

## Near-infrared studies of nova V5584 Sgr in the pre-maximum and early decline phase

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**Abstract** We present near-infrared spectroscopic and photometric observations of nova V5584 Sgr taken during the first 12 d following its discovery on Oct. 26.439 UT 2009. The evolution of the spectra is shown from the initial P Cygni phase to an emission line phase. The prominent carbon lines seen in the *JHK* spectra closely match those observed in an Fe II class nova outburst. The spectra show first-overtone CO bands in emission between 2.29–2.40  $\mu\text{m}$ . By examining WISE and other publicly available data, we show that the nova underwent a pronounced dust formation phase between February - April 2010.

**Key words:** line: identification — techniques: spectroscopic — stars: individual (V5584 Sgr) — novae cataclysmic variables

### 1 INTRODUCTION

Nova Sagittarii 2009 No. 4 (V5584 Sgr) was discovered on Oct. 26.439 UT 2009 by Nishiyama and Kabashima on two 60 s unfiltered CCD frames at a magnitude of 9.3 in *V* (Nishiyama et al. 2009). Nothing was visible at this position on their two survey frames taken respectively on Oct 20.449 UT 2009 with limiting magnitude 13.9 and Oct. 21.451 UT 2009 with limiting magnitude 13.4. Corelli (2009) has reported that nothing was visible at the nova position on the Palomar plate (limiting magnitude 21) taken on Oct. 26.764 UT 2008.

A low-resolution optical spectrum obtained by Kinugasa et al. (2009) on Oct. 27.4 UT 2009, with the 1.5 m telescope at Gunma Astronomical Observatory showed hydrogen Balmer series absorption lines, with  $H\alpha$  having a prominent P-Cygni profile and a full width at half-maximum (FWHM) of about  $600 \text{ km s}^{-1}$  suggesting the object to be a nova in its early stage. The absorption minimum of the  $H\alpha$  was blue-shifted by  $900 \text{ km s}^{-1}$  from the emission peak. Another low-resolution spectrum obtained by Maehara (2009) on Oct. 27.42 UT 2009 also showed a similar profile of the  $H\alpha$  line, suggesting that the object is a classical nova. Munari et al. (2009) have taken low-, medium-, and high-resolution spectra for this nova with the 0.6 m telescope of the Schiaparelli Observatory in Varese. The low- and medium-resolution spectra taken on Oct. 28.73 UT 2009 show a well-developed and highly reddened absorption continuum. The FWHM of the absorption lines are  $\sim 310 \text{ km s}^{-1}$ . The heliocentric radial velocity of the absorption lines were  $\sim -283 \text{ km s}^{-1}$  and

the separation between the absorption and emission components was  $440 \text{ km s}^{-1}$ . The high resolution echelle spectra taken on Oct. 29.72 UT 2009 show very weak emission from Balmer and Fe II multiplets. They report  $V$  magnitudes of 9.74, 9.31 and 9.21 on Oct. 27.719 UT, 28.709 UT and 29.708 UT 2009, respectively. Munari et al. (2009) have pointed out that the object is a nova of Fe II class and was approaching its optical maximum at that time.

The near-infrared (NIR) spectrum taken by Raj et al. (2009) on Oct. 29.58 UT 2009 showed the strong P-Cygni profiles for H I, O I, C I and N I lines. Subsequent observations showed strengthening of the emission components and the first overtone CO bands were detected in the spectrum taken on Nov. 5.64 UT 2009. The near-IR observations obtained on Feb. 10 UT 2010 by Russell et al. (2010), after V5584 Sgr came out of the solar conjunction, showed dust formation in the nova ejecta and the dust temperature was estimated as  $880 \pm 50 \text{ K}$ . The optical spectra taken on Jun. 4 and Aug. 10 UT 2010 by Poggiani (2011) showed that the nova had entered the nebular phase.

The observations and data analysis technique are discussed in Section 2. Section 3 contains the results obtained from these observations and the summary is given in Section 4.

## 2 OBSERVATIONS

The near-IR observations were obtained using the 1.2 m telescope of the Mt. Abu Infrared Observatory from Oct. 28.59 to Nov. 8.56 UT 2009 covering one epoch before the optical maximum and the early decline phase. The spectra were obtained at a resolution of  $\sim 1000$  using a Near-Infrared Imager/Spectrometer with a  $256 \times 256$  HgCdTe NICMOS3 array. Spectral calibration was done using the OH sky lines that are recorded simultaneously with the stellar spectra. The spectra of the comparison star SAO 161520 (spectral type A1V; effective temperature 9230 K) were taken at a similar airmass to that of V5584 Sgr to ensure that the ratioing process (nova spectrum divided by the standard star spectrum) reliably removed the telluric features. The H I absorption lines in the spectra of a standard star were removed manually before ratioing to avoid artificially generated emission lines in the ratioed spectrum. The ratioed spectra were then multiplied by a blackbody curve corresponding to the standard star's effective temperature to yield the final spectra.

The photometry was done in clear sky conditions using the NICMOS3 array in imaging mode using  $JHK$  bands. Several frames were obtained in all the bands, in four dithered positions, offset by  $\sim 30''$ . The sky frames, which were subtracted from the nova frames, were generated by median combining the dithered frames. The star SAO 161520 (with the  $JHK$ -band magnitudes of 4.803, 4.622 and 4.360, respectively) located close to the nova was used for photometric calibration. All data reduction and analysis were done using IRAF. The log of the spectroscopic and photometric observations, and the  $JHK$  magnitudes are given in Table 1.

## 3 RESULTS

We describe the key results in the following subsections.

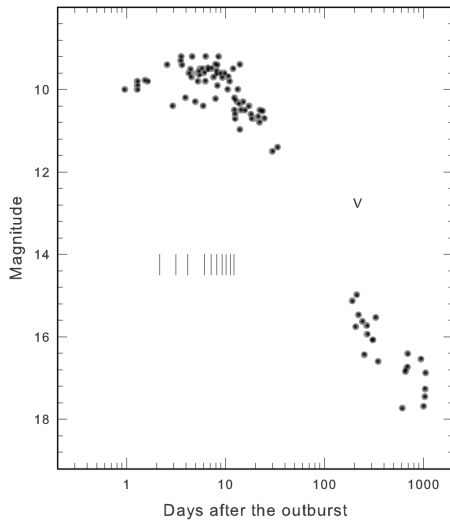
### 3.1 General characteristics of $V$ and $JHK$ light curves

The  $V$  band light curve based on the data from the American Association of Variable Star Observers (AAVSO) and the  $JHK$  band light curves from the Mt. Abu Observatory are presented in Figures 1 and 2, respectively. The nova reached a maximum value of  $V_{\text{max}} = 9.2$  on Oct. 29.71 UT 2009. We estimate  $t_2$  (time taken by the nova to decline by 2 magnitudes from the optical maximum) to be  $25 \pm 1 \text{ d}$  from a least squares regression fit to the post maximum light curve. We determine the absolute magnitude of the nova to be  $M_V = -7.7 \pm 0.2$  using the maximum magnitude versus rate of decline (MMRD) relation of della Valle & Livio (1995). We derive the reddening  $E(B - V) = 0.94$  from Schlafly & Finkbeiner (2011) towards the direction of the nova which gives interstellar extinction  $A_V = 2.9$  for  $R = 3.1$ . Using the distance modulus relation, we obtain a value of the

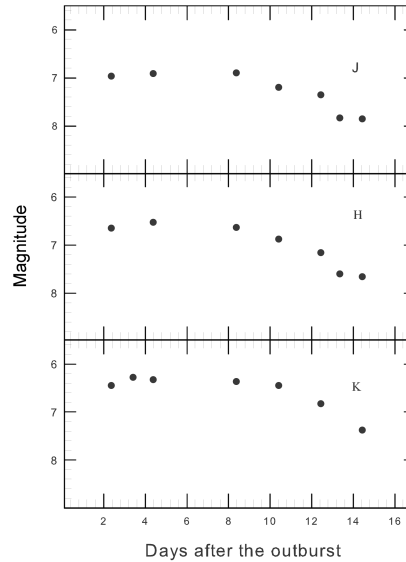
**Table 1** A log of near-infrared spectroscopic and photometric observations of V5584 Sgr. The optical maximum is assumed to be its detection date. The date of optical maximum is taken as Oct. 29.71 UT 2009.

| Date of Observation (UT) | Days since optical max | Integration time (s)       |                |                | Integration time (s)     |                |                | Nova Magnitude |                |                |
|--------------------------|------------------------|----------------------------|----------------|----------------|--------------------------|----------------|----------------|----------------|----------------|----------------|
|                          |                        | <i>J</i> -band             | <i>H</i> -band | <i>K</i> -band | <i>J</i> -band           | <i>H</i> -band | <i>K</i> -band | <i>J</i> -band | <i>H</i> -band | <i>K</i> -band |
|                          |                        | Spectroscopic Observations |                |                | Photometric Observations |                |                |                |                |                |
| 2009 Oct. 28.59          | -1.12                  | –                          | –              | –              | 250                      | 220            | 105            | 6.97±0.04      | 6.65±0.04      | 6.45±0.07      |
| 2009 Oct. 29.58          | -0.13                  | 60                         | 50             | 90             | 25                       | 110            | 50             | –              | –              | 6.28±0.06      |
| 2009 Oct. 30.58          | 0.87                   | –                          | –              | –              | 75                       | 110            | 30             | 6.92±0.05      | 6.53±0.03      | 6.33±0.04      |
| 2009 Nov. 02.59          | 3.88                   | –                          | –              | –              | 50                       | 110            | 105            | 6.90±0.02      | 6.64±0.04      | 6.37±0.06      |
| 2009 Nov. 03.59          | 4.88                   | 120                        | 120            | –              | –                        | –              | –              | –              | –              |                |
| 2009 Nov. 04.60          | 5.89                   | 90                         | –              | –              | 75                       | 110            | 30             | 7.20±0.06      | 6.88±0.05      | 6.45±0.04      |
| 2009 Nov. 05.64          | 6.93                   | 90                         | 90             | 90             | –                        | –              | –              | –              | –              | –              |
| 2009 Nov. 06.58          | 7.87                   | 90                         | 90             | –              | 75                       | 110            | 50             | 7.36±0.03      | 7.16±0.02      | 6.83±0.06      |
| 2009 Nov. 07.61          | 8.90                   | –                          | –              | –              | 100                      | 50             | –              | 7.84±0.02      | 7.60±0.08      | –              |
| 2009 Nov. 08.56          | 9.85                   | 120                        | 120            | 120            | 125                      | 75             | 55             | 7.86±0.04      | 7.66±0.03      | 7.38±0.07      |

distance  $d = 6.3 \pm 0.5$  kpc to the nova. Using this value of  $d$  and the Galactic latitude of the nova  $-3.1$  deg, we estimate the height of the nova to be  $z = 341 \pm 30$  pc below the Galactic plane. The outburst bolometric luminosity of V5584 Sgr as calculated from  $M_V$  is  $L_O \sim 1.1 \times 10^5 L_\odot$ . As there are no observations after  $\sim 30$  d from the discovery date due to the solar conjunction of the nova, we estimate the time taken by the nova to decline by 3 magnitudes from the optical maximum  $t_3 = 46 \pm 1$  d by using the relation  $t_3 = 2.7(t_2)^{0.88}$  of Warner (1995). The observed value of the outburst amplitude (difference between the limiting magnitude of detection and the optical maximum magnitude)  $\Delta V = 12$  and  $t_2 = 25$  d for V5584 Sgr is consistent with the outburst amplitude versus decline rate plot for classical novae presented by Warner (2008), which shows  $\Delta V = 10 - 13$  for  $t_2 = 25$  d.



**Fig. 1** The *V* band light curve of V5584 Sgr from AAVSO data. The days when spectroscopic and photometric observations were taken are shown as solid lines below the data points.



**Fig. 2** The Mt. Abu *JHK* band light curves of V5584 Sgr.

A classification scheme of novae based on the optical light curves is presented by Strope et al. (2010). Such a classification is based on the post-maximum time when the light curve declined by 3.0 magnitudes, namely  $t_3$  and the shape of the light curve. We classify the optical light curve of V5584 Sgr as D(46) according to the estimated value of  $t_3$  (46d), where D(46) denotes the dust formation as discussed later in Section 3.5.

### 3.2 Line identification, evolution and general characteristics of the *JHK* spectra

The *JHK* spectra are presented in Figures 3 to 5 respectively and the line identification in graphical and tabular form are given in Figure 6 and Table 2, respectively. The near-IR observations presented here cover the pre-maximum light to early post-maximum decline. The first infrared spectra taken on Oct. 29.58 UT 2009 are dominated by lines of hydrogen, neutral nitrogen, carbon and oxygen with prominent P-Cygni profiles. The FWHM of the absorption and emission components of the Pa $\beta$  line are 400 and 560 km s<sup>-1</sup> respectively and the separation between the absorption and emission peaks for all the lines is typically in the range of 550–650 km s<sup>-1</sup>. The next spectra taken on Nov. 3.59 UT 2009 show considerable strengthening of the emission components having P-Cygni absorption with reduced intensity. Spectral templates in the NIR for the characteristic spectra of the Fe II and He/N class of novae have been presented by Banerjee & Ashok (2012). The essential NIR spectral features that distinguish between the Fe II and He/N class of novae are the strong carbon lines in the former class. The *JHK* spectra presented here show the presence of carbon lines at 1.166  $\mu$ m and 1.175  $\mu$ m in the *J* band, 1.689  $\mu$ m and several lines between 1.72  $\mu$ m and 1.79  $\mu$ m in the *H* band and lines from 2.11  $\mu$ m to 2.13  $\mu$ m and from 2.29  $\mu$ m to 2.31  $\mu$ m lines in the *K* band. Thus the carbon rich spectra indicate that V5584 Sgr belongs to Fe II class. The presence of Na and Mg lines (e.g., Na I 2.2056  $\mu$ m, 2.2084  $\mu$ m) in the spectrum can be regarded as an indicator of dust formation in the nova ejecta (Das et al. 2008) and this gets further support from the analysis of the 3- to 14- $\mu$ m spectroscopy (Russell et al. 2010).

### 3.3 First overtone CO detection and modeling

The first *K* band spectrum taken on Oct. 29.58 UT 2009, very close to optical maximum, does not show evidence for first overtone CO emission at 2.29  $\mu$ m and beyond. It is possible that CO was present at this stage but below or just at the detection level (see Raj et al. 2011). Nevertheless, we notice that the *K*-band spectrum taken on Nov. 5.64 UT 2009 shows clear evidence for first overtone CO emission. This is one of the most interesting results in V5584 Sgr since CO detections are very rare in novae. Among more than 300 Galactic novae, only nine have been found to show CO emissions (i.e., < 3%). The next *K* band spectrum taken on Nov. 8.56 UT 2009 does not cover the CO emission region so it is not possible to comment on the duration of the CO emission. Based on the detailed studies by Das et al. (2009) and Raj et al. (2012), we have compiled in Table 3 the complete list of novae known to have shown first overtone CO emission. Theoretically, Pontefract & Rawlings (2004) pointed out that CO should form early after outburst and remain approximately constant in strength for 12–15 d thereafter and then get rapidly destroyed. The early appearance of CO in V5584 Sgr is consistent with the predictions. It may be mentioned that models for CO emission as developed by Rawlings (1988) and Pontefract & Rawlings (2004) found that the outer parts of the ejecta have to be much denser and less ionized than the bulk of the wind which favors the formation of substantial molecules. Carbon has to be neutral and in such a neutral carbon region, the carbon ionization continuum, which extends to less than 1102Å, shields several molecular species against the dissociative UV flux from the central star. The relatively denser and cooler environment that is conducive for molecular growth also favors dust formation and every CO forming nova has always been known to form dust. However, the converse case has not been seen. The reason for the non-detection of CO in other dust forming novae is not known. A possible reason for the non-detection

**Table 2** A list of the lines identified from the *JHK* spectra. The additional lines contributing to the identified lines are listed.

| Wavelength ( $\mu\text{m}$ ) | Species     | Other contributing lines and remarks         |
|------------------------------|-------------|--|
| 1.0938                       | Pa $\gamma$ |  |
| 1.1287                       | O I         |  |
| 1.1330                       | C I         |  |
| 1.1381–1.1404                | Na I        | C I 1.1415                                   |
| 1.1600–1.1674                | C I         | strongest lines at 1.1653, 1.1659, 1.16696   |
| 1.1748–1.1800                | C I         | strongest lines at 1.1748, 1.1753, 1.1755    |
| 1.11819–1.1896               | C I         |  |
| 1.1819–1.2614                | C I, N I    | blend of several C I and N I lines           |
| 1.2461, 1.2469               | N I         | blended with O I 1.2464                      |
| 1.2562, 1.2569               | C I         | blended with O I 1.2570                      |
| 1.2818                       | Pa $\beta$  |  |
| 1.3164                       | O I         |  |
| 1.5256                       | Br 19       |  |
| 1.5341                       | Br 18       |  |
| 1.5439                       | Br 17       |  |
| 1.5557                       | Br 16       |  |
| 1.5701                       | Br 15       |  |
| 1.5749                       | Mg I        | blended with Mg I 1.5741, 1.5766, C I 1.5788 |
| 1.5881                       | Br 14       | blended with C I 1.5853                      |
| 1.6005                       | C I         |  |
| 1.6109                       | Br 13       |  |
| 1.6407                       | Br 12       |  |
| 1.6806                       | Br 11       |  |
| 1.6890                       | C I         |  |
| 1.7045                       | C I         |  |
| 1.7109                       | Mg I        |  |
| 1.7362                       | Br 10       | affected by C I 1.7339 line                  |
| 1.7449                       | C I         |  |
| 1.7605–1.7638                | C I         |  |
| 2.1156–2.1295                | C I         |  |
| 2.1655                       | Br $\gamma$ |  |
| 2.2056, 2.2084               | Na I        |  |
| 2.2156–2.2167                | C I         |  |
| 2.29–2.40                    | CO          | $\Delta v = 2$ bands                         |
| 2.2906                       | C I         |  |
| 2.3130                       | C I         |  |
| 2.3348                       | Na I        |  |
| 2.3379                       | Na I        |  |

of CO emission in novae with dust formation is the paucity of near-infrared spectral observations in the early phase of nova evolution and its shorter duration. Alternatively, in these novae either CO did not form for reasons which are not clearly understood or it was present but below the detection limit of observations.

We used the model developed by Das et al. (2009) in the case of V2615 Oph to characterize the CO emission in V5584 Sgr (Fig. 7). Compared to V2615 Oph, the CO detection here is only for one epoch and the signal to noise ratio (S/N) of the spectrum is poor (approximately 10) and thus not conducive for accurate modeling. However, since CO detections are rare, it is desirable to have

**Table 3** A list of all Galactic Novae which have shown first-overtone CO emission.

| Nova      | Detection epoch after outburst (d) | Reference                              |
|-----------|------------------------------------|--|
| NQ Vul    | 19                                 | Ferland et al. (1979)                  |
| V842 Cen  | 25                                 | Wichmann et al. (1991)                 |
| V705 Cas  | 6                                  | Evans et al. (1996)                    |
| V2274 Cyg | 17                                 | Rudy et al. (2003)                     |
| V2615 Oph | 9                                  | Das et al. (2009)                      |
| V5584 Sgr | 12                                 | This work                              |
| V496 Sct  | 19                                 | Rudy et al. (2009) & Raj et al. (2012) |
| V2676 Oph | 37                                 | Rudy et al. (2012b)                    |
| V1724 Aql | 7                                  | Rudy et al. (2012a)                    |

rough model estimates of the CO parameters even if such estimates are not quite accurate. In the model calculations the CO gas is considered to be in thermal equilibrium with the same temperature for calculating the level populations of rotation and vibration bands (see Das et al. 2009 for more details). The data only cover three of the bands ( $\nu = 2-0, 3-1, 4-2$ ) and the C I lines at 2.2906 and 2.3130  $\mu\text{m}$  are likely blended with Na I lines at 2.3348 and 2.3379  $\mu\text{m}$ , thereby giving rise to further complications. Allowing for all these factors, we estimate the temperature to be  $3500 \pm 750$  K and constrain the upper limit for the mass of the CO gas to be in the range  $1-6 \times 10^{-8} M_{\odot}$ . The errors are fairly large but the central values of the mass and temperature are very similar to the values obtained in V2615 Oph (Das et al. 2009) and V496 Sct (Raj et al. 2012). We do not make any attempt to determine the  $^{12}\text{C}/^{13}\text{C}$  ratio given the low S/N of the spectrum.

### 3.4 Fireball phase

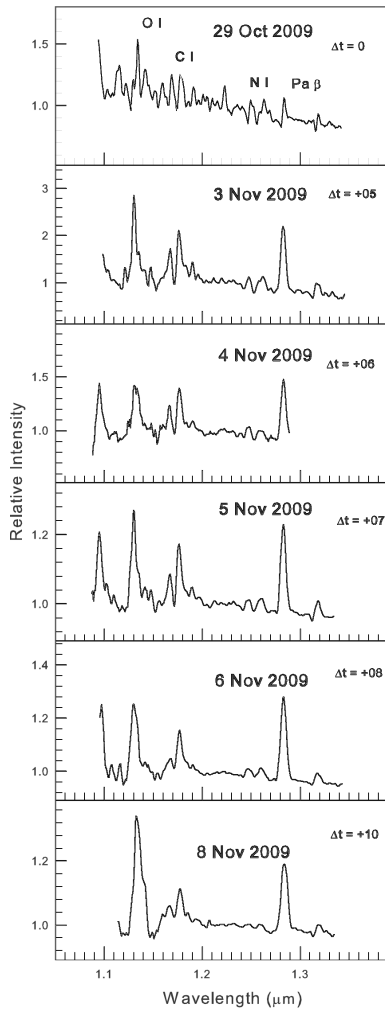
The continuum from a nova's ejecta near maximum light is known to mimic the photosphere of an A-F spectral type star (Gehrz 2008). The spectral energy distribution (SED) of the pseudo-photosphere during this fireball stage is generally well approximated by a blackbody. As V5584 Sgr showed a pre-maximum rise and has a well-defined optical maximum, we have constructed the SED to study the fireball phase for the nova. Using the AAVSO data for the following optical magnitudes  $B = 10.4$ ,  $V = 9.5$ ,  $R_C = 8.7$  and  $I_C = 7.6$  for Nov. 2 UT 2009 along with the present *JHK* magnitudes of Nov. 2.59 UT 2009, we derived the SED in the fireball phase. The observed magnitudes were corrected for extinction using Schlafly & Finkbeiner (2011). We obtain a temperature of  $T_{\text{bb}} = 9000 \pm 500$  K from a blackbody fit to the SED shown in the top panel of Figure 8. This is consistent with the A-F spectral type for the pseudo-photospheres displayed by novae at outburst (Gehrz 2008). Using the relation given by Ney & Hatfield (1978), the blackbody angular diameter  $\theta_{\text{bb}}$  in arcseconds is calculated, viz,

$$\theta_{\text{bb}} = 2.0 \times 10^{11} (\lambda F_{\lambda})_{\text{max}}^{1/2} \times T_{\text{bb}}^{-2},$$

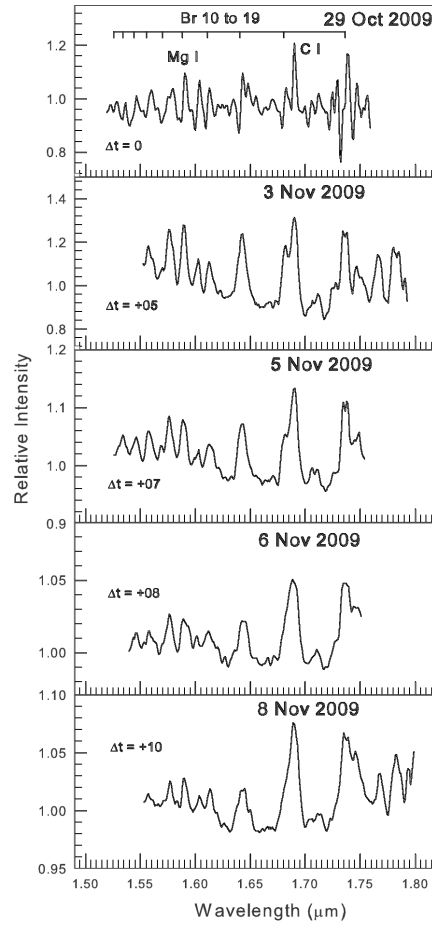
where  $(\lambda F_{\lambda})_{\text{max}} = 6.56 \times 10^{-15} \text{ W cm}^{-2}$  and  $T_{\text{bb}} = 9000$  K. We obtain a value of 0.2 milliarcsec for the angular diameter. This value for the angular diameter can be used to estimate the distance to the nova by assuming a constant expansion rate for the ejecta and the relation given by Gehrz (2008), which follows as

$$d = 1.15 \times 10^{-3} (V_{\text{ej}}) t / \theta_{\text{bb}},$$

where  $d$  is in kpc,  $V_{\text{ej}}$  in  $\text{km s}^{-1}$ ,  $t$  is time after the outburst in days and  $\theta_{\text{bb}}$  in milliarcsec. The estimated value of  $\theta_{\text{bb}}$  will always be a lower limit since it is applicable for a blackbody (Ney & Hatfield 1978; Gehrz et al. 1980). Taking  $\theta_{\text{bb}} = 0.2$  milliarcsec estimated above and a value of  $600 \text{ km s}^{-1}$  observed for the FWHM of the emission line profile of the  $\text{Pa}\beta$  line in the spectrum taken on Nov. 3.59 UT 2009 for  $V_{\text{ej}}$ , we get  $d = 24$  kpc. This value for  $d$  is about a factor of 4 larger than



**Fig. 3** The *J* band spectra of V5584 Sgr are shown at different epochs. The relative intensity is normalized to unity at 1.25  $\mu\text{m}$ . The epoch relative to the optical maximum is given in days for each spectrum.

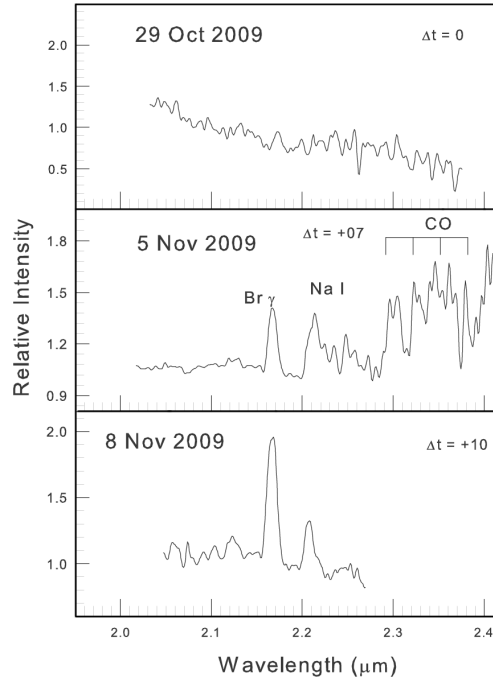


**Fig. 4** The *H* band spectra of V5584 Sgr are shown at different epochs. The relative intensity is normalized to unity at 1.65  $\mu\text{m}$ . The epoch relative to the optical maximum is given in days for each spectrum.

the distance derived earlier in Section 3.1 and indicates that the pseudo-photosphere behaves like a grey body with reduced emissivity (see Das et al. 2008; Raj et al. 2011).

### 3.5 Dust formation and ejecta mass estimate

The detection of the CO first overtone emission in the spectrum taken on Nov. 5.64 UT 2009 is consistent with the detection of the dust in the nova ejecta reported by Russell et al. (2010) on Feb. 10 UT 2010. Although a decline in brightness at optical wavelengths is expected at the time of dust formation, the lack of observations from  $\sim 30$  till  $\sim 110$  d after the discovery due to the solar conjunction is the likely reason for the absence of a sharp fall in the *V* band light



**Fig. 5** The  $K$  band spectra of V5584 Sgr are shown at different epochs. The relative intensity is normalized to unity at 2.2  $\mu\text{m}$ . The epoch relative to the optical maximum is given in days for each spectrum.

curve shown in Figure 1. The dust formation most likely took place during this time period. The thermal emission from the dust contributes to the near-IR bands and one expects a brightening at these wavelengths. Although our NIR photometric observations presented in Figure 2 do not cover the dust formation phase, data are available in the Stony Brook database (SMARTS Spectral Atlas of Southern Novae) which clearly show a brightening in the  $K$  band from Feb. 14 UT 2010 ([www.astro.sunysb.edu/fwalter/SMARTS/NovaAtlas/](http://www.astro.sunysb.edu/fwalter/SMARTS/NovaAtlas/), Walter et al. 2012). From this database, using  $JHK$  magnitudes obtained on Feb. 14 UT 2010 (11.36 mag in  $J$ , 9.05 mag in  $H$  and 6.78 mag in  $K$ ), we estimate a value of  $1100 \pm 200$  K for the dust shell temperature from the SED plot shown in the lower panel of Figure 8. It is possible that the thermal emission from the dust, which is seen to be increasing up to the  $K$  band, peaks at even longer wavelengths.

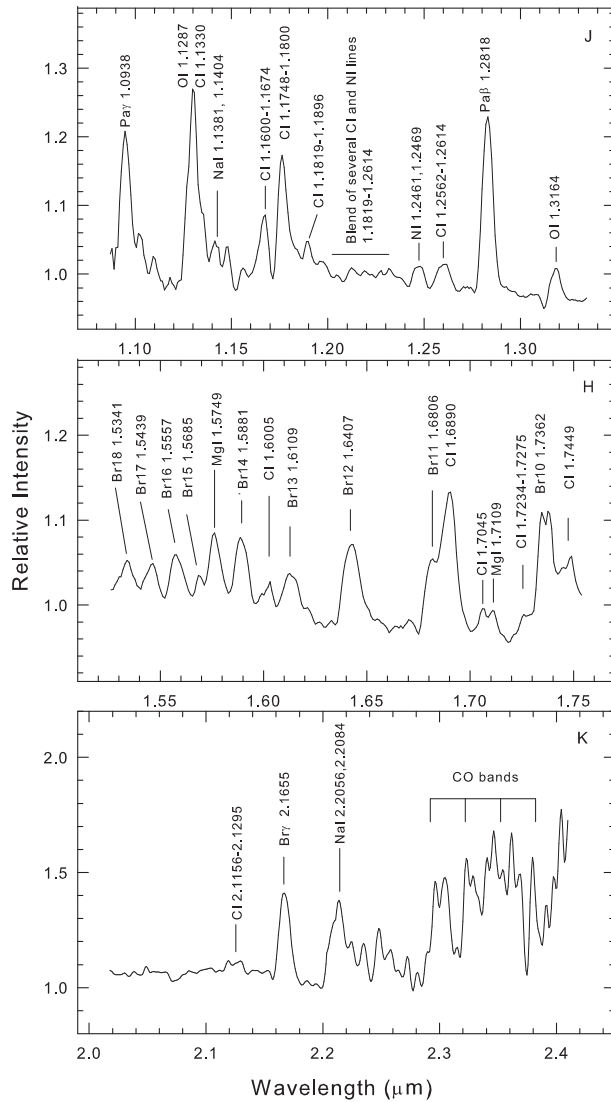
An approximate estimate of the mass of the dust shell can be made from the thermal component of the SED of Feb. 14 UT 2010 shown in Figure 8 (lower panel). Using the Woodward et al. (1993) relation, we have calculated the mass of the dust shell, viz,

$$M_{\text{dust}} = 1.1 \times 10^6 (\lambda F_{\lambda})_{\text{max}} d^2 / T_{\text{dust}}^6.$$

The mass of the dust shell  $M_{\text{dust}}$  is in units of  $M_{\odot}$ ,  $(\lambda F_{\lambda})_{\text{max}}$  is in  $\text{W cm}^{-2}$ , the blackbody temperature of the dust shell  $T_{\text{dust}}$  is in units of  $10^3$  K, and the distance to the nova  $d$  is in kpc in the above relation.

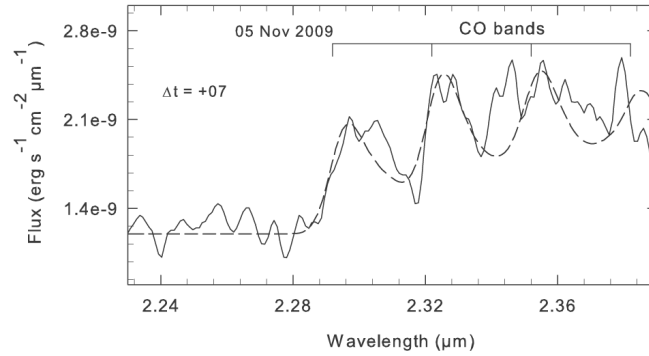
We obtain  $M_{\text{dust}} = 7.35 \times 10^{-9} M_{\odot}$  for Feb. 14 UT 2010 taking the observed parameters of  $(\lambda F_{\lambda})_{\text{max}} = 2.98 \times 10^{-16} \text{ W cm}^{-2}$ ,  $T_{\text{dust}} = 1.1 \times 10^3$  K and  $d = 6.3$  kpc. Taking a canonical value of 200 for the gas-to-dust ratio, we get  $1.5 \times 10^{-7} M_{\odot}$  for the gaseous component of the ejecta. This value is smaller than the typically observed value of  $10^{-6}$  to  $10^{-4} M_{\odot}$ .



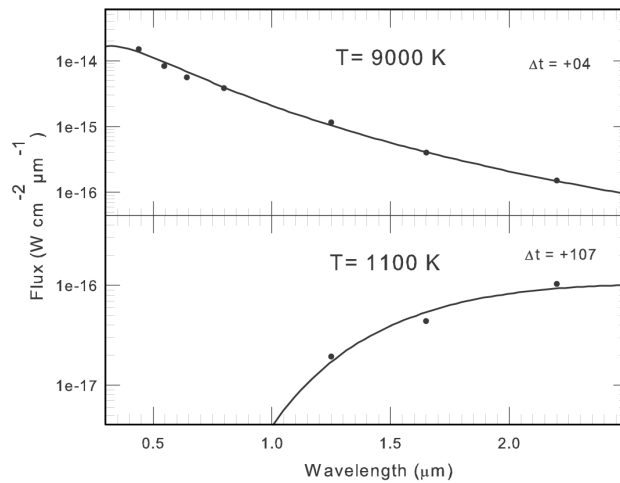


**Fig. 6** The line identification is shown for the spectra of Nov. 5.64 UT 2009 in the *JHK* bands as given in Table 2.

There could be several reasons for the lower mass estimate. It is possible that dust condensation has occurred only in certain regions and not over the entire extent of the ejecta. Further, the blackbody temperatures may not represent the actual dust temperatures in an accurate manner for two reasons. First, the emissivity of the dust grains depends on their composition and size distribution and the frequency dependence of the emissivity can deviate from that of a blackbody (Kruegel 2003). Second, the data used for fitting the SED only cover the region 1 to 2.5  $\mu\text{m}$  resulting in an overestimation of the dust temperature as emission at longer wavelengths is not considered. The dust mass is very sensitive to  $T_{\text{dust}}$  and its correct estimate should result in enhanced dust mass. The lower dust temperature of  $880 \pm 50$  K derived by Russell et al. (2010) from the 3 to 14  $\mu\text{m}$  spectroscopic



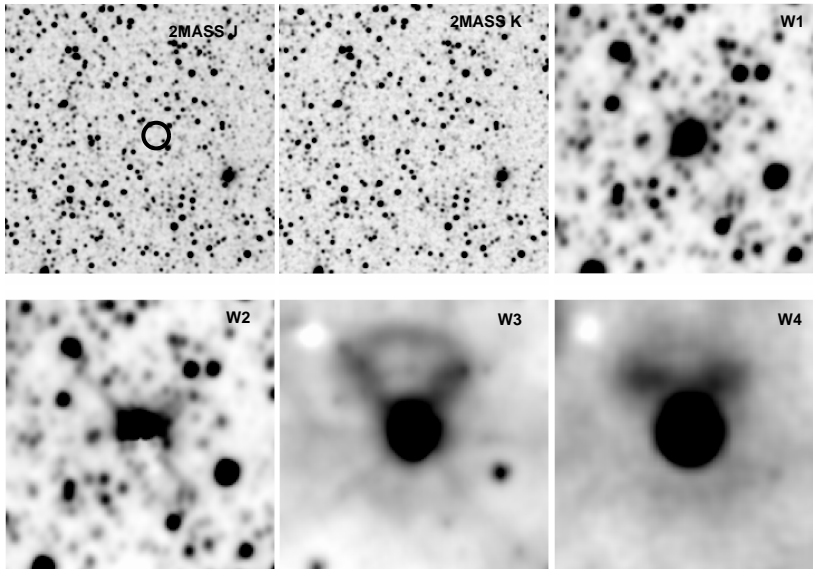
**Fig. 7** The model curve is shown as a dashed line in comparison with the first overtone CO bands observed in V5584 Sgr. The fit is made for a constant CO mass of  $3 \times 10^{-8} M_{\odot}$  and the temperature of the gas  $T_{\text{CO}}$  is 3500 K. The epoch relative to the optical maximum is given in days for each spectrum.



**Fig. 8** The top panel shows the SED for the fireball phase data of Nov. 2 UT 2009 with a blackbody temperature fit of 9000 K. The bottom panel shows a blackbody fit to the data taken on Feb. 14 UT 2010, with a temperature of about 1100 K.

observations indicates that there is significant contribution at longer wavelengths. The observations from the Wide field Infrared Survey Explorer (WISE) also support emission from the dust at longer wavelengths. WISE detects the source in all its bands, including 3.4 (W1), 4.6 (W2), 12 (W3) and 22  $\mu\text{m}$  (W4); the emission at the longer W3 and W4 bands is very pronounced.

A few notes on the WISE images in Figure 9 are necessary. The W1 and W2 images were taken at two epochs separated by nearly six months, namely on Mar. 27 and Sep. 28 UT 2010. These double-epoch images appear to have been combined for the resultant W1 and W2 images available at the WISE portal and which are presented here in the figure. For reasons that are not clear, in the process of combining the images certain artifacts have been created in the W2 image and the image of V5584 Sgr was smeared out and also partially obliterated. This is the likely reason why none of the W1, W2, W3 or W4 magnitudes are reported for the source. On the other hand the W3 and W4



**Fig. 9** A mosaic of the same  $4 \times 4$  arcminute square field around V5584 Sgr. Shown are the pre-outburst 2MASS *J* and *K* band images with the nova progenitor barely visible; its position is circled in the *J* band image. The WISE images detect the source in all the 3.4 (W1), 4.6 (W2), 12 (W3) and 22  $\mu\text{m}$  (W4) bands; the emission at the longer W3 and W4 bands is very pronounced. The WISE images were taken between March–April 2010 (more details in Section 3.5), nearly five months since its discovery on Oct. 26.439 UT 2009. Although the nova had faded below magnitude 15 in the *V* band by this time (see Fig. 1), it remained strikingly bright in the near and mid IR due to emission from newly formed dust in the ejecta.

images were taken on two very nearby epochs, namely on Mar. 27 and Apr. 06 UT 2010 which give a good qualitative idea that pronounced dust emission is present in these wavebands.

#### 4 SUMMARY

We have presented near-infrared spectroscopy and photometry of nova V5584 Sgr which erupted on Oct. 26.439 UT 2009. From the optical light curve, V5584 Sgr is seen to be a moderately fast nova with  $t_2 = 25$  d and a light curve classification of D(46) following the classification scheme of Strobe et al. (2010). The distance to the nova and its height below the Galactic plane are estimated to be  $6.3 \pm 0.5$  kpc and  $341 \pm 30$  pc, respectively. The outburst bolometric luminosity of V5584 Sgr as derived from its estimated  $M_V$  is  $L_O \sim 1.1 \times 10^5 L_\odot$ . The infrared spectra indicate that the nova is of the Fe II type. The first overtone CO emission is a notable feature of the near-infrared spectrum in the early decline phase. The CO emission is modeled to make estimates of the CO mass and temperature. We discuss dust formation in the nova and make estimates of the mass of the dust and gas in the ejecta.

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