Non-emission line young stars of intermediate mass

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ABSTRACT
We present optical spectra of four intermediate mass candidate young stellar objects that have often been classified as Herbig Ae/Be stars. Typical Herbig Ae/Be emission features are not present in the spectra of these stars. Three of them, HD 36917, HD 36982 and HD 37062 are members of the young Orion Nebula Cluster (ONC). This association constrains their ages to be $\leq 1$ Myr. The lack of appreciable near infrared excess in them suggests the absence of hot dust close to the central star. But they do possess significant amounts of cold and extended dust component as revealed by the large excess emission observed at far infrared wavelengths. Fractional infrared luminosity ($L_{ir}/L_\star$) and the dust masses computed from IRAS fluxes are systematically lower than that found for Herbig Ae/Be stars but higher than those for Vega-like stars. These stars may then represent the youngest examples of Vega phenomenon known so far. In contrast, the other star in our sample, HD 58647, is more likely to be a classical Be star as evident from the low $L_{ir}/L_\star$, scarcity of circumstellar dust, low polarization, presence of H$\alpha$ emission and near infrared excess and far infrared spectral energy distribution consistent with free-free emission similar to other well known classical Be stars.

Key words: stars: pre-main-sequence - circumstellar matter - stars: emission-line, Be - infrared: stars - stars: early type

1 INTRODUCTION
Pre-main sequence stars of intermediate mass ($2 \leq M/M_\odot \leq 8$) which show emission lines in their spectra are called Herbig Ae/Be (HAEBE) stars. They were first discussed as a group by Herbig (1960). He identified 26 stars which are of spectral type A or B, located in obscured star-forming regions and illuminating a bright nebulosity in its immediate vicinity. Additions to the original list were made by Finkenzeller & Mundt (1984) and Herbig & Bell (1988). Recently, a more extended catalogue of HAEBE stars and related objects was published by Thé et al. (1994). In this catalogue 287 HAEBE stars and related objects are listed in five tables, which include stars with later spectral type (G0 or earlier) and those found relatively isolated from star forming clouds. Out of this, only 109 stars which are listed in Table 1 of the catalogue, are recognized as either HAEBE stars or potential candidate members. Other stars listed in the catalogue are either of very uncertain or unknown spectral type or have not been identified to belong to any specific group.

The following set of properties are often taken as a working definition of HAEBE stars (Waters & Waelkens 1998). (a) Spectral type B or A with emission lines. (b) Infrared excess due to hot or cool circumstellar dust or both. (c) Luminosity class III to V. The emission lines are believed to be formed in a stellar wind originating from a hot and extended chromosphere around the star (Bouret & Catala 1998), and is closely connected with the accretion related disc activity. The near and far infrared excesses which characterize the spectral energy distribution (SED) of these stars is attributed to the presence of significant amounts of circumstellar dust around them with a wide range in temperature (e.g. Hillenbrand et al. 1992). Submillimeter and millimeter observations have clearly established the existence of dust. Dust masses estimated from these studies range from $\sim 10^{-5}$ to $10^{-1} M_\odot$ (Waters & Waelkens 1998 and references therein). Scattering of central star light by the circumstellar dust manifests in large values of intrinsic polarization measured for HAEBE stars (e.g. Grinin 1994). However, the geometry of the circumstellar environment of HAEBE stars is still a matter of debate. Evidence for the presence of discs as well as envelopes has been found. Recently Natta et al. (2001) have argued that irradiated discs with a puffed-up inner wall of optically thick dust provide a good fit to the observations over the entire range of wavelengths.

Though the pre-main sequence (PMS) nature of the HAEBE stars is now well established, several questions concerning their PMS evolution remain to be answered. Do all PMS stars of intermediate mass go through the Herbig Ae/Be phase? What happens to the attendant circumstellar material around a HAEBE star by the time it evolves into a main sequence star? There have been suggestions in literature that HAEBE stars evolve into Vega-like stars (c) $\odot 2001$ RAS
Table 1. Log of spectroscopic observations

| Object   | Date of Observation | Exposure Time |
|----------|---------------------|---------------|
| AB Aur   | 23 December 2000    | 600s          |
| HD 36917 | 27 February 2002    | 600s          |
| HD 36982 | 27 February 2002    | 600s          |
| HD 37062 | 26 February 2002    | 300s          |
| HD 58647 | 22 December 2000    | 600s          |

eg, Malfait et al. 1998, Waters & Waellens 1998). Vega-like stars are characterized by substantial far infrared excess due to cool dust, relatively low near infrared excess, low polarization and lack of emission lines in their spectra. The dust masses found around them are a few orders of magnitudes lower than that of HAEBEs. Also, Vega-like discs in general are gas depleted (Lagrange et al. 2000). Do all HAEBE stars pass through a Vega-like phase with gas depleted discs? These questions are critical to our understanding of the nature of the pre-main sequence evolution of intermediate mass stars.

A study of non-emission line young stellar candidate objects listed in Table 5 of the catalogue by Thé et al. (1994) may shed some light on the issues raised above. There are fourteen stars listed in this table. Typical PMS properties are less clearly seen in these stars. One of them, β Pic, is a bona fide Vega-like star. The evolutionary status of other stars is not very clear. They are believed to be, as the authors suggest, transition objects between PMS and MS phase.

In this paper we present the results of a study of four non-emission line stars listed in the afore-mentioned catalogue. Spectroscopic and polarimetric observations of these stars were carried out. In Section 2 of this paper we present our observations. Together with the information available from literature in different wavelength ranges, we discuss the structure of circumstellar environment and the evolutionary status of these stars in Section 3. Summary of our study is presented in Section 4.

2 OBSERVATIONS

Medium resolution (λ/Δλ ~ 3000) optical CCD spectra were obtained for stars HD 36917 (V372 Ori), HD 36982 (LP Ori) and HD 37062 (V361 Ori) with the Optometrics Research (OMR) spectrograph on the 2.3 meter Vainu Bappu Telescope (VBT) and for HD 58647 with the Universal Astronomical Grating Spectrograph (UAGS) on the 1 meter telescope at the Vainu Bappu Observatory, Kavalur, India. Log of spectroscopic observations is given in Table 1. The prototype Herbig Ae/Be star AB Aur was also observed with the UAGS on the 1 meter telescope and is included in Table 1. All spectra were bias subtracted, flat-field corrected, extracted and wavelength calibrated in the standard manner using the IRAF reduction package. In view of the presence of surrounding diffuse HII region nebulosity in the direction of three of the programme stars, the background sky subtraction was performed in the following way. The stellar spectra were extracted by summing up over ten pixels (plate scale = 0.2′/pixel) perpendicular to the dispersion axis. The sky background subtracted was obtained by summing up ten pixels, ten pixels (2″) away from the star on either side. The spectra were corrected for instrumental response and brought to a relative flux scale using the spectrophotometric standard observed on the same night. Each spectrum spans a wavelength range of ~ 2400˚A, centered roughly at Hα(λ ~ 6562˚A). Reduced spectra of HD 36917, HD 36982 and HD 37062 along with that of AB Aur are presented in Figure 1(a) and that of HD 58647 in Figure 1(b). Optical linear polarization measurements were made with a fast star-and-sky chopping polarimeter (Jain & Srinivasulu 1991) coupled at the f/13 Cassegrain focus of the 1 meter telescope at the Vainu Bappu Observatory, Kavalur, the Indian Institute of Astrophysics. A dry-ice cooled R943-02 Hamamatsu photomultiplier tube was used as the detector. All measurements were made in the V band with an aperture of 15″. The instrumental polarization was determined by observing unpolarized standard stars from Serkowski (1974). It was found to be ~ 0.1%, and has been subtracted vectorially from the observed polarization of the programme stars. The zero of the polarization position angle was determined by observing the polarized standard stars from Hsu & Breger (1982). The position angle is measured from the celestial north, increasing eastward. Observed polarization and position angle values are presented in Table 2. Object name and date of observations are presented in column 1 and 2 of the table. Percentage polarization in V band and the probable error in the measurement are given in columns 3 and 4 and position angle and probable error in columns 5 and 6.

It can be seen from Figure 1(a) and 1(b) that emission lines are not present in the spectra of these stars except HD 58647. In Figure 1(a) we have also included a spectrum of AB Aur, a prototype Herbig Ae star, in the same wavelength range and of similar resolution as of the other spectra for comparison. Typical HAEBE emission features such as Hα, HeI (λ5875 & λ6678) and OI (λ7774) which are promi-

1 IRAF is distributed by National Optical Astronomy Observatories, USA.

Table 2. Polarization observations from Kavalur

| Object   | Date of Observation | P(%) | εP(%) | θ(°) | εθ(°) |
|----------|---------------------|------|-------|------|-------|
| HD 36917 | 12 March 1999       | 0.53 | 0.11  | 55   | 8     |
| HD 36982 | 03 March 2000       | 0.23 | 0.07  | 123  | 7     |

Table 3. Polarization measurements in V band compiled from literature

| Object   | P(%) | εP(%) | θ(°) | εθ(°) | Reference |
|----------|------|-------|------|-------|-----------|
| HD 36917 | 0.97 | 0.032 | 43   | 0.9   | 1         |
| HD 36982 | 1.01 | 0.021 | 56   | 0.6   | 1         |
| HD 37062 | 0.41 | 0.032 | 162  | 2.2   | 1         |
| HD 58647 | 0.22 | 0.04  | 133.3| 4.6   | 2         |

a 1. Heiles (2000), 2. Oudmaijer et al. (2001)
Non-emission line young stars of intermediate mass

3

Figure 1. (a) Optical spectra of the Orion Nebula Cluster (ONC) member stars and AB Aur. In HD 37062, HD 36917 and HD 36982 typical Herbig Ae/Be emission lines are absent.

We note that three of the programme stars, viz., HD 36917, HD 36982, HD 37062 are towards the direction of the Orion Nebula and the diffuse HII region present there is projected on to the line of sight to these stars. Therefore a careful subtraction of the surrounding nebular emission from the observed spectra is very important. This is illustrated in Figure 2 which presents the raw spectrum with superposed nebular lines and the reduced spectrum with surrounding nebular emission subtracted for HD 37062.

In Table 3 we present polarization data for these stars already existing in literature. The polarization values measured are typical of that of pre-main sequence stars except, again, for HD 58647 which shows a relatively low value of polarization. Also, LP Ori for which we have more than one polarization measurements shows variability which is again an indicator of the youth of the star.

3 DISCUSSION

All the stars in our sample have earlier been treated as HAEBE stars by different authors (e.g. Malfait et al. 1998, Yudin 2000, Valenti et al. 2000) though in the catalogue by Thé et al. (1994) they are identified as non-emission line stars. Spectra presented in Figure 1 show that the characteristic HAEBE emission features \( \text{HeI} \lambda 5875 & \lambda 6678 \) and \( \text{OI} \lambda 7774 \) are conspicuously absent in these stars. Their classification as HAEBE stars is, therefore, doubtful. A strong \( \text{H}_\alpha \) emission is present in HD 58647, but as argued later in this paper this star is likely to be a classical Be star. Weak \( \text{H}_\alpha \) emission, filling in the absorption core is present in HD 36917 even upon the subtraction of the possible contribution of the surrounding nebulous. By comparing with synthetic spectra (Pickles 1985) of normal spectrophotometric standard stars of similar spectral type, we determine the equivalent width of the \( \text{H}_\alpha \) emission in this star to be 2.5 Å. This upper limit (for any residual nebular emission) to the \( \text{H}_\alpha \) equivalent width for HD 36917 is much smaller than those for typical Herbig Ae/Be stars (for the Herbig Ae/Be proto-
We have constructed near infrared (NIR) colour-colour diagram from the 2MASS magnitudes for our programme stars which is shown in Figure 3. Along with the four programme stars, HAEBE stars and main sequence stars are also plotted in the diagram. The colours for the main sequence stars are from Koornneef (1983). HAEBE stars are taken from Thé et al. (1994) and their colours are derived from 2MASS magnitudes. The two parallel dotted lines form reddening band for normal stellar photospheres. These lines are parallel to the reddening vector and bound the range in the colour-colour diagram within which stars with purely reddened normal stellar photospheres can fall (Lada & Adams 1992). It can be seen that all the four stars are distinctly separated from the region occupied by HAEBE stars. Their near infrared characteristics are different from that of HAEBE stars. The near infrared excess of all the four stars are considerably lower than that of HAEBE stars. HD 36982 and HD 37062 have very little near infrared excess, if any. The near infrared excess in HAEBE stars is attributed to reradiation from hot dust less than \( \sim 1 \mu \text{m} \) from the star. The low near infrared excess shown by our programme stars, then, would strongly suggest the absence of submicron sized dust grains close to the star.

In Table 5 we present far infrared data for the stars and the quantities estimated from them except for HD 37062 which does not have an IRAS entry. HD number of the stars, their IRAS source names and the IRAS flux densities at 12, 25, 60 and 100\( \mu \text{m} \) are listed in the first six columns. In column 7 we list the fractional infrared luminosity \( (L_{\text{ir}}/L_{\star}) \) estimated from IRAS fluxes. \( L_{\text{ir}} = 4 \pi d^2 F_{\text{ir}} \) with

\[
F_{\text{ir}} = \left[ 20.653 f_{12} + 7.53 f_{25} + 4.578 f_{60} + 1.762 f_{100} \right] \times 10^{-14} \text{W m}^{-2}
\]

and \( d \) being the distance to the star (Cox 2000). The IRAS flux densities \( (J\mu) \) at 12, 25, 60 and 100\( \mu \text{m} \) are given by \( f_{12}, f_{25}, f_{60}, \text{and} f_{100} \) respectively. \( L_{\star} \) is computed from \( M_{\star} \) using standard bolometric corrections (Cox 2000) where \( M_{\star} \) is evaluated from dereddened \( V \) magnitude and distance to the star. Since the star HD 36982 is located below the ZAMS in the colour - magnitude diagram (cf. Fig. 4) \( L_{\star} \) for this star is taken to be the ZAMS luminosity expected for its spectral type. The black body colour temperatures derived from the ratio of fluxes at 25\( \mu \text{m} \) and 60\( \mu \text{m} \) are considered to be the dust temperatures and are listed in column 8. The dust temperature derived for HD 36917 is a lower limit since the IRAS 60\( \mu \text{m} \) flux density is only an upper limit. Dust masses (in units of \( M_{\oplus} \), the mass of earth = \( 6 \times 10^{27} \) g) listed in column 9 are computed using the relation,

\[
M_d = 4 \pi a \rho_d d^2 F_{\text{ir}} / 3 Q_{\nu} \sigma T_d^4
\]

assuming a grain size of \( a = 1 \mu \text{m} \), dust grain material density \( \rho_d = 2 \text{g/cc} \), absorption efficiency \( Q_{\nu} = 0.5 \), and with \( F_{\text{ir}} \) computed from the flux densities at four IRAS bands. Since IRAS flux densities at 100\( \mu \text{m} \) are upper limits for all the stars we have used flux densities expected at 100\( \mu \text{m} \) for the derived colour temperatures in estimating \( F_{\text{ir}} \).

The fractional infrared luminosities \( L_{\text{ir}}/L_{\star} \) estimated for HD 36917 and HD 36982 are quite significant \( (L_{\text{ir}}/L_{\star} \sim 0.15) \). Here it is assumed that the IRAS flux densities

Figure 3. Near infrared colour-colour diagram for the stars. Also plotted are Herbig Ae/Be stars (triangles) and main sequence stars (crosses).
Non-emission line young stars of intermediate mass

Table 4. Data compiled from literature and quantities estimated from them

| Object      | Sp. Type | $vsini$ $kms^{-1}$ | B    | V    | J    | H    | K    | $E(B - V)$ |
|-------------|----------|--------------------|------|------|------|------|------|------------|
| HD 36917 B9.5+A0.5 | 117      | 8.18               | 8.06 | 7.269 | 7.012 | 6.615 | 0.14 |
| HD 36982 B1.5V | 98       | 8.48               | 8.44 | 7.754 | 7.762 | 7.521 | 0.29 |
| HD 37062 B4V  | 78       | 7.80               | 8.24 | 7.850 | 7.725 | 7.576 | -0.26 |
| HD 58647 B9Ive | 280      | 6.82               | 6.85 | 6.464 | 6.115 | 5.433 | 0.10 |

$^a$ Spectroscopic binary (Lavato & Abt 1976)

quoted do represent emission from these sources and are not due to other sources in the IRAS beam. We note that IRAS point sources 05323-0536, 05327-0529 and 07236-1404 have positional coincidences with HD 36917, HD 36982 and HD 58647 to within 4$,^\prime$, 2$^\prime$ and 2$^\prime$ respectively. The surface density of IRAS point sources in this region is $\sim 3 \times 10^{-3}$ to $10^{-2}$ sources/(arcmin)$^2$. Therefore, for a given star, in the 12 and 25 µ bands, the probability that an unrelated IRAS point source is in the IRAS beam $(0.75 \times 4.5')$ is only $\sim 1 - 3\%$. If the IRAS fluxes observed for these stars are dominated by thermal emission from the circumstellar dust present around these stars, which is most likely the case in view of the relatively low surface density of IRAS point sources and low probability of chance projections, then for the derived dust temperatures listed in Table 5 the emitting dust is at distances of $\sim 10$ AU (HD 36917) and $\sim 100$ AU (HD 36982) from the central star, assuming the dust to be distributed in an optically thick disc as in some models of HAEBE stars (Hillenbrand et al. 1992). On the other hand if the dust is distributed in optically thin shells as in Vega-like stars, then the dust is located at $\sim 100$ AU (HD 36917) and $\sim 1000$ AU (HD 36982) from the stars. These dimensions of dust shells or rings are quite similar to those of Vega-like stars and are compatible with the dust responsible for emission being part of the circumstellar environment. It is clear from Table 5 that these two stars have significant amounts of cold circumstellar dust present around them. The dust masses estimated are systematically lower than those for HAEBE stars but higher than that found around Vega-like stars.

In Figure 4 we present the far infrared spectral energy distribution for the three stars. Their IRAS flux densities are plotted against the wavelength together with the expected photospheric flux densities at IRAS wavelengths (Song 2001) for a star of that spectral type. It is clearly seen that HD 36917 and HD 36982 have considerable excess at far infrared wavelengths whereas HD 58647 has a low excess and an energy distribution that is decreasing with wavelength.

It is clear from the above discussion that the three member stars of Orion Nebula Cluster (ONC) are extremely young and lack emission lines in their spectra. This would imply the absence of a hot and extended chromosphere around them where the emission lines are thought to be formed. In the case of HD 36982 and HD 37062, which are early B type stars it is possible that this is an evolutionary effect. They are possibly at the end of their pre-main sequence phase, which is roughly $\sim 1 - 2 \text{ Myr}$. The absence of He$\lambda$ line in emission, which is an indicator of accretion, also suggests that these stars are beyond their accretion phase. Almost complete absence of near infrared excess further supports the absence of an inner accretion disc. This evolutionary picture is further supported by the fact that HD 36917, which is of a later spectral type and thus has a longer PMS life time, shows near infrared excess though at a much lower level than seen in HAEBEs. Binarity of the star cannot account for the near infrared excess. The $J - H$ and $H - K$ colours computed by adding up the individual fluxes expected for each component of the binary $(B9.5 + A0.5)$ and estimating the combined magnitudes, are only 0.006 and $-0.002$ whereas the observed colours are 0.257 and 0.397 respectively. Thus it could be concluded that the inner disc has not been completely disrupted in this star.

However, we do not rule out the possibility of the stars not passing through a HAEBE phase with emission lines and near infrared excess. A different formation mechanism or a very destructive cluster environment can drastically alter the PMS properties and evolutionary sequence that a young star passes through.

In any case these stars fit well with the definition of Vega-like stars though the far infrared excesses, fractional infrared luminosities ($L_{ir}/L_{\star}$), and the dust masses computed for HD 36982 and HD 36917 are much higher than...
that for the prototype Vega-like stars and for "old PMS" (OPMS) and "young main sequence" (YMS) systems discussed recently by Lagrange et al. (2000). Their circumstellar dust may not be the debris product but rather what is left over from their PMS phase. These stars, then, are the youngest Vega-like stars hitherto known.

Unlike the stars which are members of the Orion Nebula Cluster, HD 58647 may not be a young star. This object is about 30 degree away from the Orion complex and is not associated with any star forming cloud. Though it shows an excess at the near infrared wavelengths, it’s far infrared excess is small. $L_{ir}/L_{*}$ indicates the scarcity of dust present around the star. Low polarization observed reinforces this fact. Colour temperature derived from the IRAS fluxes is very high and is much larger than the dust sublimation temperature. The dust mass estimated formally from IRAS fluxes is negligibly low and is unphysical as the colour temperature is much larger than the dust sublimation temperature (see text).

A colour-absolute magnitude diagram constructed for all the four programme stars is shown in Figure 5. The zero-age main sequence data is taken from Schmidt-Kaler (1965). For the ONC member stars a distance of 470 pc is assumed and a Hipparcos distance of 277 pc is used for HD 58647 in computing the absolute magnitude. Major contribution to the error bars shown in the figure results from uncertainties in distance. Further, the average interstellar value of 3.1 is used for the ratio $R = A_v/E(B - V)$ . Significance of their position in the colour-magnitude diagram (CMD) is discussed below.

HD 36917 which is a spectroscopic binary (B9.5 + A0.5) (Lavato & Abt 1976) is found to be way above the main sequence in the colour - magnitude diagram. Increase in the brightness caused by binarity would only account for $\sim 0.7\, \text{mag}$. Thus it’s location in the colour - magnitude diagram is consistent with the star being a pre-main sequence and the age indicated by its kinematic association with the ONC.

The other two stars which are members of the ONC, viz., HD 36982 and HD 37062 fall below the zero-age main sequence (in particular HD 36982) in the CMD. A possible explanation for their anomalous position is that they have an anomalous circumstellar extinction component. If they have already reached the zero age main sequence then the extinction towards HD 36982 and HD 37062, implied by their location in the CMD and computed from the observed and absolute V magnitudes for a distance of 470 pc are $\sim 2.12\, \text{mag}$ and $\sim 0.7\, \text{mag}$ respectively. Such large extinction and a rather low $E(B - V)$ cannot be produced by interstellar grains of submicron size. This would imply the presence of large grains around these stars. The neutral extinction produced by these grains can be even larger than that estimated assuming the stars to be zero age main sequence stars, without causing any change in the colour excess. The possibility of these stars being intrinsically brighter than a ZAMS star of similar spectral type cannot be ruled out. They could be pre-main sequence stars with very high extinction.

### 4 SUMMARY

We have obtained optical spectra of four non-emission line stars listed in the catalogue by Thé et al. (1994). Emission lines which characterize the typical HAEBE spectrum are not seen in any of the stars. Also, their near infrared prop-

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**Table 5.** Far infrared data for the stars and the quantities estimated from them

| Object   | IRAS source | IRAS Flux Densities, $f_v$ (Jy) | $L_{ir}/L_{*}$ | $T_d$ (K) | $M_d/M_\odot$ |
|----------|-------------|---------------------------------|----------------|-----------|--------------|
| HD 36917 | 05323-0536  | $5.73$ $3.37$ $37.8^*$ $7.40^*$ | $0.13$         | $\geq 70$ | $\leq 2$     |
| HD 36982 | 05327-0529  | $33.9$ $367$ $4800$ $24.5^*$ $7.36^*$ | $0.01$         | $\uparrow 10^4$ | $\uparrow 5 \times 10^{-10}$ |
| HD 58647 | 07236-1404  | $4.95$ $2.87$ $0.47$ $7.36^*$ | $0.17$         | $68$      | $230$        |

* Upperlimits
† Unphysical, since the colour temperature is much larger than the dust sublimation temperature (see text)
Non-emission line young stars of intermediate mass

Properties are very unlike HAEBE stars. The amount of circumstellar dust present is also systematically lower than that found around HAEBE stars. We argue that these stars cannot be unambiguously classified as HAEBE stars. Nevertheless, three of the stars which are kinematic members of Orion Nebula Cluster are very young. This association constrains their ages to be less than a few Myr. Absence of emission lines, low near infrared excesses and presence of far infrared excesses in these objects make them somewhat similar to Vega-like stars though the dust masses estimated for them are much higher than that of prototype Vega-like stars. These stars may then represent the youngest examples of Vega phenomenon and may well be the intermediate mass counter parts of weak line T Tauri stars. The observed reddening and estimated extinction for these stars indicate presence of larger than submicron sized dust grains around these stars. One of the stars in our sample, HD 58647, is more likely to be a classical Be star as evident from the low $L_\text{IR}/L_\star$, scarcity of circumstellar dust, low polarization, presence of $H\alpha$ emission and appreciable near infrared excess and far IR spectral energy distribution consistent with free-free emission similar to other well known classical Be stars.

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