Nova KT Eri 2009: infrared studies of a very fast and small amplitude He/N nova

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ABSTRACT

We present near-infrared spectroscopic and photometric observations of the nova KT Eridani taken during the first 100 d following its discovery in 2009 November. The $JHK$ spectra of the object have been taken from the Mount Abu Infrared Observatory using the Near-Infrared Imager/Spectrometer. The spectra, typical of the He/N class novae, show strong He I emission lines together with H I and OI emission features. The H I, Pa β and Br γ spectral lines and the He I line at 2.0581 μm show broad wings with a relatively narrow central component. The broad wings extend to $\sim$1900 km s$^{-1}$ while the central component has full width at half-maximum (FWHM) of $\sim$2100 km s$^{-1}$. The $V$ and near-infrared $JHK$ light curves show an additional small amplitude outburst near 40 days after optical maximum. The distance to the nova $d = 6.3 \pm 0.1$ kpc is derived using the MMRD relation and the estimated value of $t_2 = 5.7 \pm 0.3$ d. The small value of $t_2$ places KT Eri in the class of very fast novae. Using the value of the distance to the nova $d$, we estimate the height of the nova to be $z = 3.3 \pm 0.1$ kpc below the Galactic plane. We have also calculated the upper limit for the ejecta mass for KT Eri to be in the range 2.4–7.4 $\times 10^{-5}$ M$_\odot$. Kinematic evidence is presented from the shape of the line profiles for a possible bipolar flow. We analyse the temporal evolution of the continuum and also discuss the possibility of KT Eri being a recurrent nova.

Key words: line: identification – techniques: spectroscopic – stars: individual: KT Eri – novae, cataclysmic variables.

1 INTRODUCTION

Nova KT Eridani has an interesting history pre-dating its optical discovery. Its discovery was reported several days after its actual outburst had commenced but in spite of this delay, recourse to archival material not only helped in pinpointing its exact date of eruption but also tracked its immediate post-outburst evolution as graphically as real-time nova observations usually do. The nova was discovered on 2009 November 25.536 UT by K. Itagaki at $V = 8.1$ (Yamaoka & Itagaki 2009) with a 0.21-m telescope patrol system. Itagaki also noted the presence of a faint object near the position of KT Eri in his archival patrol images. Yamaoka pointed out that the All Sky Automated Survey (ASAS-3) system (Pojmanski 1997) had detected KT Eri on three occasions prior to the discovery announcement of Yamaoka. These pre-discovery magnitudes along with additional detections are listed in Table 1. In addition Yamaoka suggested that the discovery of KT Eri might be the result of brightening of a 15th magnitude blue star, listed in many catalogues, with one of the identifications being USNO-B1.0 0798−0048707. Guido et al. (2009) confirmed the discovery of KT Eri using their CCD observations using a 0.25-m reflector and pointed out the presence of a star of $\sim$15 mag close to the position of KT Eri on the DSS red plate of 1990 November 23 UT. The nature of KT Eri as a nova was confirmed by several low-resolution optical spectra obtained during 2009 November 26.5–26.6 UT by Fujii, Arai & Isogai and Imamura (Maehara, Arai & Isogai 2009). These spectra showed broad Balmer emission (FWHM of Hα 3200–3400 km s$^{-1}$) together with prominent emission features of He I, N I, N II, Na D, O I and Mg II leading Maehara to suggest that KT Eri is a nova of the He/N class. Rudy et al. (2009) also suggested KT Eri to be a nova of He/N class on the basis of their near-infrared spectra obtained on 2009 November 26.4 UT spanning the spectral range of 0.9 to 2.5 μm. The He I line at 1.083 μm was already the strongest line in the spectrum with a P Cygni absorption extending to 3600 km s$^{-1}$. The emission lines of H I, N I and O I were very strong and broad with FWHM $\sim 4000$ km s$^{-1}$. The reports of clear detection of KT Eri prior to its discovery has resulted in additional studies by different groups to obtain its pre-discovery light curves. Drake et al. (2009) carried out a search of the Catalina Sky Survey data covering the location of KT Eri during period 2005 January 17 to 2009 November 18. KT Eri was clearly seen in outburst in the images taken on 2009 November 18 and they pointed out that the outburst occurred after 2009 November 10.41 UT. The study of pre-discovery light curve has
shown clear variations of approximately 1.8 mag. The association of an unresolved fainter companion to the 15th magnitude star to be the progenitor of KT Eri would mean a very high level of variability. As this possibility is unlikely Drake et al. (2009) conclude that the 15th magnitude star is most likely associated with KT Eri.

Ragan et al. (2009) derived a distance of ~6.5 kpc to KT Eri and pointed out that the 15th magnitude star located close to the KT Eri position in pre-discovery images is too bright to be its progenitor. McQuillen et al. (2012) and Hounsell et al. (2010) have obtained an impressive high cadence optical light curve of KT Eri before, during and after the outburst using data from SuperWASP (Pollacco et al. 2006) and the USAF/NASA Solar Mass Ejection Imager (SMEI) (Jackson et al. 2004) on board the Coriolis Satellite (Eyles et al. 2003), respectively. The SMEI observations are spread over the period 2009 November 1.3 to 30.62 UT. The light curve, obtained by SMEI, indicates that the initial rise of the nova is steep (rising 4.1 mag over 2.7 d) with evidence of a pre-maximum halt occurring on 2009 November 13.90 ± 0.04 UT at m_{SMEI} ~ 6. The duration of this halt would seem to be only a few hours, which is appropriate for the speed of the nova (e.g. Payne-Gaposchkin 1964). The nova reached maximum light on 2009 November 14.67 ± 0.04 UT with an unfiltered SMEI apparent magnitude of m_{SMEI} ~ 5.42 ± 0.02. It subsequently declined rapidly with a t_{1/2} value of 6.6 d confirming KT Eri as a very fast nova. The SMEI observations are consistent with the observed high expansion velocities (FWHM ~ 3400 km s^{-1}) and assignment of He/N spectral class to KT Eri described earlier.

Nesci, Mickaelian & Rossi (2009) have used the pre-outburst spectrum of the suspected 15th magnitude progenitor available in the Digitized First Byurakan Survey of the field containing KT Eri to study its nature. The spectra taken on 1971 January 25 show a strong UV continuum with several emission lines that include [Ne v] 3426, [Ne iii] 3868 and a large blend around Hγ. As these features are typical of cataclysmic variables, Nesci et al. (2009) favour the identification of the 15th magnitude star with the actual progenitor of KT Eri and point out that the forbidden lines of [Ne iii] & [Ne v] were also seen in the transient source CSS 081007: 030559+54715 (HV Cet) suggested to be a possible He/N nova located at high Galactic latitude ~43:7 (Pejcha, Prieto & Denney 2008; Prieto et al. 2008). A search for previous outbursts of KT Eri was done by Jurdana-Sepic et al. (2012) using the Harvard College Observatory archive plates spanning the period 1888 to 1962. As no earlier outbursts were found, they have suggested that if KT Eri is a recurrent nova, the recurrence time is likely to be on a time-scale of centuries. Jurdana-Sepic et al. (2012) find a periodicity at quiescence of 737 d for the 15th magnitude progenitor that may arise from reflection effects and/or eclipses in the underlying binary system in KT Eri. KT Eri was detected later as a luminous soft X-ray source (Beardmore et al. 2010; Bode et al. 2010; Ness et al. 2010) and also detected at radio wavelengths (O’Brien et al. 2010).

2 OBSERVATIONS

Near-IR observations were obtained using the 1.2-m telescope of Mt. Abu Infrared Observatory from 2009 November 28 to 2010 March 3. The log of the spectroscopic and photometric observations is given in Table 2. The spectra were obtained at a resolution of ~1000 using a Near-Infrared Imager/Spectrometer with a 256 × 256 HgCdTe NICMOS3 array. In each of the JHK bands a set of spectra was taken with the nova off-set to two different positions along the slit which were subtracted from each other to remove sky and detector dark current contributions. Spectral calibration was done using the OH sky lines that register with the stellar spectra. The spectra of the comparison star SAO 131794 (spectral type A3 III; effective temperature 8600 K) were taken at similar airmass as that of KT Eri to ensure that the ratioing process (nova spectrum divided by the standard star spectrum) removes the telluric features reliably. To avoid artificially generated emission lines in the ratioed spectrum, the H absorption lines in the spectra of standard star were removed before ratioing. The ratioed spectra were then multiplied by a blackbody curve corresponding to the standard star’s effective temperature to yield the final spectra.

Photometry in the JHK bands was done in clear sky conditions using the NICMOS3 array in the imaging mode. Several frames, in four dithered positions, offset by ~30 arcsec were obtained in all the bands. The sky frames, which are subtracted from the nova frames, were generated by median combining the dithered frames. The star SAO 131500 (spectral type A0, effective temperature 9800K), located close to the nova and having 2MASS JHK magnitudes 7.35, 7.41 and 7.40, respectively, was used for photometric calibration. Further details of the data reduction are described in Banerjee & Ashok (2002). The data were reduced and analysed using IRAF.

3 RESULTS

Before presenting the results proper, we estimate some of the useful parameters of KT Eri like its reddening, distance and height relative to the Galactic plane from an analysis of its light curve.

3.1 General characteristics of V and JHK light curves

The light curves based on the V-band data from Table 1 and American Association of Variable Star Observers (AAVSO) and the JHK magnitudes from Mt. Abu are presented in Fig. 1. The AAVSO data span the period 2009 November 27 to 2010 March 20. The pre-discovery observations presented in Table 1 from Yamamoto et al. (2009) are also used for the optical light curve. The epoch of optical maximum for KT Eri is taken as 2009 November 14.67 UT when it reached a value of V_{max} = 5.4. This corresponds to the value of 2009 November 14.67 ± 0.04 UT obtained by Hounsell et al. (2010) using the SMEI data.

From a least-squares regression fit to the post maximum light curve we estimate t_{1/2} and t_{2} to be 5.7 ± 0.3 d and 9 ± 0.3, respectively, making KT Eri one of the fast He/N class of novae in recent years. Using the maximum magnitude versus rate of decline (MMRD) relation of della Valle & Livio (1995), we determine the absolute magnitude of the nova to be M_V = −8.9 ± 0.1. The reddening

| Date in UT | Magnitude | Observers |
|------------|-----------|-----------|
| 2009 November 10.236 | <14.0 | ASAS |
| 14.572 | 5.7 | Ootsuki |
| 14.652 | 5.4 | Watanabe & Miyasaita |
| 14.813 | 5.6 | Ootsuki & Ohshima |
| 17.226 | 6.9 | Hankey |
| 17.758 | 6.7 | Tanaka |
| 17.807 | 6.6 | Kawamura |
| 18.760 | 7.0 | Yamamoto |
| 18.809 | 7.0 | Yamamoto |
| 19.241 | 7.34 | ASAS |
| 22.179 | 7.98 | ASAS |
| 24.269 | 8.12 | ASAS |
Log of the Mt. Abu near-infrared observations of KT Eri. The date of optical maximum is taken as 2009 November 14.67 ± 0.03.

Spectroscopic observations are presented in Figs 2 to 4, respectively; line identification is given in Table 3. The infrared observations presented here cover the phase after optical maximum with the first infrared spectra taken on 2009 November 28. In case of He/N class of novae a smaller number of spectral lines in the near-IR are normally seen.

### Table 2. Log of the Mt. Abu near-infrared observations of KT Eri. The date of optical maximum is taken as 2009 November 14.67 UT (Hounsell et al. 2010).

| Date of observation (UT) | Days since optical maximum | Integration time (s) | Nova Magnitude |
|--------------------------|---------------------------|---------------------|----------------|
|                          |                           | J band  | H band  | K band  | J band  | H band  | K band  |
| 2009 Nov. 28.854         | 14.18                     | 90      | 90      | 90      | 25      | 55      | 105     | 7.39 ± 0.03 | 7.45 ± 0.03 | 7.04 ± 0.04 |
| 2009 Dec. 01.813         | 17.14                     | 120     | 90      | 120     | 25      | 55      | 105     | 7.89 ± 0.03 | 7.91 ± 0.04 | 7.37 ± 0.06 |
| 2009 Dec. 03.844         | 19.17                     | –       | –       | –       | 75      | 165     | 105     | 7.88 ± 0.06 | 7.79 ± 0.04 | 7.35 ± 0.04 |
| 2009 Dec. 04.834         | 20.16                     | 120     | 120     | 120     | –       | –       | –       | –           | –           | –           |
| 2009 Dec. 05.844         | 21.17                     | 90      | 90      | 120     | 75      | 110     | 105     | 8.21 ± 0.08 | 8.08 ± 0.04 | 7.69 ± 0.05 |
| 2009 Dec. 06.813         | 22.14                     | 90      | 90      | 120     | –       | –       | –       | –           | –           | –           |
| 2009 Dec. 07.865         | 23.19                     | 90      | 90      | 120     | 75      | 110     | 105     | 8.36 ± 0.01 | 8.39 ± 0.02 | 7.95 ± 0.06 |
| 2009 Dec. 08.834         | 24.16                     | 120     | 90      | 120     | –       | –       | –       | –           | –           | –           |
| 2009 Dec. 09.823         | 25.15                     | 120     | 90      | 120     | 75      | 110     | 105     | 8.39 ± 0.05 | 8.42 ± 0.07 | 8.02 ± 0.06 |
| 2009 Dec. 15.776         | 31.10                     | 120     | 90      | 120     | 75      | 110     | 105     | 8.80 ± 0.03 | 8.82 ± 0.10 | 8.35 ± 0.02 |
| 2009 Dec. 16.782         | 32.11                     | 120     | 90      | 120     | –       | –       | –       | –           | –           | –           |
| 2009 Dec. 17.786         | 33.11                     | –       | –       | –       | 100     | 110     | 105     | 9.06 ± 0.06 | 8.94 ± 0.04 | 8.55 ± 0.07 |
| 2009 Dec. 27.779         | 43.10                     | –       | –       | –       | 100     | 220     | 105     | 9.44 ± 0.05 | 9.34 ± 0.05 | 9.02 ± 0.13 |
| 2009 Dec. 29.767         | 45.09                     | –       | –       | –       | 125     | 220     | 105     | 9.53 ± 0.14 | 9.36 ± 0.03 | 8.93 ± 0.12 |
| 2009 Dec. 31.757         | 47.08                     | –       | –       | –       | 100     | 165     | 105     | 9.30 ± 0.06 | 9.19 ± 0.04 | 8.85 ± 0.09 |
| 2010 Jan. 03.750         | 50.08                     | –       | –       | –       | 250     | 550     | 105     | 9.30 ± 0.05 | 9.91 ± 0.04 | 8.67 ± 0.07 |
| 2010 Jan. 25.755         | 72.85                     | –       | –       | –       | 500     | 825     | 105     | 10.58 ± 0.06 | 10.41 ± 0.05 | 9.50 ± 0.04 |
| 2010 Jan. 27.744         | 74.07                     | –       | –       | –       | 750     | 1100    | 105     | 10.65 ± 0.02 | 10.51 ± 0.03 | 9.51 ± 0.10 |
| 2010 Feb. 28.735         | 106.065                   | –       | –       | –       | 600     | 660     | 63      | 11.23 ± 0.08 | 11.01 ± 0.08 | 9.99 ± 0.10 |
| 2010 Mar. 01.725         | 106.790                   | –       | –       | –       | 600     | 660     | 63      | 11.26 ± 0.04 | 11.05 ± 0.10 | 9.89 ± 0.10 |
| 2010 Mar. 03.734         | 108.799                   | –       | –       | –       | 825     | 63      | –       | 11.05 ± 0.10 | 9.89 ± 0.10 | –           |

Figure 1. The V and JHK band light curves of KT Eri are presented. The V-band data are taken from Table 1 and AAVSO and JHK band data are taken from Mt. Abu observations.

$E(B - V) = 0.09$ is derived from Schlegel, Finkbeiner & Davis (1998) towards the nova’s direction for which $A_V = 0.29$ for $R = 3.1$. Based on the above we obtain a value of the distance $d = 6.3 \pm 0.1$ kpc to the nova. Using the value of $d$ we estimated the height $z = 3.3 \pm 0.1$ kpc below the Galactic plane. The high Galactic latitude is consistent with the low reddening towards the nova. Taking a bolometric correction of $-0.1$ appropriate for the SED of novae which resemble A- to F-type supergiants near maximum light and the absolute magnitude $M_V = -8.9$ determined above gives the bolometric outburst luminosity of KT Eri to be $L_O \sim 3.2 \times 10^5$ $L_\odot$.

The optical and JHK light curves show an additional small amplitude outburst near day 40 from the optical maximum. A plateau was also seen in the V-band light curve after 80 d from optical maximum. The duration of the plateau could be tracked for 60 d but its entire duration is difficult to assess as the nova went into conjunction with the Sun afterwards. The shape of the optical light curve of KT Eri presented in Fig. 1 has all the characteristics of a P class of nova as per the classification system presented by Strope, Schaefer & Henden (2010).

The observed value of the outburst amplitude of $\Delta V = 9.6$ and $t_2 = 5.7$ d for KT Eri is well below the lower limit in the amplitude versus decline rate plot for classical novae presented by Warner (2008) which shows an expected value of $\Delta V = 12$ to 15 for $t_2 = 5.7$ d. It is also interesting to note that the estimated values of $t_2$, $t_1$ and $\Delta V$ are very much similar to those of the recurrent nova V745 Sco which had corresponding values of 6.2, 9.0 and 9.2, respectively (see table 17, Schaefer 2010). So, if KT Eri is indeed a recurrent nova, then the system may be similar to V745 Sco and a possibility exists that the recurrence time for KT Eri may be expected to be around 50 years similar to the 52 yr recurrence time for V745 Sco which had recorded outbursts in 1937 and 1989 (Schaefer 2010).

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

The JHK spectra are presented in Figs 2 to 4, respectively; line identification is given in Table 3. The infrared observations presented here cover the phase after optical maximum with the first infrared spectra taken on 2009 November 28.
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Figure 2. The J-band spectra of KT Eri are shown at different epochs. The relative intensity is normalized to unity at 1.25 µm. The time ∆t from optical maximum is given for each spectrum. The continuum flux level (W cm⁻² µm⁻¹) can be calculated for those spectra that have broad-band JHK magnitudes for flux calibration. For such days, the continuum levels in the plot may be obtained by multiplying with 3.8e-16, 2.4e-16, 1.8e-16, 1.5e-16, 1.4e-16 and 1.0e-16 for the data of 2009 November 28 and 2009 December 1, 5, 7, 9, 15, respectively.

as compared to the Fe II type of novae (Banerjee & Ashok 2012). Apart from this intrinsic difference between the two nova classes, the possibility exists of relatively weaker individual lines in He/N novae blending with each other due to large expansion velocities and becoming indistinguishable against the underlying continuum. The prominent lines seen in case of KT Eri are those due to H₁, O₁ and He₁. The typical FWHM of the H₁ lines ranges from 1900 to 2300 km s⁻¹ with full width at zero intensity (FWZI) reaching a value of ∼4000 km s⁻¹. A noticeable feature of these early spectra is the strong presence of lines due to He₁. In the spectra taken on 2009 November 28 the He₁ lines at 1.0830 µm, 1.7002 µm, 2.0581 µm, 2.1120 µm and 2.1132 µm are clearly seen. Although it is blended with Pa γ at 1.093 µm, He₁ 1.0830 µm is strikingly strong in the spectra. These He₁ lines are seen to strengthen and become even stronger as the nova evolves.

No coronal lines are seen during the course of our observations. An upper limit can be set for the line flux, for e.g. the [S ix] 1.2520 µm line, of 4.6 × 10⁻¹⁹ W cm⁻² assuming that a detection could be claimed if the line was present at 5σ of the observed continuum noise level (measured to have a standard deviation of 1σ) around the expected position of the line. This is based on the later spectra obtained in 2009 December. It is, however, difficult to set meaningful upper limits for other coronal lines generally seen in novae spectra because these either are not covered by us (e.g. lines from [Si vi] 1.964 µm, [Si vii] 2.481 µm and [Ca viii] 2.322 µm in the K band) or could be severely blended, if present, with other lines in the region (e.g. [Al ix] 2.040 µm would be blended with the blue wing of the He₁ 2.0581 µm; Br 10 line at 1.7362 µm would blend with [P viii] at the same position, etc.). Even the upper limit derived above for [S ix] 1.2520 µm assumes no contribution from He₁ 1.2534 µm which occurs at almost the same wavelength.

There is also no indication of dust formation in the nova which is consistent with the absence of emission lines from low ionization
species like Na and Mg which are potential harbingers of dust formation (Das et al. 2008; Banerjee & Ashok 2012).

3.3 Recombination analysis of the H\(_1\) lines and estimate of the ejecta mass

Recombination case B analysis for the H\(_1\) lines was done for the observed spectra of all days. Representative results for four days (see Fig. 5) show the observed strength of the Brackett lines with respect to Br12 which is normalized to unity. Also shown are the predicted Case B values from Storey & Hummer (1995) if the lines are optically thin. The Case B values are for \(T = 10^4\) K and for a few representative electron densities of \(n_e = 10^8\), \(10^9\) and \(10^{11}\) cm\(^{-3}\). High electron densities are also considered because the ejecta material may be expected to be dense in the early stages after the outburst. Fig. 5 shows that the observed line intensities clearly deviate from case B values during the initial observations. Specifically, Br\(_\gamma\), which is expected to be relatively stronger, for any combination of electron density and temperature in the Case B scenario, than the other Br lines considered here, is observed to be considerably weaker in the early observations. This is certainly due to large optical depths in the Br gamma line and possibly also in the other Brackett lines (e.g. Lynch et al. 2000). Such deviations from case B strengths, early after outburst, can be expected and have been observed in other novae too like V2491 Cyg and V597 Pup (Naik, Banerjee & Ashok 2009). However, 25 d after maximum on 2009 December 9 (fourth panel of Fig. 5) there is a clear-cut indication that case B conditions have begun to prevail implying the lines have become optically thin. For 2009 December 9, it is found that the observed data match well with the predicted values for the recombination case B values of \(T = 10^4\) K and an electron density \(n_e = 10^9\) cm\(^{-3}\). We use additional arguments to constrain the electron density and thereby estimate the mass.

It is known from Hummer & Storey (1987) and Storey & Hummer (1995) that line centre optical depth values can be significant when the electron densities become large. The value of the opacity factor...
Figure 4. The K band spectra of KT Eri are shown at different epochs. The relative intensity is normalized to unity at 2.2 \( \mu \)m. The time \( \Delta t \) from optical maximum is given for each spectrum. The continuum flux level (W cm\(^{-2} \) \( \mu \)m\(^{-1} \)) can be calculated for those spectra that have broad-band JHK magnitudes for flux calibration. For such days, the continuum levels in the plot may be obtained by multiplying with 6.2e-17, 4.6e-17, 3.4e-17, 2.7e-17, 2.5e-17 and 1.9e-17 for the data of 2009 November 28 and 2009 December 1, 5, 7, 9, 15, respectively.

\( \Omega_{n,n'} \) for different H\( I \) lines for transitions between levels \((n, n')\) at different temperatures and densities [equation 29 of Hummer & Storey (1987)] is tabulated in these studies. From the value of \( \Omega_{n,n'} \), the optical depth at line-centre \( \tau_{n,n'} \) is given by \( \tau = n_e n'_e \Omega L \), where \( L \) is the path length in cm. In our case, for the data of 2009 December 9, we take \( L = 4.84 - 7.26 \times 10^{14} \) cm corresponding to the kinematic extent of the ejecta using an expansion velocity between 2000 and 3000 km s\(^{-1} \) (Ribeiro 2011; this work) and a time of 28 d since start of outburst. Slight variations in these numbers do not affect our analysis. Since the lines are optically thin on 2009 December 9, this means that \( \tau \) must be less than 1. For \( T_e = 10^4 \) K and \( n_e = 10^9 \) cm\(^{-3} \), the corresponding value of the optical depth \( \tau \) from Storey & Hummer (1995) is then found to be 0.016 for Br\( \gamma \) and this then decreases monotonically down the series to a value of \( \tau = 0.003 \) for Br 19. At a higher density of \( n_e = 10^{10} \) cm\(^{-3} \), the \( \tau \) values increase sharply by approximately a factor of a few hundreds (since \( \tau \propto n_e n'_e \)) to \( \tau \approx 8 \) for Br\( \gamma \) and 0.31 for Br19. Hence, it is seen that the Br\( \gamma \) line (as also the other Br lines) is/are optically thin at a density of \( 10^9 \) cm\(^{-3} \) but becomes thick at \( 10^{10} \) cm\(^{-3} \). We therefore adopt \( n_e = 10^9 \) cm\(^{-3} \) in our calculations. In applying the relation \( \tau = n_e n'_e \Omega L \) given by Hummer & Storey (1987), it is assumed that the volume filling factor is unity. This assumption is also carried into the analysis below which only aims at setting an upper limit for the ejecta mass.

Following Banerjee et al. (2010), a constraint on the mass of the emitting gas can be obtained from:

\[
M = \left[ \frac{4 \pi d^2 (m_H)^2 (f V/\epsilon)}{3} \right]^{0.5},
\]

where \( d \) is the distance, \( m_H \) the proton mass, \( f \) the observed flux in a particular line, \( \epsilon \) the corresponding case B emissivity; \( V \) is the volume of the emitting gas, which is \([4/3 \pi (vt)^3 \phi] \), where \( \phi, v \) and \( t \) are the filling factor, velocity and time after outburst, respectively.
Table 3. A list of the lines identified from the $JHK$ spectra.

| Wavelength ($\mu$m) | Species |
|---------------------|---------|
| 1.0830              | He I    |
| 1.0938              | Pa $\gamma$ |
| 1.1287              | O I    |
| 1.2818              | Pa $\beta$ |
| 1.5256              | Br 19  |
| 1.5341              | Br 18  |
| 1.5439              | Br 17  |
| 1.5557              | Br 16  |
| 1.5701              | Br 15  |
| 1.5881              | Br 14  |
| 1.6109              | Br 13  |
| 1.6407              | Br 12  |
| 1.6806              | Br 11  |
| 1.7002              | He I    |
| 1.7362              | Br 10  |
| 1.9451              | Br 8   |
| 2.0581              | He I    |
| 2.1120, 2.1132      | He I    |
| 2.1656              | Br $\gamma$ |

Using the value of temperature and electron density we calculated the mass of the gas in the ejecta in the range $2.4-7.4 \times 10^{-5} M_\odot$. As the filling factor $\phi < 1$, this range is an upper limit for the mass of the ejecta.

3.4 Evidence for a bipolar flow

A significant finding that has emerged from the analysis of line-profile studies of KT Eri is the likely presence of a bipolar flow in the ejected material (Ribeiro 2011). Bipolar morphologies are commonly encountered in planetary nebulae and explained on the basis of the fast-winds from the hot PN nuclei interacting with a non-uniform circumstellar environment. In this anisotropic scenario, the pre-existing circumstellar material has a density enhancement in the equatorial plane which impedes the outflowing ejecta from expanding in the equatorial region while expanding relatively more freely in the polar direction. This leads to a constriction of the nebula with an hourglass shape. Kinematically, this would imply that the matter in the poles would flow out with a high velocity relative to the matter in the waist of the hourglass. It is possible that the secondary, which has colours suggestive of a cool giant (Jurdana-Sepic et al. 2012), has either through mass loss or a common envelope phase provided the necessary equatorial density contrast needed to create the bipolar morphology (Bond & Livio 1990). It is also becoming increasingly apparent with the aid of high-spatial resolution imaging that hourglass or bipolar morphologies could be commonplace in novae shells (Chesneau & Banerjee 2012). Striking examples of these are seen in the novae V1280 Sco (Chesneau et al. 2012), V445 Pup (Woudt & Steeghs 2005) and RS Oph (Bode et al. 2007; Harman et al. 2008).

The kinematic evidence for a bipolar flow in KT Eri is also seen from our near-IR data. To illustrate this, we present in Fig. 6,
representative profiles of the Paβ and Brγ lines on 2009 December 7.865 UT (similar analysis was also done for the data of 2009 December 6.813 and 8.834 UT). As can be seen, the profiles have a strong central component flanked by two weaker components. In both panels of Fig. 6, we have fitted the profile with three Gaussians viz. a central Gaussian for the core emission component and two Gaussians for the satellite components in the wings.

It is seen that a three-component Gaussian fits the data reasonably well. The fits for 2009 December 6, 7 and 8 indicate the presence of two high-velocity components at mean radial velocities (averaged over the three days) of $-1790 \pm 75$ and $2080 \pm 60 \text{ km s}^{-1}$ for Paβ and at $-1800 \pm 115$ and $2040 \pm 150 \text{ km s}^{-1}$ for the Brγ lines, respectively [these high-velocity components appear to be associated with the faster structure reported by Bode et al. (2010)]. The central components have full width at half-maximum (FWHM) of $2340 \pm 125$ and $1930 \pm 85 \text{ km s}^{-1}$ for the Paβ and Brγ lines, respectively. We can interpret the results of Fig. 6 as follows viz. the core emission can be associated with the slower expanding material from the waist of the bipolar ejecta while the higher velocity satellite components are associated with the flow from the polar regions. A similar high-velocity bipolar flow in the case of the 2006 outburst of the recurrent nova RS Oph was also deduced by Banerjee, Das & Ashok (2009) on the basis of broad observed wings in Paβ and Brγ line profiles.

### 3.5 Evolution of the continuum

We analyse and discuss the evolution of the spectral continuum of KT Eri. 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 KT Eri 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 2.

At the epoch of optical maximum, a blackbody fit which will have an index of $\alpha = 4.0$ at longer wavelengths is expected to fit the continuum flux distribution. As our observations begin from day 14 after optical maximum, we have done power-law fits, $F_\lambda \propto \lambda^{-\alpha}$, to see the evolution of continuum spectra shown in Fig. 7. In the beginning of our observations i.e. on 2009 November 28 (14 d after optical maximum) and 2009 December 9, the continuum spectrum is well matched with fits having spectral indices of $\alpha = 3.34 \pm 0.10$ and $\alpha = 3.25 \pm 0.13$, respectively. The subsequent spectra taken on 2009 December 15 have become slightly flatter with the slope of $\alpha = 3.08 \pm 0.07$. As a comparison, we also show a plot (with dotted line in Fig. 7) of the expected slope for a case of pure free–free emission evaluated at a representative temperature of $T = 10000 \text{ K}$.

Proceeding further, we have also specifically tried to fit the SED for 2010 February 22 to 28, shown in Fig. 8, because of the availability of contemporaneous data at that time including WISE (Wide Field Infrared Survey Explorer) observations (Wright et al. 2010). Such data allow the SED to be fit over a much larger range in wavelength. In Fig. 8 we have used the UBVRI data from AAVSO, JHK data from Mt. Abu and WISE data in the W1, W2, W3 and W4 wavebands which are centred at 3.4, 4.6, 12 and 22 μm, respectively. The corrected flux values corresponding to all these various magnitudes are given in Table 4. What we find in Fig. 8 is that the continuum is remarkably well fitted by a power law, with the spectral index $\alpha$ further reduced to 2.67. The slow change in the slope of the continuum spectrum index with time is also evident in the case of other novae, for example, V4643 Sagittarii where it changed from a slope of about 3 to 2 within about three months (Ashok et al. 2006). However, in the case of another nova viz. V4633 Sagittarii (Lynch,
Russel & Sitko (2001) the change in the slope of the continuum was found to be in the opposite direction, i.e. the slope changed from 2 to 2.7 in observations taken 525 and 850 days after outburst. Therefore, the evolution of the continuum in a nova’s development can be fairly complex as also remarked by Lynch et al. (2001).

It is also worth noting that the SED fit in Fig. 8 represents the behaviour of the nova in the plateau phase. The optical mid-plateau phase has been clearly seen earlier in a limited number of novae, notably in the recurrent nova RS Oph, U Sco and CI Aql (Hachisu, Kato & Luna 2007, and references therein). It is usually associated with a super-soft X-ray phase (e.g. in RS Oph as described in Osborne et al. 2011) and is interpreted as being caused by the accretion disc being irradiated by the central hot white dwarf (Hachisu et al. 2007). The disc is bright as long as the white dwarf, which is rapidly shrinking and becoming hotter at this stage, is luminous because of a thin hydrogen shell still burning on its surface and it becomes dark when the shell-burning ends. The mid-plateau phase is poorly studied and a SED covering such a large extent in wavelength, possibly not available for any other nova, should be useful in interpreting this stage in a nova’s development. In the case of a steady-state accretion disc around a white dwarf, the continuum radiation from the disc can be described by a $F_\nu \alpha^{1/3}$ relation (Mayo, Wickramasinghe & Whelan 1980, and references therein) or equivalently $F_\lambda \alpha^{-\gamma}$ where $\alpha = 2.33$. The observed spectral index $\alpha$ of the SED is rather close to this value. However, the near-IR magnitudes of the suggested progenitor in quiescence indicate the secondary to be an evolved star (discussed later in Section 4; Jurdana-Sepic et al. 2012) so its contribution should dominate over the emission component from the accretion disc. But it would be interesting to verify, more stringently, what fraction of the observed energy arises due to the irradiated accretion disc emitting the reprocessed radiation of the central white dwarf.

### 4 EVOLUTION OF LINE PROFILE WIDTHS:

#### THE RECURRENT NOVA POSSIBILITY

The similarity of many of the pre- and post-outburst UV and optical properties of KT Eri with those of the recurrent novae has raised the question whether KT Eri could be a recurrent nova (Hung, Chen & Walter 2011; Jurdana-Sepic et al. 2012; Chen, Hung & Walter 2013). Jurdana-Sepic et al. (2012) have analyzed and listed many of these similarities in details. There are similarities in X-ray properties too. KT Eri is the second nova, after the recurrent nova RS Oph, to exhibit an ~35 s oscillation in its super soft X-ray emission (Ness et al. 2007; Nelson et al. 2008; Beardmore et al. 2010). Further, if the bright 15th magnitude star coincident with the nova’s position is its progenitor, its observed magnitude is suggestive of it being a bright evolved giant. It is recognized that of 10 known recurrent novae, at least eight are known to harbour evolved secondary stars rather than the main-sequence secondaries typical in classical novae (Darnley et al. 2012).

The present near-IR observations can, to some extent, test the suggestion made by Jurdana-Sepic et al. (2012) that the progenitor may be a cool giant star. These authors have utilized the 2MASS infrared magnitudes to study the properties of the secondary star in KT Eri as the IR colours are more sensitive to show signature of the secondary star. They have calculated the absolute magnitudes of the secondary star to be $M_J = 0.48 \pm 0.03$, $M_H = 0.05 \pm 0.05$ and $M_K = 0.00 \pm 0.07$ and point out that these magnitudes are more in line with those of cool giant stars and that the magnitudes are significantly brighter than those of typical quiescent CNe (Darnley et al. 2011).

If KT Eri is indeed an RNe of the RS Oph type, harbouring a red-giant companion, a significant or dramatic decrease in the width of the emission line profiles may be expected with time after outburst. As the secondary stars in the RS Oph type RNe lose mass at a high rate, the nova ejecta expelled with high velocity is rapidly decelerated as it moves through the wind of the companion. This deceleration results in a fast temporal decrease of the expansion velocity of the ejecta as clearly seen from IR lines in the case of the 2006 outburst of RS Oph (e.g. Das, Banerjee & Ashok 2006). We looked for similar behaviour in KT Eridani by studying the evolution of the FWHM of the Brγ line. The line profiles of Brγ for six days are shown in Fig. 9. These line profiles do not show significant changes during the period 2009 November 28 to 2009 December 16 implying a lack of deceleration during this period. There are no observations in the period between 2009 November 14 to 2009 November 28 to know whether the FWHMs decreased during this period, but it is expected that any deceleration if it took place would be seen in the near-IR observations.

### Table 4.

List of broad-band fluxes corrected for $A_V = 0.29$ for optical, near-IR and mid-IR data during the plateau phase between 2010 February 22 and 28.

| Date of observation (UT) | Band | Flux (W cm$^{-2}$ µm$^{-1}$) |
|--------------------------|------|-----------------------------|
| 2010 Feb. 26.433         | U    | $3.3 \times 10^{-16}$       |
| 2010 Feb. 26.428         | B    | $2.3 \times 10^{-16}$       |
| 2010 Feb. 26.428         | V    | $1.1 \times 10^{-16}$       |
| 2010 Feb. 26.431         | R    | $7.8 \times 10^{-17}$       |
| 2010 Feb. 26.452         | I    | $4.2 \times 10^{-17}$       |
| 2010 Feb. 28.735         | J    | $1.1 \times 10^{-17}$       |
| 2010 Feb. 28.735         | H    | $4.7 \times 10^{-18}$       |
| 2010 Feb. 28.735         | K    | $4.1 \times 10^{-18}$       |
| 2010 Feb. 22.768         | W1   | $1.4 \times 10^{-18}$       |
| 2010 Feb. 22.768         | W2   | $3.2 \times 10^{-19}$       |
| 2010 Feb. 22.863         | W3   | $4.4 \times 10^{-20}$       |
| 2010 Feb. 22.982         | W4   | $5.9 \times 10^{-21}$       |

Figure 9. The evolution of Brγ line throughout the near-IR observations of KT Eri. The line profiles did not change significantly during this period.
place, would persist for a much longer time (i.e. beyond November 28). This is what was seen in the near-IR in RS Oph (Das et al. 2006) and also in the optical and near-IR in the symbiotic nova V407 Cyg (Munari et al. 2011) whose secondary consists of a high mass losing Mira variable.

5 SUMMARY

We have presented multi-epoch near-infrared spectroscopy and photometry of nova KT Eri which erupted in mid-November 2009. From the optical light curve, the distance to the nova, height below the Galactic plane and outburst luminosity are estimated. The light-curve classification for KT Eri is seen to be type based the plateau observed in its optical and near-IR light curve. The infrared spectra indicate that the nova is of the He/N type. Recombination analysis is used to estimate the mass of the gaseous component of the ejecta. Kinematic evidence is presented from the shape of the line profiles for a possible bipolar flow. We analyse the evolution of the continuum with time and also discuss the possibility of KT Eri being a recurrent nova.

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