavior and spectral evolution was seen in V574 Pup, which was classified by Naik et al. (2010) as a hybrid nova. We thus suggest a hybrid classification for V2468 Cyg. At optical wavelengths the signatures of the hybrid class of novae are the spectral features of He II 3923, 6683, 6981 Å, N II 5001, 5479, 6482 Å, and N I 7452 Å. The optical spectra of V2468 Cyg show the presence of the N II 5679 Å line on 2008 March 10 (Iijima & Naito 2011), traces of N II 5938 Å on 2008 March 23, and N II 6482 Å on 2008 May 22 (Tarasova 2013). The presence of spectral lines of He and N at such early epochs is consistent with our suggestion that V2468 Cyg belongs to the hybrid class of nova.

An example of a well studied nova that showed a transition between Fe II and He/N spectral classes is the recent 2011 outburst of recurrent nova T Pyx. Unlike hybrid novae, T Pyx showed a transition from the He/N to Fe II spectral class (Izzo et al. 2012; Surina et al. 2014). The high-resolution spectroscopic observations of T Pyx by Shore et al. (2011) reported absorption line systems that show an accelerated displacement in velocity and they attribute these features to a fast moving tenuous outer envelope. The optical spectroscopic observations of V2468 Cyg by Chochol et al. (2012) show absorption components in the H ß emission feature indicating the presence of an expanding outer envelope.

As Williams (2012) has pointed out, the Fe II spectral features are formed in a post-outburst wind while the He/N spectral features arise in discrete expanding shells. It is likely that in the case of hybrid novae the spectrum is dominated by Fe II lines with weak emission from He and N in the initial phase and then changes over to the He/N class as the nova evolves to the nebular phase. The slow moving optically thick discrete shells with lower ionization are responsible for the spectral feature of Fe II class in the initial phase and these are replaced by the optically thin shells with increased ionization, responsible for the spectral features of He/N class in later phase. The geometry of the ejecta could be another likely reason for the hybrid nature of selected novae. If the underlying white dwarf in the nova happens to be massive—a value of 1.1 $M_{\odot}$ is estimated for V2468 Cyg in Section 3.3 and Tarasova (2013)—it may have magnetic field that could be strong enough to influence the expanding ejecta and change its geometry. The detection of any deviations from the spherical geometry by high angular resolution observations of hybrid novae will give credence to the idea that their ejecta are concentrated in jets.

The recent addition to the list of hybrid novae, namely, V5558 Sgr (Das et al. 2015) and V5588 Sgr (Munari et al. 2015) suggests that the transition between Fe II and He/N class in novae may be more frequent than was believed in earlier years.

3.5. Recombination Analysis of the H I Lines and Estimate of the Ejecta Mass

We tried to estimate the ejecta mass by using recombination line analysis of H I lines and the representative results for three epochs of our observations are shown in Figure 5. However, we find that the strengths of these lines, relative to each other deviate considerably (specially for Brγ) from Case B values for 2008 March 13 and 2008 April 12 clearly indicates that the observed line intensities are different from Case B values (Storey & Hummer 1995). This is not surprising given the strength of the O I lines that are fluorescently excited by Lyß. For this process to occur so productively, Hα must be optically thick, which violates the criterion for Case B conditions. We have plotted in Figure 5 the observed relative strength of Brackett series lines with the line strength of Br 12 as unity along with the predicted values for three different recombination Case B emissivity values from Storey & Hummer (1995). These predicted values cover a representative temperature of $T = 10^4$ K and the electron densities of $n_e = 10^5$, $10^7$, and $10^{11}$ cm$^{-3}$. High electron densities are considered because the ejecta material is dense in the early stages after the outburst as we do not see any auroral and nebular lines in this phase of observations. Figure 5 (middle panel) shows that the observed line intensities clearly match from Case B values in the initial phase i.e., on 2008 March 15 and started deviating afterwards. Specifically, Br γ, which becomes relatively stronger than the other Br lines showing thinning of the ejecta.

For 2008 March 15, it is found that the observed data match well with the predicted recombination Case B values of $T = 10^4$ K and an electron density $n_e = 10^8$ cm$^{-3}$. Following Banerjee et al. (2010), a constraint on the mass of the emitting gas can be obtained from:

$$M = \left( 4\pi d^2 (m_H)^2 (f V/e) \right)^{0.5}$$  (1)

where $d$ is the distance derived in Section 3.3, $m_H$ the proton mass, $f$ the observed flux in a particular line, $e$ the corresponding Case B emissivity, $V$ is the volume of the emitting gas. We calculate the volume of the nova shell following Mustel & Boyarchuk (1970) for an estimate for its thickness and clumpiness. In the early stage of nova evolution the typical value of the filling factor vary from $10^{-1}$ to $10^{-2}$ (see Ederoclite et al. 2006). Considering a value of $10^{-1}$–$10^{-2}$ for the filling factor we estimated the ejecta mass in the range $3 \times 10^{-6}$–$10^{-5} M_{\odot}$ which is similar to the values obtained by Iijima & Naito (2011) and Tarasova (2013) from their optical observations. Although the ejecta mass is little closer to the mass of the ejecta seen in recurrent novae (e.g., Prialnik & Kovetz 1995) but V2468 Cyg can not be a recurrent nova (e.g., RS Oph, T Pyx) as it developed at a more leisurely rate and stayed bright for a very long time, displaying moderately strong emission lines more than four years after outburst. This behavior argues for a more massive shell and persistent, low-level burning of material on the WD surface.

4. SUMMARY

We have presented the infrared spectroscopy and photometry of nova V2468 Cyg, which erupted in early March 2008. The infrared spectra indicate that the nova is an Fe II or hybrid class nova that shows Fe II type behavior in early stages and then changes to He/N type later on. The reddening and distance to the nova are also calculated. Recombination analysis is used to estimate the mass of the gaseous component of the ejecta in V2468 Cyg.

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