Infrared studies of the Be star X Per

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ABSTRACT
Photometric and spectroscopic results are presented for the Be star X Per/HD 24534 from near-infrared monitoring in 2010 – 2011. The star is one of a sample of selected Be/X-ray binaries being monitored by us in the near-IR to study correlations between their X-ray and near-IR behaviour. Comparison of the star’s present near-IR magnitudes with earlier records shows the star to be currently in a prominently bright state with mean J, H, K magnitudes of 5.49, 5.33 and 5.06 respectively. The JHK spectra are dominated by emission lines of He i and Paschen and Brackett lines of H i. Lines of O i 1.1287 and 1.3165 µm are also present and their relative strength indicates, since O i 1.1287 is stronger among the two lines, that Lyman β fluorescence plays an important role in their excitation. Recombination analysis of the H i lines is done which shows that the Paschen and Brackett line strengths deviate considerably from case B predictions. These deviations are attributed to the lines being optically thick and this supposition is verified by calculating the line center optical depths predicted by recombination theory. Similar calculations indicate that the Pfund and Humphrey series lines should also be expected to be optically thick which is found to be consistent with observations reported in other studies. The spectral energy distribution of the star is constructed and shown to have an infrared excess. Based on the magnitude of the IR excess, which is modeled using a free-free contribution from the disc, the electron density in the disc is estimated and shown to be within the range of values expected in Be star discs.

Key words: (stars:) binaries: general – stars: emission-line, Be – infrared: stars: opacity – stars: individual (X Per)

1 INTRODUCTION
The Be star X Per/HD 24534 is the optical/IR counterpart of the X-ray source 4U0352+30 and belongs to the class of Be/X-ray binaries. The orbital parameters of the system have been estimated by Delgado-Martí et al. (2001) as follows: a period of 250 days, an eccentricity of 0.11 and an inclination angle between 26 and 33 degrees. White et al. (1976) found evidence of 13.9 min modulations of the X-ray flux using the data taken with Copernicus and Ariel 5 satellites. Delgado-Martí et al. (2001) found similar modulation of 837 s in RXTE data, which possibly corresponds to the spin period of the neutron star. The Be star was classified to be of O9.5 iii type with a rotation velocity (v sin i) of 200 km s⁻¹ and lying at a distance of 1300 ± 400 pc. Slettebak (1982) and Norton et al. (1991) re-estimated the spectral type, v sin i and distance using the data taken during a low-luminosity disc-less phase (1989-91) to be B0Ve, 215 ± 10 km s⁻¹ and 700 ± 300 pc, respectively. From optical and infrared photometric data spanning a decade (1987-95), Roche et al. (1997) estimated the spectral type and distance as B0V and 900 ± 300 pc, respectively, during the disc-less phase.

From optical spectroscopy and infrared photometry during the period 1988-90, Norton et al. (1991) identified the loss of the circumstellar disc in X Per. This was based on the change of the Hα profile from emission to absorption, an associated decrease in the infrared flux and the flattening of the infrared spectrum. Fabregat et al. (1992) used this dataset to study the astrophysical parameters of X Per since the loss of disc revealed the normal B-type star. They estimated the spectral type of the star to be O9.5 iii and set a lower age limit of 6 Myr for X Per system. From high resolution optical spectroscopy and V band photometry, Clark et al. (2001) identified an episode of complete disc loss during 1988 May – 1989 June, characterised by reduction in flux of 0.6 mag in V band and the presence of absorption profiles of Hα and He i 6678 Å lines. Roche et al. (1994) identified an extended low state during 1974-77 which may be associated with a disc loss event from the analysis of optical, infrared and X-ray observations of X Per over a period of 25 years. Tarasov & Roche (1995) reported the in-
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interesting formation of a double circumstellar disc in X Per, inferred from the quadruple emission peak structure in Het 6678 Å line.

X Per was monitored as part of a program to observe Be/X-ray binaries in the near-IR using the 1.2m Mt. Abu telescope. The first photometric observations indicated that X Per was brighter by ~ 0.7 mag in J, H, K compared to its listed 2MASS values providing the initial motivation to continue observing the object. At present, photometry and spectroscopy spanning 8 nights spaced over a period of 3 months are reported.

Since much of this work is related to near-IR spectroscopy, it is worthwhile to summarize the major near-IR spectroscopic studies of Be stars that are relevant to this work. A large sample of 57 and 66 stars in the H and K bands respectively of spectral types O9 – B9 and luminosity classes III, IV and V were studied by Steele & Clark (2001) and Clark & Steele (2000) in two studies separately devoted to the H and K bands respectively. The major emphasis of these studies was on characterization of the stars based on the lines of different species seen in their spectra. Both studies serve as good templates for comparing or contrasting newly obtained H and K spectroscopic data of other Be stars. A significant extension into understanding the L band spectra of Be stars was recently made by Granada et al. (2010). These authors used simultaneous K and L band spectroscopy to understand the circumstellar envelope properties from the Brackett, Pfund and Humphrey lines of hydrogen seen in the spectra. From the ISO spectra, Lenorzer, de Koter & Waters (2002) used the line flux ratio of Hu(14)/Bra and Hu(14)/Pγ as a diagnostic tool to constrain the geometry of the ionized circumstellar material. In the J band, there appears to be a paucity of spectroscopic results - either of isolated stars or of larger samples - although this band contains certain diagnostic lines of considerable physical interest as discussed in section 3.1.

2 OBSERVATIONS

The photometric and spectroscopic observations of X Per were carried out from the 1.2m Mt. Abu telescope, operated by the Physical Research Laboratory. The log of the photometric observations along with derived JHK magnitudes is given in Table 1. The log of the spectroscopic observations is given in Table 2. The near-IR JHK spectra presented here were obtained at similar dispersions of ~ 9.5 Å /pixel in each of the J, H, K bands using the Near-Infrared Imager/Spectrometer with a 256 × 256 HgCdTe NICMOS3 array. The 1 arc second wide slit images to 2 pixels on the detector thereby yielding a resolving power of 800–1000 in the near-IR bands. A set of two spectra were taken with the object dithered to two positions along the slit. The spectra were extracted using IRAF and wavelength calibration was done using a combination of OH sky lines and telluric lines that register with the stellar spectra. Following the standard procedure, the object spectra were then ratioed with the spectra of a comparison star (SAO 56762; A5V, $T_{\text{eff}} = 8200$ K (Schmidt-Kaler 1982)) observed at similar airmass as the object. Prior to the ratioing process the hydrogen Paschen and Brackett absorption lines in the comparison stars spectrum are removed using a Gaussian fit using IRAF. The ratioed spectra were then multiplied by a blackbody curve at the effective temperature of the comparison star to yield the final spectra. Photometry in the JHK bands was done in photometric sky conditions using the imaging mode of the NICMOS3 array. Several frames, in five dithered positions offset typically by 20 arcsec, were obtained of both the program object and a selected standard star (SAO 56762; A5V) in each of the J, H, K filters. Near-IR JHK magnitudes were then derived using IRAF tasks and following the regular procedure followed by us for photometric reduction (e.g. Banerjee & Ashok (2002)).

3 RESULTS

3.1 Photometric results and general characteristics of the spectra

The light curve of X Per taken over 6 epochs is shown in Figure 1, indicating no significant variations over this period. The mean near-IR brightness is high when compared with the compilation of JHK magnitudes collected over 25 years by Telting et al. (1998). For example, two of the sets of data with lowest J, H, K magnitudes (highest flux values) recorded by these authors are 5.82, 5.21 and 5.15 on 1987 August 30 and 5.44, 5.41 and 5.29 respectively between 1994 September 16 – 20. This enhanced near-IR brightness could be an indication of the accumulation of more material in the disc, resulting from episodes of stellar mass loss events.

Regarding the spectra, the recombination emission lines of hydrogen and helium are seen to dominate the JHK spectra. The prominent lines seen are Paschen β 1.2818μm, Paschen γ 1.0938 μm and Hel 1.0830 μm in the J band (Figure 2); Brackett 10 to 18 and Hel 1.7002 μm in the H band (Figure 3) and Brackett γ 2.1656 μm, Hel 2.058, 2.1120, 2.1132 μm in the K band (Figure 4). The H and K band spectra of X Per are similar to those of classical Be stars observed by Steele & Clark (2001) and Clark & Steele (2000). Based on their K band spectra, Clark & Steele (2000) classified Be stars into five groups based on the strength and presence of the Brγ, Hε and MgI 2.138, 2.144 μm features which are seen in the K band. Group 1 candidates are those stars which show Brγ in emission along with Hel line features which can either be in emission or in absorption. It was also seen that all Group 1 candidates belonged to spectral class B3 or earlier. The observed presence of both Brγ and Hel in emission in X Per would indicate that it belongs to Group 1 and its spectral type is hence expected to be earlier than B3 — this is consistent with its present spectral classification of O9.5 Iie.

An interesting aspect of the spectroscopy is the presence of the O I 1.2877 μm and 1.3165 μm lines in the J band spectra. The relative strengths of these lines can help discriminate whether the Lyβ fluorescence mechanism is operational or not in the star. The Lyβ fluorescence mechanism was proposed by Bowen (1947) wherein due to the near coincidence of wavelengths, hydrogen Lyβ photons at 1025.72 Å can pump the O I ground state resonance line at 1025.77 Å thereby populating the O I 3dP 3D level. The subsequent downward cascade produces the 11287, 8446 and 1304 Å lines in emission thereby enhancing the strengths of these lines. It is expected that $W(1.3165)/W(1.1287) \geq 1$ if continuum fluorescence is the significant excitation mechanism.
for these lines (Strittmatter et al. 1977, Grandi 1975; W is the equivalent width). On the other hand, if excitation by the Lyβ fluorescence process is significant, the 1.1287 µm line should become stronger of the two lines. Since we measure a mean value of $W(1.3165)/W(1.1287) = 0.43$ for for all epochs of our observations, it is implied that the Lyβ fluorescence process is operative and has a significant role in the excitation of the OI lines.

The equivalent widths of the prominent lines, measured in Å are given in Table 3 – the typical error in the measurement of the equivalent width values is 10 %.

### 3.2 Analysis of the continuum

We construct and analyse the spectral energy distribution of the object in this section based on the near-IR magnitudes. Since the JHK photometric estimates during the period of observation do not change much (Table 1), it is adequate to model the SED by considering the data for one representative epoch - we have taken the 2010 December 04 data for this purpose. Figure 5 shows the SED where the JHK spectra have been dereddened using the corresponding JHK photometric values and $E(B−V) = 0.39$ (Fabregat et al. 1992) using the task DEREDDEN in IRAF. We have shown a blackbody curve at $T = 31400$ K corresponding to the effective temperature determined for X Per (Fabregat et al. 1992). In spite of a thorough search of available databases, we are unable to locate any V band measurement contemporaneous with our near-IR observations.

We have thus used the long-term compilation of photometric magnitudes of Telting et al. (1998) and assume that the colors of the star (for e.g. $(V−J)$, $(V−H)$ etc.) should remain fairly the same at similar brightness levels. That is, similar JHK magnitudes in Telting’s and the present study should be accompanied by similar V magnitudes. As mentioned earlier, our JHK values are similar to that obtained on 1994 September 16 – 20 when X Per was in a high brightness state. Hence we have taken the V magnitude as 6.24, corresponding to 1994 September 25, as given in Telting et al. (1998).

### Table 2. Journal of the spectroscopic observations.

| Date    | Spectroscopy Exp.time (s) | Airmass | X Per (J, H, K) | SAO 56762 (J, H, K) |
|---------|---------------------------|---------|----------------|--|------------------|
| 2010    |                           |         | J H K          |                 |
| Dec. 05 | 40 40 50                  | (1.01,1.02,1.05) | (1.13,1.17,1.19) |
| Dec. 10 | 50 50 50                  | (1.14,1.16,1.19) | (1.12,1.18,1.20) |
| Dec. 15 | 90 60 60                  | (1.08,1.10,1.22) | (1.08,1.12,1.19) |
| 2011    |                           |         | J H K          |                 |
| Jan. 13 | 60 60 60                  | (1.09,1.10,1.13) | (1.09,1.11,1.16) |
| Jan. 26 | 60 40 40                  | (1.14,1.16,1.19) | (1.14,1.18,1.20) |
| Jan. 28 | 40 40 40                  | (1.33,1.28,1.25) | (1.36,1.30,1.25) |
| Feb. 08 | 60 60 120                 | (1.06,1.05,1.04) | (1.06,1.05,1.03) |

Figure 2. Flux calibrated J band spectra of X Per are displayed at different epochs with an offset between adjacent spectra for clarity. The amount of offset in units of $10^{-15}$ W cm$^{-2}$ µm$^{-1}$ is shown in brackets after the date of observation.
The blackbody curve in Figure 5 has hence been anchored to this $V$ band magnitude which is also dereddened using $E(B-V) = 0.39$. From Figure 5 it is evident that a blackbody curve poorly fits the SED of X Per and an infrared excess is seen which we attribute to free-free (f-f) emission from the disc.

The observed free-free excess can be modeled to obtain an average value of the electron density in the disc. Given a distance $D$ to the object, a volume $v$ for the emitting ionized gas of the disc, the observed flux $F$ (in units of W cm$^{-2}$ $\mu$m$^{-1}$) due to f-f contribution will be given by

$$ F = j_{\lambda ff} \times v / 4 \pi D^2 $$

where the free-free volume emission coefficient, $j_{\lambda ff}$ (in units of W cm$^{-3}$ $\mu$m$^{-1}$) can be calculated from

$$ j_{\lambda ff} = 2.05 \times 10^{-30} \lambda^{-2} z^2 g T_e^{1/2} n_e n_i \exp(-c2/\lambda T_e) $$

In the above $\lambda$ is the wavelength of emission in $\mu$m, $z$ is the charge, $g$ is the Gaunt factor, $T_e$ is the disc temperature, $n_e$ and $n_i$ are the electron and ion densities respectively and $c2 = 1.438$ cm K (Banerjee, Janardhan & Ashok 2001). In the case of a circumstellar disc, the volume of the emission region ($v$) is reasonably estimated as $\pi R_d^2 H$, where $R_d$ and $H$ are the disc radius and thickness respectively.

In the case of Be stars, the disc thickness can be approximated to be one-fifth of stellar radius (Gehrz et al. 1974). We assume $g$ and $z$ to be unity, $n_e = n_i$ for a pure hydrogen shell, and adopt a distance to the object of 1300 pc from Fabregat et al. (1992). The calculated values of free-free electron flux as a function of wavelength is shown as dotted line in Figure 5 for a temperature of 10,000 K and $n_e = 4 \times 10^{13}$ cm$^{-3}$. The free-free contribution, computed for a choice of these parameters, when added to the blackbody curve is found to reproduce the observed SED much better than a blackbody alone. This value of electron density is comparable with that expected from observational modeling (e.g. Silva et al. 2010; Carciofi et al. 2008; Gies et al. 2007). A realistic model should take into account the optical depth effects while calculating the continuum emission.

### 3.3 Recombination analysis of the hydrogen lines

Of the H lines, only two of the Paschen series lines could be covered in the spectra presented here viz. Pa$\beta$ at 1.2818 $\mu$m and Pa$\gamma$ at 1.0938 $\mu$m. Whenever recorded, Pa$\gamma$ is found to be stronger than Pa$\beta$ contrary to what is expected (see Figure 2). This indicates that these Paschen lines are optically thick since the expected ratio in recombination case B conditions is $I(Pa\beta)/I(Pa\gamma) \sim 1.57 - 2.01$ for typical densities and temperatures prevailing in Be star discs (i.e. $T_e = 10^4$ K, $n_e$ in the range $10^{10}$ to $10^{14}$ cm$^{-3}$; here $I$ is the line intensity in units of erg cm$^{-2}$ s$^{-1}$ whose values are taken from Storey & Hummer (1993)). In essence, Pa$\beta$ is always expected to be stronger than Pa$\gamma$ under optically thin case B conditions. Optical depth effects are more clearly seen in the Brackett series lines viz. Br$\gamma$ in the $K$ band and Br10 to 18 in the $H$ band. In Figure 6, we present plots of the observed strength of Br lines versus their predicted intensities under recombination case B conditions. The line fluxes used in this figure were derived from the spectra which were flux calibrated by the broad-band $JHK$ magnitudes of Table 1 and dereddened using a value of $A_V = 1.19$ (Valencic & Smith 2005).

We have presented the data only for 2010 December 10 and 2011 January 26 in Figure 6 since there is considerable cluttering and loss of clarity if the observed data of all 5 days are presented. But we found that a similar trend for the line strengths, as presented in Figure 6, is seen too for...
Table 3. Measured equivalent widths of the emission lines in Å.

| Date   | Paβ (1.08μm) | Paγ (1.70μm) | HeI Br10 (2.05μm) | HeI Br11 | HeI Br12 | HeI Br13 | HeI Br14 | HeI Br15 | HeI Br16 | HeI Br17 | HeI Br18 | HeI Brγ (2.05μm) |
|--------|--------------|--------------|------------------|----------|----------|----------|----------|----------|----------|----------|----------|------------------|
| 2010   |              |              |                  |          |          |          |          |          |          |          |          |                  |
| Dec. 05| 14.3         | –            | 15.4             | 3.6      | 15.2     | 11.1     | 12.0     | 11.2     | 7.5      | 9.8      | 9.6     | 4.3    | 15.1            | 23.7 |
| Dec. 10| 21.0         | –            | 13.1             | 4.1      | 14.6     | 13.5     | 11.6     | 12.9     | 10.8     | 13.1     | 8.0     | 7.7    | 20.8            | 23.8 |
| Dec. 15| 14.3         | –            | 11.0             | 4.7      | 13.0     | 12.7     | 10.7     | 11.7     | 11.1     | 11.8     | 8.4     | 8.2    | –              | –   |
| 2011   |              |              |                  |          |          |          |          |          |          |          |          |          |                  |
| Jan. 13| 22.6         | 18.4         | –                | –        | 4.1      | 14.9     | 11.2     | 9.9      | 11.4     | 13.5     | 10.3    | 7.3    | 19.7            | 24.0 |
| Jan. 26| 16.8         | 15.9         | 28.9             | 11.4     | 4.0      | 13.5     | 14.1     | 11.4     | 14.2     | 9.6      | 10.0   | 9.4    | 7.8             | 18.1 | 22.1 |
| Jan. 28| 12.8         | 17.0         | 19.0             | 13.1     | 4.1      | 10.8     | 12.1     | 10.2     | 10.8     | 7.4      | 12.2   | 7.4    | 9.8             | 16.2 | 20.6 |
| Feb. 08| 17.4         | 20.4         | –                | 11.8     | 4.1      | 11.3     | 12.7     | 10.4     | 11.6     | 9.6      | 11.7   | 9.1    | 7.2             | 14.3 | 22.8 |

Figure 5. The spectral energy distribution of X Per for the epoch 2010 December 10 is shown in the figure. The flux calibrated HJK spectra are dereddened using $E(B-V) = 0.39$. The blackbody corresponding to the central stars temperature of $T = 31400$ K is shown by a dashed line, the free-free contribution from the disc by a dotted line and their co-added sum by a solid line. Also shown is the V band flux corresponding to high brightness state (filled circle). For further details see section 3.2.

Figure 6. Recombination case B analysis of the Brackett lines of hydrogen are shown for X Per where the Br line fluxes are all normalized with respect to the line flux of Pa β. The lines shown are Br10 – 18 (1.7367 – 1.5346 μm) and Brγ. A large deviation from case B predictions is seen especially in the behavior of the higher Br lines. Filled triangles indicate the observations taken on 2010 December 10 while the filled circles correspond to that on 2011 January 26. Solid lines represent case B values for $T_e = 10^4$ K, $n_e = 10^{10}$ (shown as continuous line), $10^{12}$ (shown as dashed line) and $10^{14}$ cm$^{-3}$ (shown as dot-dashed line). Its inclusion here in Figure 6 brings out the deviation from case B values even more clearly. From recombination theory it is qualitatively expected, under optically thin conditions, that when strengths of lines of the same series are compared, a lower line of the series should be stronger than a higher line. For example, it is expected that Brγ (corresponding to a transition between levels 7–4) is expected to be stronger than any higher line of the series like Br10 or Br11 (transitions between 10—4 and 11–4 respectively). But the reverse is actually being observed here.

It is interesting to note that lines of even the higher Pfund (Pf) and Humphrey (Hu) series could in general

the data of the other days. The case B line intensities are from Storey & Hummer (1995) for a temperature $T_e = 10^4$ K and for three representative values of the electron density $n_e = 10^{10}$, $10^{12}$ and $10^{14}$ cm$^{-3}$, respectively. As can be seen from Figure 6, the observed line intensities deviate significantly from the optically thin case B values. This indicates that Brackett lines are optically thick during all the epochs of observation of X Per. This observed behaviour of the Br line strengths is consistent with that seen in Be stars in general. Steele & Clark (2001), from their H band spectroscopy of 57 Be stars, showed that the strengths of Br 11 to Br 18, relative to each other, do not in general fit case B theory particularly well. Being a paper devoted to the H band, they did not include Brγ in their analysis, but

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be optically thick in Be stars. For e.g., of the 8 Be stars for which the L band spectra have been presented by Granada et al. [2010], the spectra of EW Lac and BK Cam cover several of the Pf and Hu lines viz. Pf 8, 9, 10 and 17 – 27 & Hu 14 – 25. Analysis of their strengths, and comparison with case B predictions, shows a strong departure from the optically thin case (Figures 4 and 5 in Granada et al. [2010]).

We analyzed the case B model values to check whether opacity effects are expected to affect the strengths of the Br line shown in Figure 6 under the density conditions prevailing in Be discs. It is verified from Hummer & Storey [1987] and Storey & Hummer [1995] that line center optical depth values can be significant when the densities become large as in Be star discs. The above studies tabulate the value of the opacity factor Ω in Be star discs. The above studies tabulate the value of the opacity factor Ω in Be star discs. The above studies tabulate the value of the opacity factor Ω in Be star discs. The above studies tabulate the value of the opacity factor Ω in Be star discs. The above studies tabulate the value of the opacity factor Ω in Be star discs.

4 DISCUSSION

In Be stars the situation regarding optical depth effects could be complex since the optical depth in a line will also depend on the region from where the line emanates. Interferometric results indicate that different lines originate from different regions in the circumstellar disc, i.e., regions of different electron density and hence different τ values. The presence of density enhancements due to spiral waves in the disk could complicate matters further (Wisniewski et al. [2007], Hesselbach [2009]). Disc size estimates that are now available show considerable variation in sizes from measurements around the Hα emission line (e.g. Quirrenbach et al. [1997], Stee et al. [2003]; several papers by Tycner and collaborators); in the infrared 10 μm N band continuum (Chesneau et al. [2003]), in the near-IR K band (e.g. Gies et al. [2007]); in the H band continuum and also in K band Brγ and HeI 2.058 μm emission lines (Millan-Gabet et al. 2010). A summary of the interferometric results available up to fairly recent times may be found in Gies et al. [2007] and Monnier (2003; and references therein). Variations in disc sizes, though not measured directly, are also suggested by the modeling of Jaschek & Jaschek [1993] for the OI and Paschen lines.

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