Near-infrared studies during maximum and early decline of Nova Cephei 2014 and Nova Scorpii 2015

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ABSTRACT

We present multiple epoch near-infrared photospectroscopic observations of Nova Cephei 2014 and Nova Scorpii 2015, discovered in outburst on 2014 March 8.79 UT and 2015 February 11.84 UT, respectively. Nova Cep 2014 shows the conventional NIR characteristics of a Fe II class nova characterized by strong C I, H I and O I lines, whereas Nova Sco 2015 is shown to belong to the He/N class with strong He I, H I and O I emission lines. The highlight of the results consists in demonstrating that Nova Sco 2015 is a symbiotic system containing a giant secondary. Leaving aside the T CrB class of recurrent novae, all of which have giant donors, Nova Sco 2015 is shown to be only the third classical nova to be found with a giant secondary. The evidence for the symbiotic nature is threefold; first is the presence of a strong deaccelerative shock accompanying the passage of the nova’s ejecta through the giant’s wind, second is the Hα excess seen from the system and third is the spectral energy distribution of the secondary in quiescence typical of a cool late-type giant. The evolution of the strength and shape of the emission line profiles shows that the ejecta velocity follows a power-law decay with time (t^{−1.13±0.17}). A Case B recombination analysis of the H β Brackett lines shows that these lines are affected by optical depth effects for both the novae. Using this analysis, we make estimates for both the novae of the emission measure n_e^2 L, the electron density n_e and the mass of the ejecta.

Key words: line: identification – techniques: photometric – techniques: spectroscopic – stars: individual: Nova Cephei 2014 – stars: individual: Nova Scorpii 2015 – novae, cataclysmic variables.

1 INTRODUCTION

Nova Cephei 2014 was discovered as a transient by Nishiyama & Kabashima (2014) at a magnitude of 11.7 on unfiltered CCD frames (limiting magnitude 13.7) taken around 2014 March 8.792 UT. The object was confirmed to be a classical nova by Munari et al. (2014) who obtained a low-resolution spectrum (range 395–852 nm, 0.21 nm pixel−1) on 2014 March 9.792 UT. The spectrum showed a red continuum with strong emission lines from the Balmer series, O I 777.4 and 844.6 nm, Ca II 849.8 nm and Fe II multiplets 42, 48 and 49. All emission lines showed strong P-Cyg absorptions which were blueshifted by 660 km s−1 for the Balmer lines, 780 km s−1 for the Fe II lines and 900 km s−1 for the O I lines. The emission lines had a width of about 800 km s−1. The intensity of the O I 844.6 nm emission line was seen to be about twice that of O I 777.4 nm, indicating that there was fluorescent pumping from hydrogen Lyman β photons. Photometry on 2014 March 10.094 UT showed a large value of the colour B−V = +1.27 which indicated significant reddening consistent with the red slope of the continuum observed in the spectrum. The object’s spectrum showed it to be a highly reddened Fe II class nova observed close to maximum brightness. No detailed study of this nova, in any wavelength regime, has been presented till date.

Nova Sco 2015 was discovered as a bright transient on 2015 February 11.8367 UT at an unfiltered CCD magnitude of 8.2 by Tadashi Kojima using a 150-mm f/2.8 lens + a digital camera (Nakano 2015). Nothing was visible on a frame from the same camera on February 10.827 UT. (vsnet-alert 18276;¹ AAVSO special notice no. 397 ²). The object was designated PNV J17032620−3504140 on the CBAT Transient Object Confirmation Page (TOCP). An echelle spectrum on 2015 February 13 at 09:38 UT (Walter 2015) confirmed that the object was a nova. Hα had an equivalent width of −14 nm and full width at half-maximum (FWHM) ~2000 km s−1. There were symmetrically displaced emission features at about

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±4500 km s⁻¹ which resembled those seen in fast He/N novae. H α and H β showed P Cyg absorption features at about −4200, −3200 and −2300 km s⁻¹. O I 777 nm and 845 nm were in emission. A strong emission line at 588 nm with a prominent P-Cyg absorption was either He I 587 nm or modestly blueshifted Na I. Broad 2000 km s⁻¹ Full Width at Zero Intensity (FWZI) He I 706 nm emission was possibly also present. Similarly, broad emission was seen in the prominent Fe II multiplet 42 lines at 492, 502 and 517 nm, though the first two may have had some He I contribution. The apparently rapid fading and bright possible near-IR counterpart suggested this was a system with an M giant donor (Walter 2015), like V745 Sco or Nova Sco 2014.

Early X-ray and radio observations of Nova Sco 2015 by Nelson et al. (2015) implicated strong shocks against a red giant wind. Their observations of Nova Sco 2015 were carried out at X-ray, UV and radio wavelengths. The X-ray observations were carried out with the Swift satellite between 2015 February 15.5 and 16.3 UT (about 4 d after discovery). An X-ray source was clearly detected at the position of the nova. The spectrum was hard and could be modelled as a highly absorbed, hot thermal plasma (N(H) ≈ 6 × 10²² cm⁻²; kT greater than 41 keV). However, a significant excess of counts over the model prediction was observed between 1 and 2 keV, possibly indicating the presence of a second, softer emission component. Nelson et al. (2015) also observed Nova Sco 2015 at radio wavelengths with the Karl G. Jansky Very Large Array (VLA) on 2015 February 14.5, approximately 3 d after optical discovery. The nova was detected at frequencies from 4.55 to 36.5 GHz with a spectrum typical of non-thermal synchrotron emission (spectral index between −0.7 and −0.9). The presence of hard, absorbed X-rays and synchrotron radio emission at this early stage of the outburst suggested that the nova-producing white dwarf was embedded within the wind of a red-giant companion, with collisions between the ejecta and this wind shock-heating plasma and accelerating particles (as in, e.g. RS Oph, V407 Cyg and V745 Sco (Banerjee, Das & Ashok 2009; Munari et al. 2011; Banerjee et al. 2014). This interpretation is supported by our NIR observations.

In this paper, we present our NIR spectroscopic and photometric observations of Nova Cep 2014 and of Nova Sco 2015, preliminary reports of which were made in Ashok et al. (2014) and Srivastava et al. (2015). The observations of Nova Cep 2014 span nine epochs covering 5–90 d after the outburst and the observations of Nova Sco 2015 span 11 epochs covering 7–47 d after the outburst. We present the observations in Section 2. The analysis and results for Nova Cep 2014 and Nova Sco 2015 are described in Section 3 and Section 4, respectively.

2 OBSERVATIONS

Near-IR spectroscopy in the 0.85–2.4-μm region at resolution ~1000 was carried out with the 1.2-m telescope of the Mount Abu Infrared Observatory using the Near-Infrared Camera/Spectrograph (NICS) equipped with a 1024×1024 HgCdTe Hawaii array. Spectra were recorded with the star dithered to two positions along the slit with one or more spectra being recorded in both of these positions. The co-added spectra in the respective dithered positions were subtracted from each other to remove sky and dark contributions. The spectra from these sky-subtracted images were extracted using IRAF tasks and wavelength calibrated using a combination of OH sky lines and telluric lines that register with the stellar spectra. To remove telluric lines from the target’s spectra, it was ratioed with the spectra of a standard star (SAO 18998 spectral-type A2IV in case of Nova Cep 2015 and SAO 206599, spectral-type A0/A1V in the case of Nova Sco 2015) from whose spectra the hydrogen Paschen and Brackett absorption lines had been removed. The spectra were finally multiplied by a blackbody at the effective temperature of the standard star to yield the resultant spectra. All spectra were covered in three settings of the grating that cover the H, J, H and K regions separately.

A spectrum of Nova Sco 2015 was obtained using the 3-m IRTF telescope on 2015 March 23,625UT covering the 0.8–2.5 μm region. This spectrum was obtained using SpeX (Rayner et al. 2003) in the cross-dispersed mode using the 0.3 arcsec × 15 arcsec slit (R = 2000) and a total integration time of 360 s. The SpeX data were reduced and calibrated using the SPEXTOOL software (Cushing, Vacca & Rayner 2004), and corrections for telluric absorption were performed using the IDL tool xtellcor (Vacca, Cushing & Rayner 2003). The log of the observations are given in Tables 1 and 2.

3 RESULTS ON NOVA CEP 2014

3.1 Light curve, extinction and distance of Nova Cep 2014

Fig. 1 shows the V- and B-band light curves of the Nova Cep 2014 using data from American Association of Variable Star Observers (AAVSO). The nova showed a climb to maximum that lasted for 5 d before peaking at ~11.05 mag in V on 2014 March 13.9198 (JD 245 6730.4198). From the light curve, we determine t₁ and t₃ – the time for the brightness to decline by 2 and 3 mag, respectively from maxima – to be 22 ± 2 d and 42 ± 1 d thereby putting it in the fast-speed class. The observed (B − V) values at maximum and at t₁ equal 1.18 and 0.9, respectively in contrast to the expected values of 0.23 ± 0.06 and −0.02 ± 0.04, respectively at these epochs (van den Berg & Younger 1987). The large values of (B − V) imply considerable reddening; the excess E(B − V) values are equal to 0.95 and 0.92, respectively. We adopt a mean value of 0.935 for the reddening and thus an extinction A_V = 3.09 × E(B − V) = 2.9. For t₂ = 22 ± 2 d, the MMRD relation of della Valle & Livio (1995) gives M_V = −7.84 ± 0.5 which implies a distance to the nova of 15.8 ± 4 kpc. Similarly, the MMRD relations for t₁ and t₃ by Downes...
being boosted up because of a low choice of extinction $A$ in the distance–modulus relation $m - M = 5 \log d - 5 + A$. The extinction of 2.9 that we have used is close to the total Galactic extinction of 2.995 mag in the direction of the nova as estimated by Schlafly & Finkbeiner (2011) from dust extinction maps. Our choice of $A_V$ is also consistent with the extinction modelling of Marshall et al. (2006) who find that the extinction $A_V$ rapidly rises, in the direction of the nova, to $3.36 \pm 0.33$ by a distance of 1.23 kpc and remains at this value for larger distances.

### 3.2 General properties of the spectra and a case B recombination analysis

The $J$, $H$- and $K$- band spectra for Nova Cep 2014 are shown in Fig. 2. These show that the outburst and evolution of Nova Cep 2014 was that of a conventional Fe II class nova. The spectra of such novae, in the near-IR, are characterized by strong H$\alpha$ lines of the Paschen and Brackett series but what differentiates them from the He$\alpha$/class is the presence of several strong C$\alpha$ lines seen around maximum and during the early decline (Banerjee & Ashok 2012). These C$\alpha$ lines are all prominently seen in the spectrum of Nova Cep 2014 (examples being C$\alpha$(1.0685, 1.165, 1.176 $\mu$m) and a strong blend of C$\alpha$ lines in the region 1.73–1.78 $\mu$m). The detailed identification of the lines is presented in Fig. 3 and is discussed in the appendix and Table A1. P-Cygni absorption components are seen in many of the lines in the spectra taken during 2014 March. The line profile widths do not vary much over time; for e.g. the FWHM of the Paschen $\beta$ 1.2818 $\mu$m line changes from $\sim 1200$ km s$^{-1}$ to $\sim 1500$ km s$^{-1}$ between the epochs 2014 March 14 (5.22 d)–2014 April 7 (29.20 d).

We do not find any evidence of dust formation in this nova, as manifested by an IR excess, during the early decline stage. To check whether dust formation may have occurred later, photometry was done recently (2015 April 28, JD 245 7140.5). However, the nova was not detected in any of the $J$, $H$ or $K$ bands. The limiting magnitudes of our observations in $J$, $H$ and $K$ band are $\sim 15.0$. This, taken in conjunction with the latest $V$ magnitudes of 18.943 on 2015 April 6.87 UT (JD 245 7119.365 53) from the AAVSO data base, yields $(V - K) < 3.9$. The small value of the $(V - K)$ colour indicates that dust formation is very unlikely to have occurred.

A recombination case B analysis was done, but only for selected dates of 2014 March 15.02, April 05.00 and April 07.99 (i.e. 6, 27 and 30 d after the outburst) when contemporaneous photometric observations were available for flux calibrating the spectra. The measured line fluxes for the H$\alpha$ Brackett lines are given in Table 3; and Fig. 4 shows the Brackett line strengths with respect to Br$\delta$ set to unity. We find that the line fluxes do not match predicted case B recombination values. In particular, it is seen from Fig. 4 that the Br$\gamma$ (Br$\gamma$) line strength is significantly lower than the predicted values of Storey & Hummer (1995). Though expected to be stronger than the other Br series of lines, it is found to be significantly weaker than, for example, Br$\delta$ and Br$\alpha$. Such behaviour is expected in the early phase of outbursts signifying that Br$\gamma$ is optically thick and so possibly are the other Br lines. Such optical depth effects in the Brackett lines are also seen in several other nova systems e.g. Nova Oph 1998 (Lynch et al. 2000), V2491 Cyg and V597 Pup (Naik, Banerjee & Ashok 2009), RS Oph (Banerjee et al. 2009) and T Pyx (Joshi, Banerjee & Ashok 2014).

Although the lines are optically thick, we can estimate the emission measure $n_e^2 L$ of the ejecta following the opacity data given by Hummer & Storey (1987) and Storey & Hummer (1995) and using the fact that Br$\gamma$ line is found to be optically thick. The optical depth

### Table 2. Log of the spectroscopy observations$^a$.

| Date of observation (UT) | Days since outburst (d) | Exposure time (s) |
|--------------------------|-------------------------|-------------------|
| Nova Cep 2014            |                         |                   |
| 2014 Mar 14.01           | 5.22                    | (300, 240, 240)   |
| 2014 Mar 15.02           | 6.23                    | (–, 180, 180)     |
| 2014 Mar 15.98           | 7.19                    | (450, 450, 600)   |
| 2014 Mar 20.99           | 12.20                   | (600, 600, 1080)  |
| 2014 Apr 05.00           | 27.21                   | (180, 3000, 300)  |
| 2014 Apr 07.99           | 30.19                   | (380, 760, 760)   |
| Nova Sco 2015            |                         |                   |
| 2015 Feb 19.00           | 7.16                    | (240, 240, 360)   |
| 2015 Feb 20.00           | 8.16                    | (360, 360, 360)   |
| 2015 Feb 21.01           | 9.17                    | (360 360 360)     |
| 2015 Feb 25.97           | 14.18                   | (360, 480, 480)   |
| 2015 Feb 26.92           | 15.18                   | (240, 240, 240)   |
| 2015 Mar 06.03           | 22.18                   | (–, 120, –)       |
| 2015 Mar 09.01           | 25.18                   | (720, –, –)       |
| 2015 Mar 23.63$^b$       | 39.80                   | 360               |

Notes: a) The spectroscopic observation of Nova Sco 2015 on 2015 March 23.63 UT was made from the IRTF Telescope. The rest of the spectra were obtained from Mt Abu.

$^b$ The J-, H- and K-band spectra for Nova Cep 2014 are shown in Fig. 2. These show that the outburst and evolution of Nova Cep 2014 was that of a conventional Fe II class nova. The spectra of such novae, in the near-IR, are characterized by strong H$\alpha$ lines of the Paschen and Brackett series but what differentiates them from the He$\alpha$/class is the presence of several strong C$\alpha$ lines seen around maximum and during the early decline (Banerjee & Ashok 2012). These C$\alpha$ lines are all prominently seen in the spectrum of Nova Cep 2014 (examples being C$\alpha$(1.0685, 1.165, 1.176 $\mu$m) and a strong blend of C$\alpha$ lines in the region 1.73–1.78 $\mu$m). The detailed identification of the lines is presented in Fig. 3 and is discussed in the appendix and Table A1. P-Cygni absorption components are seen in many of the lines in the spectra taken during 2014 March. The line profile widths do not vary much over time; for e.g. the FWHM of the Paschen $\beta$ 1.2818 $\mu$m line changes from $\sim 1200$ km s$^{-1}$ to $\sim 1500$ km s$^{-1}$ between the epochs 2014 March 14 (5.22 d)–2014 April 7 (29.20 d).

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![Figure 1.](https://academic.oup.com/mnras/article-abstract/454/2/1297/2892633)
Figure 2. $J$, $H$ and $K$ bands spectra of Nova Cep 2014 normalized to unity at the band centres of 1.25 µm, 1.65 µm and 2.20 µm, respectively and then offset for clarity. Days after the outburst are also indicated in parentheses.

Figure 3. Line identification of Nova Cep 2014 in the 0.85–1.5 µm region. The observed spectrum of Nova Cep 2014 of March 20 is shown in black and a typical model LTE spectrum is shown in grey below to help in line identification. Further details are given in the appendix.
at line-centre $\tau_{\nu,\nu'}$ is given by $\tau = n_e n_i \Omega(n, n') L$, where $n_e$, $n_i$, $L$ and $\Omega(n, n')$ are the electron number density, ion number density, path length and opacity corresponding to the transition from upper level $n$ to lower level $n'$, respectively. Further, the opacity factor $\Omega(n, n')$ does not vary significantly within the density or temperature range that is expected to prevail in the ejecta. For example from Storey & Hummer (1995), the opacity $\Omega(n, n')$ for Br$\gamma$ line for the temperature $T_e = 10000$ K, and number densities $10^9-10^{11}$ cm$^{-3}$ vary only between $1.3 \times 10^{-34}$ and $7.46 \times 10^{-34}$. We will assume that the densities in the early stage of the nova outburst are high and lie in the in the above range of $10^9-10^{13}$ cm$^{-3}$. As $\tau = n_e n_i \Omega(n, n') L \gg 1$ the emission measure $n_e^2 L$ for above values is estimated to be in the range of $1.3 \times 10^{33}-7.7 \times 10^{33}$ cm$^{-5}$.

We constrain the electron density by taking $L$ as the kinematical distance $v \times t$ travelled by the ejecta where $v$ is the velocity of ejecta and $t$ is the time after outburst. We consider a typical ejecta velocity of $v \sim 1000$ km s$^{-1}$ as measured from half the FWZI of the Pa $\beta$ 1.2818 $\mu$m line and $t$ to range from 6 to 30 d. With the constraints that $\tau$ (Br$\gamma$) = $n_e n_i \Omega(n, n') L > 1$, the lower limit on electron density $n_e$ is found to be in the range $2.2 \times 10^7$ to $1.1 \times 10^9$ cm$^{-3}$ (assuming $n_i = n_e$). It should be noted that these derived lower limits are likely to be smaller than the actual $n_e$ values because $\tau$ (Br$\gamma$) can be considerably $> 1$.

The density in the nova ejecta remains significantly high over the entire duration of our observations. Lynch et al. (2000) showed that high densities of $10^{10}$ cm$^{-3}$ or more tend to thermalize the level populations through collisions and thereby bring about deviations from case B predictions. The same has been observed here in H$\alpha$ lines.

The gas mass of the ejecta may be estimated by $M = \epsilon V n_e m_p$ where $V$ is the volume ($= 4/3\pi L^3$), $\epsilon$ is the volume filling factor and $m_p$ is the proton mass. For $L$ varying between the distance traversed in 6–30 d and the corresponding lower limits on $n_e$ as estimated above, the mass $M$ varies between $5.4 \times 10^{-6}$ and $1.3 \times 10^{-4}$ M$_\odot$. This is a wide range and the mass is poorly constrained but nevertheless the mass range is consistent with the typical nova ejecta masses estimated in novae of $10^{-4}-10^{-6}$ M$_\odot$.

### 4 RESULTS ON NOVA SCO 2015

#### 4.1 Light curve, extinction and distance of Nova Sco 2015

The V- and B-band light curves are shown in the lower panel of Fig. 1 using the data from AAVSO. The nova showed a monotonic decline and we determine $t_2$ and $t_3$ values of 14 ± 2 and 19 ± 1 d which puts the Nova Sco 2015 in the fast-speed class similar to Nova Cep 2014 discussed earlier in Section 3.1. The observed $(B-V)$ value near the optical maximum and $t_3$ are 0.87 and 0.79, respectively. Comparing these values with the expected values of 0.23 ± 0.06 and $-0.02 \pm 0.04$, respectively at these epochs from van den Berg & Younger (1987), we get an average value of 0.72 for the colour excess $E(B-V)$ and interstellar extinction $A_V = 2.23$. By using the MMRD relation of della Valle & Livio (1995) we get $M_V = -8.44 \pm 0.14$ for $t_2 = 14$ d which implies a distance of $13.7 \pm 0.4$ kpc for $A_V = 2.23$. Similarly by using the MMRD relations for $t_2$ and $t_3$ of Downes & Duerbeck (2000) we get $M_V$ values of $-8.40 \pm 0.97$ and $-8.74 \pm 1.07$ and these translate to a mean distance of $14.7 \pm 3.8$ kpc, which is adopted as the distance to Nova Sco 2015. The extinction value of $A_V = 2.23$ used in these calculations is slightly larger than the total Galactic extinction of 1.99 in the direction of the nova as estimated by Schlafly & Finkbeiner (2011) from the dust extinction maps.

### Table 3. List of emission line flux values at different epochs for Nova Cep 2014.

| Emission line and wavelength (μm) | Integrated line flux at days after outburst ($10^{-20}$ W cm$^{-2}$) |
|----------------------------------|---------------------------------------------------------------|
|                                  | 6.23 d  | 27.21 d  | 30.19 d  |
| Br17 1.5439                     | 35.0    | –        | 7.44     |
| Br16 1.5556                     | 81.4    | 28.1     | 33.5     |
| Br15 1.5701                     | 50.1    | 9.04     | –        |
| Br14 1.5881                     | 72.5    | 27.9     | 19.0     |
| Br13 1.6109                     | –       | 25.5     | 30.8     |
| Br12 1.6407                     | 92.8    | 46.0     | 41.5     |
| Br11 1.6807                     | 88.5    | 137.0    | 118.0    |
| Br10 1.7362                     | 94.1    | 147.0    | 158.0    |
| Br7 2.1655                      | 82.4    | 85.5     | 108.0    |
4.2 General properties of the spectra

The near-infrared spectra of Nova Sco 2015 at different epochs are shown in Figs 5 and 6. The prominent spectral features in these spectra are the Brackett and Paschen recombination lines of H\textsc{i} and He\textsc{i} lines at 1.0831, 1.7002 and 2.0581 \(\mu\)m, with the 1.0831 \(\mu\)m line being overwhelmingly strong. The N\textsc{i} blend at 1.2461 and 1.2469 \(\mu\)m and the Lyman \(\beta\) fluoresced O\textsc{i} lines at 0.8446 and 1.1287 \(\mu\)m are also present. These spectra are typical of the He/N class of nova with strong lines of He\textsc{i} seen starting from the first set of observations on 7.16 d after the outburst. The absence of C\textsc{i} lines all through the span of present observations is also consistent with the He/N class (Banerjee & Ashok 2012). The P-Cygni absorption features are clearly seen in the higher resolution IRTF spectra obtained on 2015 March 23.625 UT. Another notable feature seen in the IRTF spectra is the presence of blue emission components in the profiles of \(\text{Pa}\beta\), \(\text{Pa}\beta\) and \(\text{Br}\gamma\) \(\text{H}\) \text{i} emission lines. The magnified sections of the selected lines from the IRTF spectra are shown in Figs 6 and 7 to highlight the P-Cygni features and the weak blue components. A detailed list of emission lines observed in the spectra is given in the appendix and Table A1.

4.3 Evidence for a shock from the evolution of the line profiles

With the help of the present near-IR observations, we establish that the secondary component of Nova Sco 2015 is a late-type cool giant star (see Section 4.5). The evolution of the velocity profiles seen in the emission lines of Nova Sco 2015 spectra suggests and supports this possibility. The T CrB subclass of recurrent novae (RNe) with a giant cool red companion typically show a significant decrease in the width of the emission line profiles with time after outburst (Banerjee et al. 2014). This behaviour is expected as the high-velocity ejecta thrown out during the eruption moves through the wind of the companion and thereby undergoes a deceleration. Such a deceleration causes a fast temporal decrease of the expansion velocity resulting in the narrowing of the emission line widths. This behaviour has been well documented in the NIR in the case of four other similar symbiotic systems viz. in the 2006 outburst of RS Oph (Das, Banerjee & Ashok 2006), in V407 Cyg (Munari et al. 2011) where the donor is a high mass losing Mira variable, in the RN V745 Sco (Banerjee et al. 2014) and in Nova Sco 2014 (Joshi et al. 2015).

Our near-IR observations of Nova Sco 2015 show a similar behaviour. Fig. 8 shows the evolution of the \(\text{Pa}\beta\) 1.2818 \(\mu\)m line profile during our observations. The narrowing of the line profile is clearly observed here. Fig. 9 shows the time evolution of the observed line widths (FWHM) of the \(\text{Pa}\beta\) 1.2818 \(\mu\)m line. The intrinsic FWHM of the profiles have been obtained by deconvolving the observed profiles from instrumental broadening by assuming a Gaussian profile for both the observed and instrumental profiles (a reasonable assumption) from which it follows that the FWHMs will combine in quadrature (FWHM\text{intrinsic} + FWHM\text{instrument} = FWHM\text{observed}). The FWHM of the instrumental profile for 2015 February 19–March 8 data from NICS on Mt Abu Telescope is measured to be 560 km s\(^{-1}\). For the 2015 March 23 data from the IRTF Telescope, the same is measured to be 150 km s\(^{-1}\) from an argon lamp arc spectrum which is equivalent to the resolution of 2000 cited for SpeX. A power-law fit to the evolving intrinsic line widths, of the form \(r^{-\alpha}\), is shown in Fig. 9 which is seen to give a reasonable fit for a value of \(\alpha = 1.13 \pm 0.17\).
of such a shock wave into the dense ambient medium surrounding the white dwarf. It may be described as a three-stage process viz.:  

(i) A free-expansion or ejecta-dominated stage where the ejecta expands freely into the red giant wind. This phase lasts till the mass of the swept-up material from the donor wind is smaller than the mass of the nova ejecta. A constant velocity of the shock is seen during this time.

(ii) An adiabatic phase or Sedov–Taylor stage where the majority of the ejecta kinetic energy has been transferred to the swept-up ambient gas and there is negligible cooling by radiation losses. This phase is characterized by the temporal evolution of shock velocity $v$ as $v \propto t^{1/3}$, assuming an $r^{-2}$ dependence for the decrease in density of the wind.

(iii) In phase 3, the shocked material has cooled by radiation, and here the expected dependence of the shock velocity is $v \propto t^{1/2}$.

In the case of Nova Sco 2015 the free-expansion stage, if it occurred in the first instance, is clearly missed. This is possibly because our observations began late viz. our earliest spectrum being recorded 7 d after the outburst. The deceleration that accompanies phases 2 or 3 is seen but the decay is too fast and the index $\alpha = 1.13 \pm 0.17$ that we get deviates substantially from that expected in either phase 2 or 3. Such deviations were also noticed in other RNe as well, e.g. RS Oph (Das et al. 2006), V745 Sco (Banerjee et al. 2014). This likely happens due to the propagation of ejecta into a non-symmetrical wind. In such cases, the shock would be slowed down more effectively in the parts moving in the direction of the giant due to the increasing density in that direction. In addition, there could be anisotropic distribution of the material over the equatorial plane. Thus as a combination, the mass distribution of the ejecta around the white dwarf would be anisotropic and the shock front would then propagate as an aspherical one (Chomiuk et al. 2012, fig. 6 therein).

This nova possibly has a bipolar flow associated with it based on the description of the early optical spectrum by Walter (2015) where, apart from the main central feature, symmetrically displaced emission features at about $4500 \text{ km s}^{-1}$ were seen in the $H$ profile. Such a profile structure is typical of a bipolar flow and has been seen in quite a few novae viz. RS Oph (Banerjee et al. 2009), KT Eri 2009 (Ribeiro et al. 2013; Raj, Banerjee & Ashok 2013), T Pyx (Joshi et al. 2014). From our own data, indication for an asymmetrical ejecta flow also comes from the velocity profiles of the $\text{Pa} \beta$ component. The intensity of its counterpart red component could have dropped below detection limits. In short, indications are clearly present for deviations from spherical symmetry in the velocity kinematics seen in Nova Sco 2015. This could be one of the reasons for the deviation of the deceleration index $\alpha$ from model values.

### 4.4 Case B recombination line analysis

We have performed the recombination case B analysis following the same lines as done earlier for Nova Cep 2014. We analyse observed spectra spanning six epochs covering the first 33 d of our observations. The measured line strengths from the flux calibrated
Figure 7. Magnified sections of some of the lines from the IRTF spectra of Nova Sco 2015. Panel (a) shows the O i 8446 and the NIR Ca triplet at 8498.023, 8542.091 and 8662.141 Å, respectively. Panel (b) shows the He i 1.0831 µm line and panel (c) shows the P-Cygni feature of the He i 2.058 µm line.

Figure 8. Temporal evolution of the Pa β 1.2818 µm line profile in Nova Sco 2015 showing the fast decline in the expansion velocity as the shocked emitting gas decelerates. The measured FWHM (km s$^{-1}$) for each epoch is given along with the velocity profile. The date of observation is also the days after outburst (in brackets).

Figure 9. Time evolution of the line width (FWHM) of Pa β 1.2818 µm line for Nova Sco 2015. The FWHMs have been deconvolved for instrumental broadening; see text for further details.

spectra of N Sco 2015 are given in Table 4. Flux calibrations of the spectra are done using near-IR photometric observations from SMARTS consortium. Fig. 11 shows the observed relative line strengths for the Brackett lines which have been normalized with respect to Br12 set to unity. Br22 and Br23 line values (as given in Table 4) are not considered for this analysis as they are not resolved properly. The predicted case B values are shown in Fig. 11 for a representative temperature 10 000 K and for electron number densities of $n_e = 10^9$, $10^{10}$, $10^{11}$, $10^{12}$, and $10^{13}$ cm$^{-3}$. As can be seen, in this nova also, the Brγ line is weaker than expected implying it is optically thick. Thus, using the same formalism described for Nova Cep 2014, the emission measure $n_e^2 L$ is estimated to be in the range of $1.3–7.7 \times 10^{33}$ cm$^{-5}$, the corresponding lower limit of the electron density $n_e$ is in the range $1.8–5.8 \times 10^9$ cm$^{-3}$ and the mass $M$ is between $(4.5 \times 10^{-6}$ and $2.6 \times 10^{-4}) \epsilon M_\odot$ where $\epsilon$ is the filling factor. The electron density and mass estimates are again reasonably consistent with expected values.

4.5 The symbiotic nature of the secondary and possibility of RN

Our near-IR observations along with the archival data from 2MASS survey indicate that Nova Sco 2015 presents a strong case to belong to the class of symbiotic system consisting of a WD and a late-type giant companion. As symbiotic systems are rare among novae, identification of a new object likely to belong to this group is of much significance.

The bright near-IR counterpart of Nova Sco 2015 from the 2MASS archival data base (2MASS J17032617-3504178) is likely to be a symbiotic system based on its 2MASS magnitudes of $J = 13.40 \pm 0.03$, $H = 12.53 \pm 0.04$ and $K = 12.22 \pm 0.03$. These

3 www.astro.sunysb.edu/fwalter/SMARTS/NovaAtlas/nsco2015/nsco2015.html
Further support for the secondary to be in the giant class comes from its absolute magnitude estimation. Assuming that the quiescent $K$-band brightness is dominated by the secondary (i.e. $m_K$ of the secondary = 12.22 from 2MASS) and using the MMRD distance estimate to the nova of $\sim$14.7 kpc, the $K$-band absolute magnitude of the secondary, is calculated as $-3.87$. Whereas using the intrinsic colour ($V - K_{\text{intrinsic}} = 3.60$ (Bessell & Brett 1988) and absolute magnitude $M_V = -0.20$ (Lang 1990) for K5 III spectral class, the corresponding $M_K$ is determined as $-3.80$. As the two are in good agreement, it further strengthens the classification of the secondary as a red giant. On the other hand, the possibility of the companion being a dwarf instead of a giant can be ruled out from the following consideration. For a mid-K to mid-M spectral class dwarf as suggested by our previous analyses, the $K$ absolute magnitudes is in the range of 9.2–4.2, respectively (Pecaut & Mamajek 2013; see online version of table 5 therein). Using the distance modulus relation, the corresponding distance range comes out to be 50–400 pc. This is severely in disagreement with the distance estimated earlier using MMRD relations. Further for such a close distance range of 50–400 pc, the extinction versus distance models of Marshall et al. (2006) suggest that we should get an extinction value of 0.45 for A$_V$ which is again inconsistent with the observed estimate of 2.23.

An additional confirmation for the symbiotic nature of Nova Sco 2015 comes from the comparison of its $H$ and $K$-band images. The SUPERCOSMOS archive$^3$ $H$ or image is considerably brighter than the $R$-band counterpart indicating the presence of strong $H\alpha$ emission. The SUPERCOSMOS values of $H$ and short-$R$-band magnitudes are 15.48 and 16.33, respectively, whereas the mean value of the ($H \alpha$ – short R) magnitude for about 275 listed sources in a 3 arcmin square field around the object is found to be $-0.29$. That is, the source is considerably bright in H$\alpha$. In fact, pronounced H$\alpha$ emission is used as one of the principal criteria for the classification of symbiotic stars (Belczynski et al. 2000). This can be seen from the spectra of symbiotic stars, for e.g. in the catalogue of Munari & Zwitter (2002), wherein they are seen to exhibit strong $H\alpha$ emission. However, in addition to the presence of H$\alpha$ lines, the other criteria for a definitive symbiotic star classification requires the presence of higher excitation lines (e.g. [O\textsc{iii}], He\textsc{ii}). After the system has returned to quiescence, and the nova ejecta faded, it may be checked whether such lines are seen.

We estimate the outburst amplitude of Nova Sco 2015 by associating the optical counterpart NOMAD-1 0549-0492872 with $V = 17.0$ as the progenitor suggested by Guido & Howes (2015). The $V = 9.492$ near the maximum from the SMARTS data base gives an outburst amplitude (A) of $\sim$7.5 in the $V$ band which is relatively small. It lies $\sim$4.5 magnitude below the outburst amplitude (A) versus log ($t$) plot for classical novae (Warner 1995; fig. 5.4).

In an extensive study of a large sample of classical novae and the RNe, Pagnotta & Schaefer (2014) have identified the characteristics common to RNe to identify the potential RNe among the known classical novae. The data discussed earlier shows that most of these characteristics, namely, small outburst amplitude, near-IR colours resembling the colours of late-type giant, expansion velocity exceeding 2000 km s$^{-1}$ and the presence of high excitation lines are fulfilled by Nova Sco 2015, thus it presents a strong case for to be a potential RN. It is worth noting the similar case of Nova Sco 2014, wherein Joshi et al. (2015) have shown that the outburst occurred in a symbiotic binary system and also suggested that it could be an RN.

$^3$ http://www-wfau.roe.ac.uk/sss/Ha/
5 DISCUSSION

No γ-ray emission was detected by the Fermi observatory from Nova Sco 2015 or Nova Sco 2014 (Joshi et al. 2015) which are both similar systems. On the other hand, two other similar symbiotic systems were detected in γ-rays viz. V407 Cyg and V745 Sco. The non-detections in Nova Sco 2014 and Nova Sco 2015 could be a consequence of both objects being sufficiently distant that any emission from them falls below the detection threshold of Fermi.

But it is desirable to check the Fermi data from both these novae carefully for any weak or suggested signs of detection. This has bearing on the origin of γ-ray emission from novae where the latest paradigm suggests that γ-ray emission could be a generic property of all novae and not intrinsic to just symbiotic systems (Ackermann et al. 2014). Novae from which γ-ray emission has been detected, but which are not symbiotic systems, are Nova Sco 2012, Nova Mon 2012, Nova Del 2013 and Nova Cen 2013.

6 SUMMARY

We present near-infrared photometric and spectroscopic observations of Nova Cep 2014 and Nova Sco 2015 which were discovered in outburst on 2014 March 8.79 UT and 2015 February 11.84 UT, respectively. Our observations for Nova Cep 2014 cover nine epochs from 5 to 90 d after outburst and for Nova Sco 2015 cover 11 epochs covering 7–47 d after outburst. Nova Cep 2014 shows the conventional characteristics of a Fe II class characterized by strong C i lines together with H i and O i lines, whereas Nova Sco 2015 is classified as He+N class, shows strong He i emission lines together with H i and O i emission features. Using MMRD relations for the novae, we estimate the distances for Nova Cep 2014 and Nova Sco 2015 as 17.2 ± 7 and 14.7 ± 3.8 kpc, respectively. For Nova Sco 2015, the presence of a decelerative shock seen through a narrowing of the line profiles, presents a strong case for it to be a symbiotic system. We discuss the evolution of the strength and shape of the emission line profiles.

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Figures

Figure 11. Recombination Case B analysis for the Hydrogen Brackett series of lines for Nova Sco 2015. The X axis is upper level principle quantum number of the line transition. The line intensities (data points) are normalized with respect to Br12 line strength and offsets are added for the sake of clarity. The model predictions for Case B analysis are also shown for temperature = 10000 K and electron number densities of 10^9 cm^{-3} (Small dash-dotted lines), 10^{10} cm^{-3} (solid lines), 10^{11} cm^{-3} (big dash lines), 10^{12} cm^{-3} (small dash lines), 10^{13} cm^{-3} (dotted lines), and 10^{14} cm^{-3} (dash-dotted lines).

Figure 12. SED of the pre-outburst near-IR counterpart of Nova Sco 2015 based on data from 2MASS, WISE and DENIS. A blackbody spectrum with a temperature of 3225 ± 50 K gives a good fit to the SED.
APPENDIX A: LINE IDENTIFICATION

Most of the NIR lines that appear in the spectra of novae have been identified in Das et al. (2008). However, the spectra presented there were in the 1.08–2.4 μm region, whereas the present spectra are taken with a newer instrument extend up to 0.85 μm. A robust identification of the numerous lines that appear in the 0.85–1.08 μm

Table A1. A list of emission lines identified from the JHK spectra of Nova Cep 2014 and Nova Sco 2015.

| Wavelength (μm) | Species | Other contributors/ remarks | Nova Cep | Nova Sco | Wavelength (μm) | Species | Other contributors/ remarks | Nova Cep | Nova Sco |
|-----------------|---------|-----------------------------|---------|---------|-----------------|---------|-----------------------------|---------|---------|
| 0.8359          | H I Pa22 | x                           | 1.2527  | H I      |                 | x       | x                           |         |         |
| 0.8374          | H I Pa21 | x                           | 1.2562, 1.2569 | C I      |                 | x       | x                           |         |         |
| 0.8392          | H I Pa20 | x                           | 1.2620  | C I      | x               | x       | x                           |         |         |
| 0.8413          | H I Pa19 | x                           | 1.2755  | u.i     | x               | x       | x                           |         |         |
| 0.8446          | O I Pa18 | x                           | 0.8438  | u.i     | x               | x       | x                           |         |         |
| 0.8467          | Pa17     | x                           | 1.2818  | H I Pa5  | x               | x       | x                           |         |         |
| 0.8498          | Ca II Pa16 | x                           | 0.8502  | u.i     | x               | x       | x                           |         |         |
| 0.8542          | Ca II Pa15 | x                           | 0.8545  | O I     | x               | x       | x                           |         |         |
| 0.8598          | H I Pa14 | x                           | 1.34–1.38 | N I     | Blend of many   | x       | N I lines                   |         |         |
| 0.8665          | H I Pa13 | Ca II 0.8662                | x       | 1.4420  | C I            | x       | x                           |         |         |
| 0.8750          | H I Pa12 | N I x                       | 1.4539  | u.i     | C I 1.4543?     | x       | x                           |         |         |
| 0.8802          | u.i     | 0.8807 Mg I?                | x       | 1.4757  | N I            | x       | x                           |         |         |
| 0.8863          | H I Pa11 | x                           | 1.4906  | H I Br27 | x               | x       | x                           |         |         |
| 0.8909          | u.i     | x                           | 1.4938  | H I Br26 | x               | x       | x                           |         |         |
| 0.8923          | u.i     | x                           | 1.4967  | H I Br25 | x               | x       | x                           |         |         |
| 0.9015          | H I Pa10 | x                           | 1.5000  | H I Br24 | x               | x       | x                           |         |         |
| 0.9021          | N I x   | 1.5039                      | H I Br23 | x       | x               | x       | x                           |         |         |
| 0.9089          | C I x   | 1.5083                      | H I Br22 | x       | x               | x       | x                           |         |         |
| 0.9174          | u.i     | 1.5133                      | H I Br21 | x       | x               | x       | x                           |         |         |
| 0.9226          | H I Pa9 | x                           | 1.5192  | H I Br20 | x               | x       | x                           |         |         |
| 0.9264          | O I x   | 1.5261                      | H I Br19 | x       | x               | x       | x                           |         |         |
| 0.9396          | N I x   | 1.5342                      | H I Br18 | x       | x               | x       | x                           |         |         |
| 0.9406          | C I x   | 1.5439                      | H I Br17 | x       | x               | x       | x                           |         |         |
| 0.9402          | u.i     | C I 0.9406?                 | x       | 1.5556  | H I Br16       | x       | x                           |         |         |
| 0.9546          | H I Pa8 | x                           | 1.5701  | H I Br15 | x               | x       | x                           |         |         |
| 0.9863, 0.9872  | N I x   | 1.5881                      | H I Br14 | x       | x               | x       | x                           |         |         |
| 0.9993          | u.i     | 1.6005                      | C I     | x       | x               | x       | x                           |         |         |
| 1.0049          | H I Pa7 | x                           | 1.6109  | H I Br13 | x               | x       | x                           |         |         |
| 1.0112          | N I C I 1.0119 | x                           | 1.6407  | H I Br12 | x               | x       | x                           |         |         |
| 1.0124          | He II x | 1.6807                      | H I Br11 | x       | x               | x       | x                           |         |         |
| 1.0308          | u.i     | 1.6872                      | Fe II   | x       | x               | x       | x                           |         |         |
| 1.0399          | u.i     | 1.6890                      | C I     | x       | x               | x       | x                           |         |         |
| 1.0457          | u.i     | 1.7002                      | He I    | x       | x               | x       | x                           |         |         |
| 1.0497          | u.i     | 1.7362                      | H I Br10 | x       | x               | x       | x                           |         |         |
| 1.0534          | N I x   | 1.7200–1.7900               | C I     | Blend of many | x | C I lines | x | x |
(the $IJ$-band region) is thus desirable. To identify the lines that contribute to a nova’s spectrum, we use an LTE model to build synthetic spectra as in Das et al. (2008) and Ashok & Banerjee (2003).

Assumptions of LTE may not strictly prevail in an nova environment although, around maximum and the early decline stage, when the particle density can be high (up to even $10^{14}$ cm$^{-3}$) collisions will be a dominant mechanism and will tend to drive the gas towards a Boltzmann distribution and LTE. Yet, in spite of the limitations of the LTE assumption we find that the model-generated spectra, greatly aid in a more secure identification of the lines observed. Briefly (more details in Das et al. 2008) the model spectra are generated by considering only those elements whose lines can be expected at discernible strength. Since nucleosynthesis calculations of elemental abundances in novae (Starrfield, Gehrz & Truran 1997; Jose & Hernanz, 1998) show that H, He, C, O, Ne, Mg, Na, Al, Si, P, S are the elements with significant yields in novae ejecta, only these elements have been considered. The Saha ionization equation was applied to calculate the fractional percentage of the species in different ionization stages and subsequently the Boltzmann equation was applied to calculate level populations. By switching off or greatly increasing the abundance of an element, it is easy to identify the positions where the lines of that element disappear or build up.

Fig. 3 shows the $IJ$-band spectrum of Nova Cep 2014 of 2014 March 20 in black and a typical synthetic LTE spectrum in grey below. The LTE spectrum has been computed for $n_e = 10^9$ cm$^{-3}$, $T = 8000$ K and abundances typically found in CO novae as given in Starrfield et al. (1997) and Jose & Hernanz (1998). A total of $\sim 2500$ of the strongest lines were considered for these elements compiled from the Kurucz atomic line list$^5$ and National Institute of Standards and Technology (NIST)$^6$ line list data base. Based on the line identifications done here, and lines in novae spectra known from earlier studies (Williams 2012; Das et al. 2008), the observed line list is given in the Table A1.

5 http://cfa-www.harvard.edu/amp/ampdata/
6 http://physics.nist.gov/PhysRefData/ASD

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