Near-infrared observations of nova V574 Puppis (2004)

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ABSTRACT
We present results obtained from extensive near-infrared spectroscopic and photometric observations of nova V574 Pup during its 2004 outburst. The observations were obtained over 4 months, starting from 2004 November 25 (4 d after the nova outburst) to 2005 March 20. The near-infrared JHK light curve is presented – it shows no evidence of the fact that dust formation has occurred during our observations. In the early decline phase, the JHK spectra of the nova are dominated by emission lines of hydrogen Brackett and Paschen series, O I, C I and He I. We also detect the fairly uncommon Fe II line at 1.6872 μm in the early part of our observations. The strengths of the He I lines at 1.0830 and 2.0585 μm are found to become very strong towards the end of the observations indicating a progression towards higher excitation conditions in the nova ejecta. The width of the emission lines does not show any significant change during the course of our observations. The slope of the continuum spectrum was found to have a $\lambda^{-2.75}$ dependence in the early stages which gradually becomes flatter with time and changes to a free–free spectral dependence towards the later stages. Recombination analysis of the H I lines shows deviations from case B conditions during the initial stages. However, towards the end of our observations, the line strengths are well simulated with case B model values with electron density $n_e = 10^{9-10}$ cm$^{-3}$ and a temperature equal to $10^4$ K. Based on our distance estimate to the nova of 5.5 kpc and the observed free–free continuum emission in the later part of the observations, we estimate the ionized mass of the ejecta to be between $10^{-5}$ and $10^{-6}$ M$\odot$.

Key words: techniques: spectroscopic – stars: individual: V574 Pup – novae, cataclysmic variables – infrared: stars.

1 INTRODUCTION
V574 Pup was independently discovered to be in outburst by Tago (Nakano et al. 2004) on 2004 November 20.67 UT at $V \sim 7.6$ and, within a short time thereafter, by Sakurai on 2004 November 20.812 UT at $V \sim 7.4$ (Nakano et al. 2004). The follow-up observations reported by Samus & Kazarovets (2004) showed a post-discovery brightening before the onset of fading. Low dispersion optical spectra of the nova on 2004 November 21.75 UT showed H$\alpha$ and H$\beta$ emission lines with P Cygni components, along with the strong Fe II (multiplet 42) in absorption indicating that V574 Pup is an ‘Fe II’ class nova near maximum light (Ayani 2004). Subsequent near-infrared spectroscopic observations of the nova on 2004 November 26.98 UT showed strong H I emission lines from the Paschen and Brackett series, O I lines at 1.1287 and 1.3164 μm, and a blend of NI and C I lines in the spectral region of 1.175–1.25 μm (Ashok & Banerjee 2004). The optical spectra of the nova on 2004 November 26 and December 12 obtained by Siviero, Munari & Jones (2005) were found to be dominated by Balmer hydrogen and Fe II emission lines; no nebular lines were present in the spectra of December 12. 1 yr after the outburst, the nova was found to be well into the coronal phase with the detection of [Si VI], [Si VII], [Ca VIII], [S VIII] and [S IX] lines in its spectrum (Rudy et al. 2005). Along with these lines, unidentified nova features at 0.8926, 1.1110, 1.5545 and 2.0996 μm were also present in the spectrum. However, no evidence for emission from dust was seen in these observations.

V574 Pup was observed by the Spitzer Space Observatory 1 yr after the outburst and revealed strong coronal lines (Rudy et al. 2006). The spectroscopic observations by Lynch et al. (2007), 3 yr after the outburst, showed the persistence of the coronal phase. Rudy et al. (2006) have remarked that the presence of strong coronal emission lines suggests similarity with an He/N nova. Siviero et al. (2005) have inferred that V574 Pup suffers negligible interstellar extinction though it is close to the galactic plane ($b = -2^\circ$). They estimate that the nova is located at a very large distance of 15–20 kpc. In a later subsection, we determine the distance to V574 Pup using the optical light curve and maximum magnitude versus rate of decline (MMRD) relation. V574 Pup is one of the novae
detected with X-ray emission, among 12 classical novae studied by Ness et al. (2007) using Swift observations. It was observed on several occasions between 2005 May and 2005 August by Swift. The X-ray spectra showed it to be in the super soft X-ray phase. Ness et al. (2007) estimate the colour excess $E(B - V) = 0.5$ and the distance to be 3.2 kpc.

### 2 OBSERVATIONS AND DATA REDUCTION

Near-infrared spectroscopic and photometric observations of V574 Pup were carried out fairly extensively using the 1.2-m telescope of the Mt. Abu Infrared Observatory. The $V$-band light curve is shown in Fig. 1 with the epochs of our observations marked by arrows – the log of the observations is given in Table 1. The Mt. Abu spectra were obtained at a resolution of $\sim 1000$ using a near-infrared imager/spectrometer with a 256 $\times$ 256 HgCdTe [Near-Infrared Camera Multi-Object Spectrograph 3 (NICMOS3)] array. Photometric observations of the nova were carried out on several nights (Table 1) in photometric sky conditions using the NICMOS3 array in the imaging mode. Several frames were obtained in four dithered positions, typically offset by $\sim 30$ arcsec from each other, with exposure times ranging from 0.4 to 100 s depending on the brightness of the nova. The sky frames were generated by median combining the average of each set of dithered frames and subsequently subtracted from the nova frames. A nearby field-star SAO 174367, observed at similar airmass as the nova, was used as the standard star for photometric observations. Aperture photometry was done using the APHOT task in IRAF.

Spectral calibration was done using the OH sky lines that register with the stellar spectra. The spectra of the nearby field star SAO 174400 (1 Pup) were taken in $HJK$ bands at similar airmass as that of V574 Pup on all the observation nights to ensure that the ratioing process (nova spectrum divided by the standard star spectrum) removes the telluric lines reliably. 1 Pup, although an emission-line star (spectral type A3 Iab), was chosen as the standard star due to its proximity to V574 Pup to minimize the effects of differential airmass between V574 Pup and the standard star. We have carefully removed the hydrogen lines in the spectra of 1 Pup ($Pa_F$ and $Br_y$ were seen to be in emission; other Brackett lines are in absorption) before taking the ratios. The ratioed spectra were then multiplied by a blackbody curve corresponding to the standard star’s effective temperature to yield the final spectra. Extraction and reduction of the spectra were done using IRAF.

### 3 RESULTS AND DISCUSSION

#### 3.1 Distance estimation from the visual light curve

We make a distance estimate to V574 Pup by analysing the $V$-band light curve using archival data from the American Association of Variable Stars (AAVSO) and Association Francaise des Observateurs d'Ettoiles Variables (AFOEV). The $V$-band light curve is presented in Fig. 1 with AAVSO data shown in filled circles and AFOEV data shown in open circles. As a visual nova, V574 Pup is observed to have an outburst on 2004 November 20.67 UT.

#### Table 1. Log of the Mt. Abu near-infrared observations of V574 Pup. The date of outburst is taken as 2004 November 20.67 UT.

| Date of observation | Days since outburst | Integration time (s) | Nova magnitude |
|---------------------|---------------------|----------------------|----------------|
|                     |                     | J-band | H-band | K-band | J-band | H-band | K-band | J-band | APHOT Photometric observations |
| 2004 Nov. 25        | 5                   | 40     | 40     | 60     | 28     | 28     | 24     | 5.65 ± 0.04 | 5.32 ± 0.09 | 4.75 ± 0.25 |
| 2004 Nov. 26        | 6                   | 60     | 80     | 120    | 40     | 20     | 60     | 6.11 ± 0.04 | 5.72 ± 0.03 | 5.39 ± 0.03 |
| 2004 Nov. 29        | 9                   | 60     | 60     | 120    | 36     | 25     | 12     | 6.42 ± 0.03 | 6.09 ± 0.02 | 5.66 ± 0.02 |
| 2004 Dec. 01        | 11                  | 60     | 60     | 60     | 28     | 16     | 48     | 6.31 ± 0.12 | 6.07 ± 0.21 | 5.73 ± 0.14 |
| 2004 Dec. 09        | 19                  | 80     | 60     | 80     | 64     | 72     | 116    | 6.73 ± 0.09 | 7.46 ± 0.33 | 6.78 ± 0.40 |
| 2004 Dec. 14        | 24                  | 60     | 60     | 80     | 36     | 36     | 116    | 7.18 ± 0.05 | 7.33 ± 0.07 | 6.86 ± 0.40 |
| 2004 Dec. 24        | 34                  | 100    | 240    | 180    | 72     | 72     | 58     | 7.89 ± 0.02 | 8.08 ± 0.04 | 7.49 ± 0.07 |
| 2004 Dec. 25        | 35                  | 180    | 180    | 180    | 72     | 72     | 60     | 7.92 ± 0.04 | 8.14 ± 0.02 | 7.34 ± 0.22 |
| 2005 Jan. 01        | 42                  | 120    | 120    | 240    | 72     | 72     | 120    | 8.25 ± 0.02 | 8.43 ± 0.04 | 7.71 ± 0.04 |
| 2005 Jan. 02        | 43                  | 120    | 120    | 240    | 72     | 72     | 120    | 8.31 ± 0.04 | 8.53 ± 0.04 | 7.77 ± 0.04 |
| 2005 Jan. 13        | 54                  | 120    | 120    | 120    | 144    | 144    | 116    | 8.53 ± 0.09 | 8.61 ± 0.09 | 7.94 ± 0.10 |
| 2005 Jan. 14        | 55                  | 120    | 120    | 120    | –      | –      | –      | –            | –            | –            |
| 2005 Jan. 19        | 60                  | 120    | 120    | 120    | –      | –      | –      | –            | –            | –            |
| 2005 Feb. 13        | 85                  | 240    | 240    | 240    | 360    | 360    | 200    | 9.39 ± 0.03 | 9.44 ± 0.03 | 8.69 ± 0.08 |
| 2005 Feb. 19        | 91                  | –      | –      | –      | 400    | 320    | 200    | 9.47 ± 0.12 | 9.48 ± 0.14 | 8.79 ± 0.14 |
| 2005 Feb. 25        | 97                  | 360    | 360    | 360    | 360    | 360    | 160    | 9.48 ± 0.07 | 9.58 ± 0.05 | 8.58 ± 0.14 |
| 2005 Mar. 13        | 113                 | 600    | 600    | 600    | 540    | 540    | 198    | 9.93 ± 0.05 | 10.05 ± 0.11 | 9.32 ± 0.25 |
| 2005 Mar. 19        | 119                 | –      | –      | –      | 480    | 480    | 198    | 9.74 ± 0.08 | 9.88 ± 0.11 | 9.04 ± 0.29 |
| 2005 Mar. 20        | 120                 | 600    | 600    | 600    | –      | –      | –      | –            | –            | –            |
and AFOEV data shown in open circles. The present light curve shows that the discovery of V574 Pup took place on its way to the maximum that was reached on 2004 November 22.2611. The pre-maximum brightening lasted for 1 d and subsequent to the maximum, there was a sharp drop by about 2 mag again within a day. Following this drop, V574 Pup showed a relatively slower rise reaching $V = 8.06$ on 2004 November 26.2458 and steadily decreased in brightness thereafter. For the purpose of calculation of $t_2$ and $t_3$, the time for a decline of 2 and 3 mag, respectively, we assume that the sharp drop of 2 mag lasting for a day can be ignored and take $V_{\text{max}} = 6.93$ on 2004 November 22.2611 UT (JD 245 3331.7611). We then derive from the $V$-band light curve a value of $t_2 = 10 \pm 1$ d and $t_3 = 25 \pm 2$ d. The absolute magnitude of the nova is then determined to be $M_V = -8.73$ using the MMRD relation of della Valle & Livio (1995). At maximum (JD 245 3331.7611), AAVSO lists the $B$ and $V$ magnitudes as 7.79 and 6.93, respectively. The mean intrinsic colour of novae at maximum is estimated to be $E(B - V) = +0.23 \pm 0.06$ (Warner 1995). Using this relation, we obtain $E(B - V) = 0.63$ and the extinction as $A_V = 1.95$. We thus estimate the distance to V574 Pup to be $d = 5.5$ kpc and adopt this value in future calculations. Ness et al. (2007) have derived a distance of 3.2 kpc which is closer to the value obtained in the present analysis compared to the 15–20 kpc estimate by Siviero et al. (2005). The significantly higher value for the distance estimated by Siviero et al. (2005) is due to the fainter value of $V_{\text{max}}$ considered by them and also their assumption of a negligible interstellar extinction towards the nova.

### 3.2 JHK light curves of V574 Pup

The $JHK$ light curves of V574 Pup, obtained from the present photometric observations, are presented in Fig. 2. A gradual fading is seen in all the three bands similar to the $V$-band behaviour. Further, no rise is seen in any of the near-infrared bands indicating the absence of dust formation during the period of 4 months following the outburst. We note from the figure, and also from the data in Table 1, that the $(J - H)$ colour index is generally found to be negative – specially so during the later stages of the observations. A negative $(J - H)$ index is characteristic of novae as shown by Whitelock et al. (1984). The reason for this is the presence of strong emission features in the $J$-band spectra such as the $Pa\beta$ and $Pa\gamma$, $He\alpha 1.083 \mu m$ and the $1.1287 \mu m$ lines. As discussed in the following subsection, the $He\alpha 1.083 \mu m$ and the $1.1287 \mu m$ lines are specially strong in V574 Pup giving rise to the observed behaviour of the $(J - H)$ colour index (the peak-to-continuum ratio of the $He\alpha 1.083 \mu m$ line went as high as $\sim 150$ in 2005 March). However, it may be noted that a negative $(J - H)$ index is not expected if dust formation takes place [Whitelock et al. 1984; an example is the dust-forming nova V1280 Sco (Das et al. 2008)]. The observed $K$-band brightness of the nova is also affected by significant contributions from the $He\gamma 2.0585 \mu m$ and $Br\gamma$ lines.

### 3.3 Emission lines in the $JHK$ spectra

The $JHK$ spectra of V574 Pup are presented in Figs 3–5, respectively. The early spectra cover the epoch of re-brightening seen at optical wavelengths and display typical emission lines of Paschen and Brackett series lines from hydrogen and the $O\i$ lines at 1.1287 and 1.3164 $\mu m$. Also seen prominently are lines of carbon and nitrogen, particularly in the $J$ band. The details of the line identification are given in Table 2. The large observed ratio of the $O\i 1.1287/1.3164 \mu m$ lines indicates that Ly$\beta$ fluorescence is the dominant process contributing to the strength of the 1.1287 $\mu m$ line. The $He\gamma$ line at 2.0581 $\mu m$ is clearly detected in the $K$-band spectra taken on November 29. This, and the $J$-band $He\gamma$ line at 1.0830 $\mu m$, gains in strength as the nova evolves. Their strength becomes comparable to hydrogen lines by December 24 and 25 and exceed them in strength by early January, indicating a progress towards higher excitation conditions in the ejecta. Towards the end of our observations, these $He\gamma$ lines become very strong while other weaker $He\i$ lines at 1.7002 and 2.1120–2.1132 $\mu m$ are also seen. We do not detect any coronal line features during the 4 months of our observational campaign. As mentioned earlier, many coronal features were detected in V574 Pup 1 yr after the outburst that were seen to last for the next 2 yr (Rudy et al. 2005; Lynch et al. 2007).

During the course of our observations of V574 Pup, there were no significant changes seen in the width of the emission lines in the $J$-, $H$- and $K$-band spectra. This implies the absence of any significant change in the expansion velocity of the ejected envelope. In order to quantify the changes in the linewidths in V574 Pup, the evolution of Brackett series lines which are prominent was investigated. The overall width of the hydrogen Brackett series emission lines did not change appreciably during the observations. The mean velocity of the expanding gas, from the Br lines, is estimated to be $1830 \pm 400$ km s$^{-1}$ which agrees well with the findings by Rudy et al. (2006) who determined an average velocity of 1800 km s$^{-1}$.

It is also noted that no lines from low ionization species such as $Na\i$ or $Mg\i$ are seen in the $JHK$ spectra. These low ionization lines, which are indicative of low temperature conditions, have been suggested as potential diagnostic features to predict dust formation in the nova ejecta (Das et al. 2008). The absence of these lines in V574 Pup is consistent with the lack of dust formation in this nova. In this context, there is a line at 2.1452 $\mu m$ which matches an NaI transition at that wavelength. However, for reasons discussed in Das et al. (2008), we are doubtful whether this line should be attributed.
to NaI. A notable feature in the $H$-band spectra is the structure of the Br$\text{I}_{11}$ line at 1.6806 $\mu$m which is seen to be distinctly different from other Brackett series lines in terms of both width and shape. This is most likely caused due to the blending of an additional nearby emission line of significant intensity. In the following subsection, we attempt to identify this additional line and show that it most likely is due to an Fe$\text{II}$ line at 1.6872 $\mu$m.

### 3.4 Detection of the Fe$\text{II}$ 1.6872 $\mu$m emission line in V574 Pup

We examine the distinct difference seen in the structure of the Br$\text{I}_{11}$ line vis-a-vis other Br lines (Fig. 4). This difference has persisted till the middle of 2005 January. The velocity of $3000 \pm 400$ km s$^{-1}$ corresponding to the full width at half-maximum (FWHM) of the Br$\text{I}_{11}$ line is larger than the average value of $1830 \pm 400$ km s$^{-1}$ corresponding to other Brackett series lines. This indicates that there is a definite contribution to the Br$\text{I}_{11}$ line from an adjacent emission feature. It is noted in the early spectra that there is a central enhancement (spike) in the Br$\text{I}_{11}$ line which gradually decreases in strength and by late 2004 December, the Br$\text{I}_{11}$ line starts showing a prominent redward wing. Considering this behaviour, we have looked for an emission line on the higher wavelength side of Br$\text{I}_{11}$. In two recent novae studied by us, namely V2615 Oph (Das, Banerjee & Ashok 2009) and RS Oph (Banerjee, Das & Ashok 2009), an emission line at 1.6872 $\mu$m has been clearly detected which is attributed to Fe$\text{II}$. We suspect that this Fe$\text{II}$ line is present here too. To study the effect of this line on Br$\text{I}_{11}$, we have generated synthetic line profiles by adding two lines, namely a primary line centred at 1.6806 $\mu$m corresponding to Br$\text{I}_{11}$ and a second line at 1.6872 $\mu$m corresponding to Fe$\text{II}$. Since there is no a priori knowledge on the shape of the Fe$\text{II}$ line, we assume that its shape can be simulated by the Br$\text{I}_{12}$ line profile (we choose Br$\text{I}_{12}$ because it is free from blending with other lines). We have similarly assumed that Br$\text{I}_{11}$ is well simulated by the observed line profile of the Br$\text{I}_{12}$ line. Keeping the peak intensity of the synthetic Br$\text{I}_{11}$ line constant, we have varied the intensity of the Fe$\text{II}$ line to simulate the observed temporal evolution. Two such synthetic spectra are shown in Fig. 6. In the figure, we show the individual line profiles of Br$\text{I}_{11}$ and Fe$\text{II}$...
with dotted lines and their resultant, co-added profile with a dashed line along with the observed profile (solid grey line). The left-hand and right-hand panels show the profiles for 2004 November 26 and 2004 December 9, respectively. The resultant and observed profiles are shown with some offset from the individual profiles for clarity. It is seen that the synthetic profiles resulting from the combination of BrII and Fe II match the observed line profile reasonably well. This indicates that the Fe II 1.6872 µm line is present in V574 Pup. Based on the work of Banerjee et al. (2009), another Fe II line at 1.7413 µm could also be expected in the spectrum. It is possible that this line is also there, but it is difficult to draw a definitive conclusion regarding its presence since it could be blended, rather too closely with Br10 and also a cluster of C I lines in the 1.74–1.77 µm region. We note that these Fe II lines are not too commonly reported in the spectra of novae. Apart from V2615 Oph (Das et al. 2009) and RS Oph (Banerjee et al. 2009), there are two more novae, namely V2540 Ophiuchi (Rudy et al. 2002) and C I Aquila (Lynch et al. 2004), where these lines appear to be detected. The excitation mechanism for these lines is believed to be Lyman α and Lyman continuum fluorescence coupled with collisional excitation (Banerjee et al. 2009 and references therein).

3.5 Evolution of the continuum

We analyse and discuss the evolution of the continuum spectra of V574 Pup here. At the time of outburst, a nova's continuum is generally well described by a blackbody distribution from an optically thick pseudo-photosphere corresponding to a stellar spectral type A to F (Gehrz 1988). The spectral energy distribution (SED) then gradually evolves into a free–free continuum as the optical depth of the nova ejecta decreases (Ennis et al. 1977; Gehrz 1988). The evolution of the continuum of V574 Pup is shown in Fig. 7 wherein we have shown representative spectra sampling the duration of our observations. The spectra in Fig. 7 were flux calibrated using the broad-band $JHK$ photometric observations presented in Table 1. During this process of calibrating the flux in the continuum, we note that the observed broad-band flux is a sum of contributions from both the continuum and also from emission lines. As the emission

**Figure 4.** The $H$-band spectra of V574 Pup at different epochs with the continuum being normalized to unity at 1.65 µm.
lines of H\textsc{i}, O\textsc{i} and He\textsc{i} are strong and contribute significantly to the broad-band fluxes, we have first calculated the contribution of all the prominent emission lines to the observed spectra and removed this contribution from the broad-band photometric fluxes measured from the \textit{JHK} photometry. This gives the true continuum flux which was used to calibrate the spectra in Fig. 7.

We have tried to fit the spectra in Fig. 7 with power-law fits, i.e. $F_{\lambda} \propto \lambda^{-\alpha}$. In the beginning of our observation, i.e. on 2004 November 25 (4 d after outburst) and 2004 December 1, the continuum spectrum approximately fits a spectral index of $\alpha \sim 2.75$. A blackbody fit, expected to have an index of $\alpha = 4.0$ at longer wavelengths, does not simulate the data too well. The subsequent spectra gradually become flatter with a slope of $\alpha \sim 2.0$ on 2004 December 14. The nova continuum is subsequently found to become flatter with time and gradually match a free–free emission spectrum towards the end of our observation campaign. The spectrum of 2005 February 25 in Fig. 7 has been fitted with a free–free spectrum computed at a temperature of $T = 10^4$ K.

### 3.6 Case B recombination analysis

The recombination case B analysis for the H\textsc{i} lines was carried out for all the observed spectra, and the representative results for five epochs covering the first 80 d of our observations are shown in Fig. 8. We have plotted in Fig. 8 the observed relative strength of Brackett series lines with the line strength of Br\textsc{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 $n_e = 10^9, 10^{10}$ and $10^{11}$ cm$^{-3}$. High electron densities are considered because the ejecta material is expected to be dense in the early stages after the outburst. For the early epochs, namely 2004 November 25 and 2004 December 1, the Br\textsc{10} line is not included as it is at the edge of the observed spectra and not adequately covered. The errors in the estimated line strengths are $\sim$10 per cent for the Br\textsc{y}, Br\textsc{12} and Br\textsc{13} lines and $\sim$20 per cent for the Br\textsc{14}, Br\textsc{15}, Br\textsc{16} and Br\textsc{17} lines. The errors for the Br\textsc{11}
Table 2. List of prominent lines in the JHK spectra.

| Wavelength (μm) | Species | Remarks                  |
|-----------------|---------|--------------------------|
| 1.0830          | He i    | Strongest lines at 1.0852, 1.0869 μm |
| 1.0938          | Paβ     | Blend of C 1 at 1.0926 μm   |
| 1.1287          | O I     | Strongest lines at 1.1294 μm |
| 1.1600–1.1674   | C i     | Blend of several C i Lines |
| 1.1748–1.1800   | C i     | Blend of several C i Lines |
| 1.1819–1.1896   | C i     | Blend of several C i Lines |
| 1.2187–1.2382   | C i, N i| Blend of several C i Lines |
| 1.2461, 1.2469  | N i     | Blend of several C i Lines |
| 1.2562–1.2614   | C i     | Blend of several C i Lines |
| 1.2818          | Na I    | Blend of several C i Lines |
| 1.3164          | O i     | Blend of several C i Lines |
| 1.5439          | Br 17   | Blend of several C i Lines |
| 1.5557          | Br 16   | Blend of several C i Lines |
| 1.5685          | Br 15   | Blend of several C i Lines |
| 1.5881          | Br 14   | Blend of several C i Lines |
| 1.6005          | C i     | Blend of several C i Lines |
| 1.6109          | Br 13   | Blend of several C i Lines |
| 1.6407          | Br 12   | Blend of several C i Lines |
| 1.6806          | Br 11   | Blend of several C i Lines |
| 1.6872          | Fe ii   | Blend of several C i Lines |
| 1.7002          | He i    | Blend of several C i Lines |
| 1.7045          | C i     | Blend of several C i Lines |
| 1.7362          | Br 10   | Blend of several C i Lines |
| 1.74–1.77       | C i     | Blend of several C i Lines |
| 2.0585          | He i    | Blend of several C i Lines |
| 2.1120, 2.1132  | C i     | Blend of several C i Lines |
| 2.1156–2.1295   | C i     | Blend of several C i Lines |
| 2.1452          | Na I?   | Blend of several C i Lines |
| 2.1655          | Br γ    | Blend of several C i Lines |
| 2.2156–2.2167   | C i     | Blend of several C i Lines |
| 2.2906          | C i     | Blend of several C i Lines |

Fig. 6. The profiles of the Br 11 line at 1.6806 μm (dotted line), Fe ii line at 1.6872 μm (dotted line), the added line (Br 11 + Fe ii) intensity (dashed line) and the observed data (grey solid line) are shown for 2004 November 26 (left-hand panel) and for 2004 December 9 (right-hand panel). The intensity of the Fe ii line was adjusted to match the co-added profile with the observed profile. The co-added and observed profiles are shown with some offset in order to make it clear for comparison.

match well with the predicted values for the recombination case B values of $T = 10^4$ K and an electron density in the range $n_e = 10^{30}$–$10^{35}$ cm$^{-3}$.

3.7 Estimation of the mass of the nova ejecta

We estimate the mass of the ionized gas in the ejecta using the fact that on 2005 February 25, the observed SED of V574 Pup is well fitted by a free–free flux distribution at a temperature of $T = 10000$ K (Fig. 7).

The free–free volume emission coefficient from an ionized gas is given by

$$j_{\text{ff}} = 2.05 \times 10^{-30} \lambda^{-2} \frac{z^4 gT^{1/2}n_e n_i e^{-z/3T}}{\pi} \text{Wcm}^{-3} \text{μm}^{-1},$$

where $\lambda$ is the wavelength in μm, $z$ is the charge, $g$ is the Gaunt factor (assumed equal to unity), $T$ is the temperature, $n_e$ and $n_i$ are the electron and ion densities, respectively, and $c_2 = 1.438$ cm K. The total continuum emission from the nova ejecta can then be estimated by multiplying the flux given in the above equation with the shell volume $V_s$ and equating it to the observed flux $F_{\text{obs}}$, which equals

$$F_{\text{obs}} = j_{\text{ff}} \times \frac{V_s}{4\pi d^2},$$

where $d$ is the distance to the object. We use $d = 5.5$ kpc, $T = 10^4$ K and $n_e = n_i$ assuming a pure and completely ionized hydrogen ejecta ($z = 1$). At K-band centre ($\lambda = 2.2$ μm), using the observed flux on 2005 February 25 to be $1.325 \times 10^{-17}$ W cm$^{-2}$ μm$^{-1}$ and $n_e$ is $10^{10}$ cm$^{-3}$ derived from the recombination analysis, we obtain the volume of the emitting H i gas to be $V_s = 2.2 \times 10^{41}$ cm$^3$. Similar values for $V_s$ are obtained if the J- and H-band observed fluxes and corresponding central wavelengths of these bands are used instead.

The mass of the ionized gas can then be calculated using $M_{\text{gas}} = V_s n_e m_{\text{H}}$, where $m_{\text{H}}$ is the mass of the hydrogen atom. Taking $n_e = 10^{10}$ cm$^{-3}$ gives a value of $M_{\text{gas}} = 1.8 \times 10^{-4} M_\odot$. A similar
calculation for \( n_e = 10^9 \text{ cm}^{-3} \), which could also be a valid estimate in V574 Pup (as indicated from case B analysis for 2005 February 25), yields \( M_{\text{gas}} = 1.8 \times 10^{-5} \text{ M}_\odot \). Thus, within the uncertainties associated with the parameters involved, we would estimate the mass of the ionized gas to be in the range of \( 1.8 \times 10^{-5} - 1.8 \times 10^{-6} \text{ M}_\odot \). This estimate is reasonably in agreement with the observed range of the mass of nova ejecta (\( 1-30 \times 10^{-5} \text{ M}_\odot \)) and also the theoretically calculated range of \( 5.3 \times 10^{-8} - 6.6 \times 10^{-4} \text{ M}_\odot \) in the extended grid of models computed by Yaron et al. (2005).

The mass estimate made above can be checked for consistency through an alternative approach. As discussed in Section 3.6, on 2005 February 13 and 25 there is a reasonably good match between the observed line intensities of H\textsc{i} Brackett series lines with the theoretical case B values listed in Storey & Hummer (1995) for \( T = 10^4 \text{ K} \) and \( n_e = 10^9 - 10^{10} \text{ cm}^{-3} \). For these values, the emissivity in B\text{r}y is expected to be \( j(\text{Br } \gamma) \sim 4.5 \times 10^{-14} \text{ W cm}^{-3} \) (Storey & Hummer 1995). From the observed data of 2005 February 13 and 25, the B\text{r}y line is measured to have a mean line luminosity of \( \sim 5.0 \times 10^{-19} \text{ W cm}^{-2} \). Using \( d = 5.5 \text{ kpc} \), the total power in the line is thus \( 1.8 \times 10^{28} \text{ W} \). With \( j(\text{Br } \gamma) \) as estimated above, this yields the volume of the emitting gas to be \( V = 4.0 \times 10^{41} \text{ cm}^{3} \) (consistent with the value of \( 2.2 \times 10^{22} \text{ cm}^{3} \) derived from the free–free analysis) which thereby leads to a similar mass estimate as made earlier.

4 SUMMARY

We have presented an extensive set of spectroscopic and photometric observations of nova V574 Puppis. From the V-band light curve, the distance to the nova is estimated to be \( \sim 5.5 \text{ kpc} \). The near-infrared light curve shows a steady decline with time without any evidence for the buildup of an infrared excess associated with dust formation in the ejecta. However, an infrared excess at longer wavelengths cannot be ruled out. Along with lines of hydrogen, helium, oxygen and carbon, we also detect the Fe\textsc{ii} emission line at 1.6872 \( \mu \text{m} \) in the near-infrared spectra. The nova continuum is modelled and found to evolve from a \( \lambda^{-2.75} \) dependence to a free–free type of emission during the period of our observations. A recombination analysis of the H\textsc{i} lines is presented. We estimate the mass of the ionized gas in the ejecta and show it to lie in the range of \( 10^{-5} - 10^{-6} \text{ M}_\odot \).

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Figure 8. Recombination analysis for the hydrogen Brackett lines in V574 Pup on selected dates of our near-infrared observations (as noted in the figure). The abscissa is the upper level number of the Brackett series line transition. The line intensities are relative to that of Br 12 which is normalized to unity. The errors in the estimated line strengths are \( \sim 10 \) per cent for the Br\( \gamma \), Br12 and Br13 lines and \( \sim 20 \) per cent for the Br14, Br15, Br16 and Br17 lines. The errors for the Br11 line are \( \sim 30 \) per cent for 2004 November 25, \( \sim 20 \) per cent for 2004 December 1 and \( \sim 10 \) per cent for observations on the other days. The case B model predictions for the line strengths are also shown for a temperature \( T = 10^4 \) K and electron densities of \( n_e = 10^{12} \) cm\(^{-3}\) (dot–dashed line), \( 10^{10} \) cm\(^{-3}\) (solid line) and \( 10^9 \) cm\(^{-3}\) (dotted line).

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