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Studies of a possible new Herbig Ae/Be star in the open cluster NGC 7380

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Abstract We present a study of the star 2MASS J22472238+5801214 with the aim of identifying its true nature which has hitherto been uncertain. This object, which is a member of the young cluster NGC 7380, has been variously proposed to be a Be star, a D-type symbiotic and a Herbig Ae/Be star in separate studies. Here we present optical spectroscopy, near-IR photometry and narrow band H α imaging of the nebulosity in its environment. Analysis of all these results, including the spectral energy distribution constructed from available data, strongly indicate the source to be a Herbig Ae/Be star. The star is found to be accompanied by a nebulosity with an interesting structure. A bow-shock shaped structure, similar to a cometary nebula, is seen very close to the star with its apex oriented towards the photoionizing source of this region (i.e. the star DH Cep). An interesting spectroscopic finding, from the forbidden [SII] 6716, 6731 Å and [OI] 6300 Å lines, is the detection of a blue-shifted high velocity outflow (200 ± 50 km s⁻¹) from the star.

Key words: stars: emission-line – Be – stars: pre-main sequence — stars: winds, outflows — galaxies: star clusters: individual: NGC 7380

1 INTRODUCTION

2MASS J22472238+5801214 was identified as a Be star (category 4B) in the H α emission-line star survey by Kohoutek & Wehmeyer (1997) who found strong H α emission in the spectra superposed on a moderate continuum. On the other hand Corradi et al. (2008) identified this candidate as a D-type symbiotic binary from the IPHAS H α emission-line survey. This classification was based on the observed near-IR and H α excess, from the location in $(r - i)$ vs $(r - H\alpha)$ and $(J - H)$ vs $(H - K_s)$ color-color diagrams. Symbiotic systems are interacting binaries with a white dwarf (WD), a cool giant and an emitting nebula, created by the photoionizing flux from the WD and collision of the winds (Angeloni et al. 2007). Symbiotic D-type candidates are separated from S-type candidates based on the continuum excess in the 1–4 μ m spectral region (Webster & Allen 1975). If the companion belongs to an F/G giant class rather than a Mira variable one, the system is designated as D' type (Allen 1982). The spectra of symbiotic binaries are characterized by the presence of

high ionization lines and Raman scattered OVI emission lines in addition to low ionization metallic absorption lines and molecular bands.

Apart from the Be classification of Kohoutek & Wehmeyer (1997) and the D-type symbiotic classification of Corradi et al. (2008), the possibility of this object belonging to the Herbig Ae/Be (HAeBe) category was also suggested by Mathew et al. (2008). This star was detected in emission in the young cluster NGC 7380 during the survey of emission-line stars in young open clusters and cataloged as NGC 7380(4).

In all forthcoming text we use the designation 2MASS J22472238+5801214 or NGC 7380(4) equivalently. The object's classification as HAeBe was discussed by Mathew et al. (2010) based on the following characteristics. The object showed near-IR excess of ~ 1 mag in extinction corrected ($J - H$) versus ($H - K$) color-color diagram. The star was also found to be located in the position occupied by HAeBe stars in the $H\alpha$ equivalent width (EW) versus ($H - K$) diagram, which is conventionally used to separate Classical Be (CBe) and HAeBe stars.

It is thus seen that there is some uncertainty about the true nature of the object which should desirably be resolved. We attempt to do this by undertaking an in-depth analysis of the object proper, and also its environment, by using photo-spectroscopic and imaging data. We believe that we are able to make a secure classification of the object's nature in the present work. In addition it is also shown that the source is fairly interesting, by virtue of being associated with a high velocity outflow, and worthy of further studies.

A few words on the physical environment of the target object in the present study may be appropriate. Massey et al. (1995) identified this star as a member of the young open cluster (~ 2 Myr) NGC 7380 (star no: 2249) with visual magnitude $m_V = 14.72$, color excess $E(B - V) = 0.64$ and distance 3.6 kpc. The star is located away from the cluster center and associated with pre-main sequence stars. The star is less than 0.25 Myr from a pre-main sequence (PMS) isochrone fitting in the V versus ($B - V$) color magnitude diagram (Mathew et al. 2010). The target NGC 7380(4) is associated with a relatively large ($\theta = 25'$) and evolved HII region Sharpless 142 (S142; Roy & Joncas 1985). The main source of ionization is an O6 spectroscopic binary DH Cep, which is also a member of the cluster NGC 7380. The region is quite complex, showing association with an HI cloud and molecular cloud NGC 7380E (see fig. 1 in Chavarria-K. et al. 1994).

2 OBSERVATIONS

The spectroscopic observations were done using the HFOSC (Himalayan Faint Object Spectrograph Camera) available with the 2.0 m Himalayan Chandra Telescope (HCT), operated by the Indian Institute of Astrophysics, India. The CCD used for imaging was a $2\text{ K} \times 4\text{ K}$ CCD, where the central 500×3500 pixels were used for spectroscopy. The pixel size was $15\ \mu\text{m}$ with an image scale of 0.297 arcsec/pixel. The spectra were taken using a Grism 7 ($3800\text{--}6800\ \text{\AA}$) and $167\ \mu\text{m}$ slit combination in the blue region which gave an effective resolution of $10\ \text{\AA}$ near the $H\beta$ line. The spectra in the red region were taken using a Grism 8 ($5500\text{--}9000\ \text{\AA}$) and $167\ \mu\text{m}$ slit setup, which gave an effective resolution of $7\ \text{\AA}$ near the $H\alpha$ line. The spectra were found to have good signal to noise ratio (≥ 100). The HFOSC was also used in imaging mode to obtain a broad band ($6300\text{--}6740\ \text{\AA}$) $H\alpha$ image of the source and its environment.

JHK photometric observations of the object were made from Mt. Abu Infrared Observatory on 2010 October 21 using the 256×256 NICMOS3 imager-spectrograph. The procedure for the near-IR photometric observations and the subsequent reduction and analysis of data followed a standard procedure described e.g in Banerjee & Ashok (2002). All spectroscopic and photometric data were reduced and analyzed using IRAF tasks. A consolidated log of the observations is given in Table 1.

Table 1 Journal of Observations

Object	Date of Observation	Mode of Obs.	Specifics
NGC 7380(4)	2010-12-05	H α imaging	exp. 60 s, field 10' \times 10', HFOSC, 2.0 m HCT
	2010-12-05	H α imaging	exp. 40 s, field 2' \times 2', HFOSC, 2.0 m HCT
	2010-10-05	Spectroscopy	Grism 7/1671, exp. 1200 s, HFOSC, 2.0 m HCT
	2010-10-05	Spectroscopy	Grism 8/1671, exp. 1200 s, HFOSC, 2.0 m HCT
	2010-10-21	<i>JHK</i> photometry	NICMOS3, 1.2 m Mt. Abu
Nebulosity	2010-12-05	Spectroscopy	Grism 8/1671, exp. 2400 s, HFOSC, 2.0 m HCT

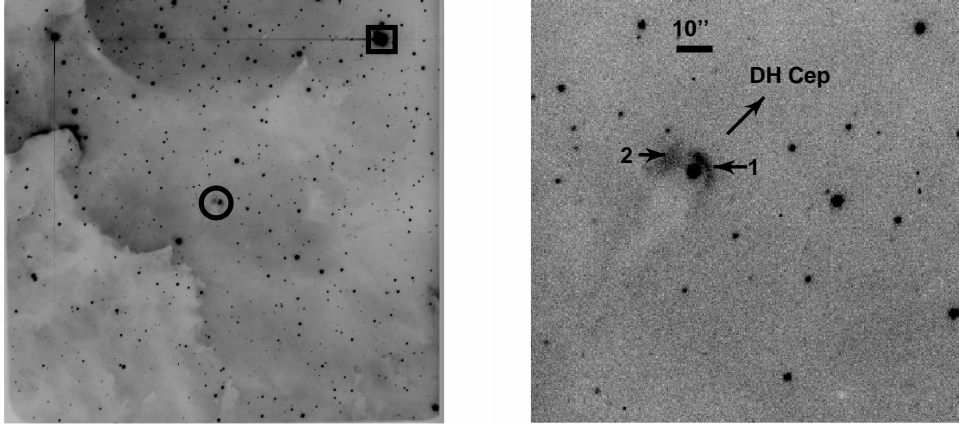


Fig. 1 Left panel shows a 10' \times 10' field around the object of interest obtained with an H α broad band filter. NGC 7380(4) and DH Cep are shown surrounded by a circle and square respectively. The right panel shows a zoomed image (2' \times 2') of the nebulosity around NGC 7380(4). In both panels, north is to the top and east to the left. More details are given in Section 3.1.

3 RESULTS

3.1 H α Imaging: A Nebulosity Around the Object

The H α image of the region and an enlarged section around the star are shown in the left and right panels of Figure 1 respectively. A nebulosity is clearly seen around the object whose principal features consist of a diffuse patch (feature 2) and a bow-shock shaped structure (feature 1) very close to the star. The bow shaped structure looks like a cometary globule (cometary nebula) with the apex, as expected in these objects, oriented towards the photoionizing source which in this particular case is DH Cep. Cometary globules are potential sites of induced star formation due to compression by ionization or shock fronts, created by the influx of UV radiation from the massive exciting star. Ikeda et al. (2008) found six H α emission stars near the tip of the cometary globule BRC 37, which are formed due to the sequential star formation triggered by O-type stars HD 206267 and HD 206183. Sugitani et al. (1991) cataloged 44 bright rimmed clouds with IRAS point sources, which are possible candidates for star formation by radiation-driven implosion. Our candidate was not listed in the catalog even though S142 was identified, which is seen as a bright rim to the left of the object in the 10' \times 10' field (Fig. 1).

Negueruela et al. (2007) studied triggered star formation in NGC 1893, which is similar to NGC 7380 in terms of age and star formation activity. From H α imaging and slitless spectroscopy

they identified a Herbig Be star SIR2N35 in the immediate vicinity of cometary nebula Sim 130 (a striking image of this cometary nebula is shown in the above work). Also one can see a bow shaped structure and nebulosity associated with this region which are triggered by nearby massive stars. This shows that the presence of a Herbig Be star in the vicinity of a cometary globule is possible and supports an HAeBe classification for NGC 7380(4).

3.2 Spectroscopy of the Source

The optical spectrum of NGC 7380(4) is presented in Figure 2. All the lines are seen in emission and absorption features, if any, are not prominent. Hydrogen lines of the Balmer and Paschen series are all in emission; it may be noted that the higher order lines of these series are usually seen in absorption in the spectrum of Be stars. The $H\alpha$ line is the most intense ($EW \sim -100 \text{ \AA}$) in the spectrum with broad wings extending from 6530 to 6595 \AA . The other prominent lines seen are due to CaII, neutral lines of NaI and KI, permitted and forbidden lines of OI, [SII], a few lines of HeI and a large number of lines from FeII. Line identification is largely based on the detailed list of lines typically seen in the spectra of HAeBe stars presented in Hernández et al. (2004). Several weak features in the spectrum of Figure 2 remain unidentified. Comparison of their wavelengths with atomic line lists suggests that many of them could be due to FeI. However, a secure identification is difficult to arrive at and for the present study we leave them as unidentified.

Table 2 presents the prominent lines seen in the spectra along with the equivalent widths which have typical measurement errors of around 5 to 10%. In the case where lines were blended, we employed a deblending procedure involving the fitting of multiple gaussians to the observed profile. The equivalent widths of the individual gaussians were then estimated. Lines with uncertain identification are marked with a question mark in the first column of Table 2.

An interesting aspect of the spectra is the evidence of a fast outflow as inferred from the behavior of the forbidden lines of [SII] $\lambda\lambda$ 6716/6731 and [OI] $\lambda\lambda$ 6300/6364. The presence of these forbidden lines in the spectra of HAeBe stars, and in their lower mass counterparts - the classical T Tauri stars (CTTS), has long been used to infer the presence of jets/outflows since such lines arise only in low

Table 2 Emission Lines in NGC 7380(4)

Element	λ (\AA)	EW (\AA)	Element	λ (\AA)	EW (\AA)	Element	λ (\AA)	EW (\AA)
CaIK	3933	-19.1	H β	4861	-18.3	H α	6563	-100.1
CaII/HI	3970	-6.5	FeII(42)	4924	-3.6	HeI	6678	-0.7
FeI ?	4063	-4.1	FeII(42)	5018	-3.1	[SII]	6716	-0.6
H δ	4101	-5.4	FeII(42)	5169	-5.6	[SII]	6731	-1.4
FeI ?	4130	-3.2	FeII(49)	5198	-3.9	HeI	7065	-0.4
FeII(27,28)	4176	-5.5	FeII(49)	5235	-2.8	FeII	7712	-1.0
FeII(27)	4233	-1.8	FeII(49)	5276	-5.4	OI	7772	-2.1
TiII(41)	4313	-1.2	FeII(48,49)	5317	-4.2	Pa21	8374	-0.8
H γ	4340	-6.6	FeII(49)	5326	-1.5	Pa20/FeI	8387	-2.2
FeII(27)	4352	-3.9	FeII(48)	5338	-2.4	Pa19	8413	-0.9
HeI+FeII(27)	4385	-1.2	FeII(48)	5363	-1.7	OI	8446	-9.7
TiII(19)	4395	-0.9	FeII(55)	5535	-0.6	Pa17	8467	-2.4
FeII(27)	4417	-1.8	HeI	5876	-1.6	CaII	8498	-34.3
HeI	4471	-1.9	NaI	5890/96	-0.9	CaII	8542	-33.5
FeII(37)	4491	-1.9	FeII(74)	6149	-0.9	Pa14	8598	-2.1
FeI/FeI ?	4519	-2.6	FeII(74)	6238	-0.5	CaII	8662	-29.0
FeII(38)	4549	-3.5	FeII(74)	6248	-1.3	FeI	8688	-2.0
FeII(37,38)	4584	-2.6	[OI]	6300	-3.3	Pa12	8750	-3.3
FeII(38)	4621	-2.6	FeII(40)	6433	-1.4	MgI	8806	-1.1
FeII(37)	4629	-3.6	FeII(74)	6456	-1.4	FeI	8824	-1.0
FeI(37)	4667	-1.0	FeII(40)	6516	-1.9	Pa11	8862	-4.1

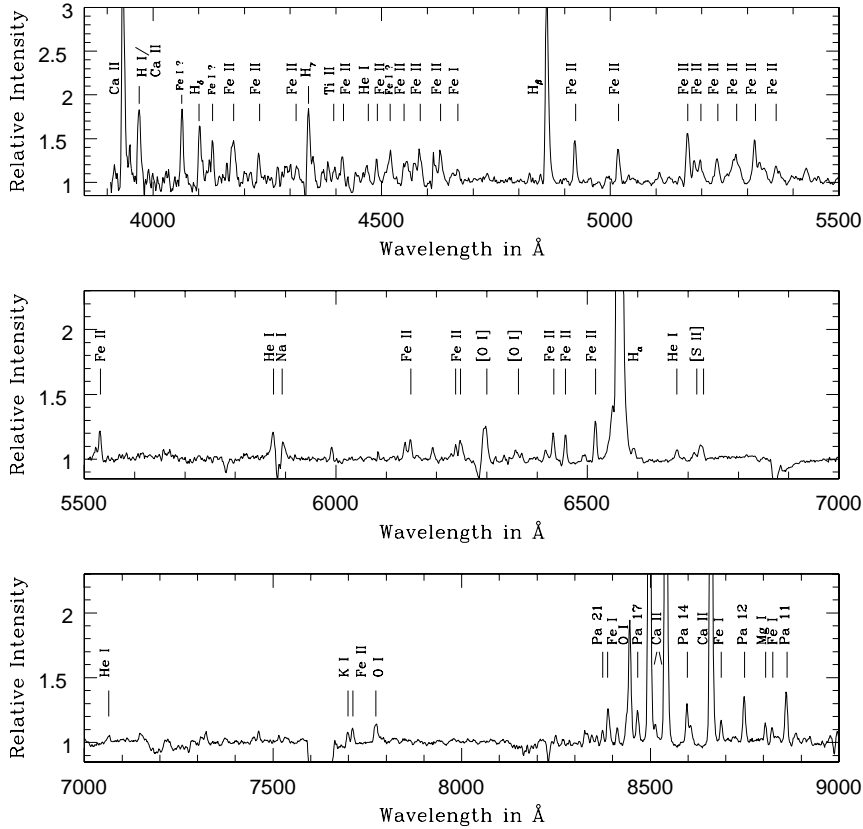


Fig. 2 Optical spectrum of NGC 7380 between 4000–9000 Å taken on 2010–10–05. The prominent lines are identified.

density conditions and hence are tracers of low density material (Finkenzeller 1985; Corcoran & Ray 1998; Appenzeller et al. 1984).

Figure 3 shows a magnified section of the spectra around the forbidden lines showing these lines to be blue shifted by ~ 4 to 5 Å whereas other lines in the spectrum are seen at their expected wavelengths. The measured mean blue-shift for the $[\text{SII}]\lambda\lambda 6716/6731$ lines is $215 \pm 50 \text{ km s}^{-1}$ while that for the $[\text{OI}]\lambda 6300$ line is $176 \pm 50 \text{ km s}^{-1}$. Thus there is evidence for the presence of a high velocity outflow emanating from the star. The ratio of the emission strengths of the $[\text{SII}]$ doublet (6716/6731) is around 0.42 indicating that the electron density is close to (or greater than) $\sim 10^4 \text{ cm}^{-3}$ if a temperature of 10 000 K is assumed (Osterbrock & Ferland 2006; Canto et al. 1980). Such a value of the electron density is slightly on the higher side compared to HII or nebular regions; but similar values have been observed in certain parts of a similar $[\text{SII}]$ outflow emanating from the HAeBe star LkH α 233 (Corcoran & Ray 1998). It may be noted that the absorption feature seen to the left of the $[\text{OI}]\lambda 6300$ line, giving it an apparent P-Cygni structure, is actually a Diffuse Interstellar Band.

The CaII triplet (8498 Å, 8542 Å, 8662 Å) lines are blended with the Paschen lines Pa16, Pa15 and Pa13 respectively. The contribution of these Paschen lines is estimated by interpolating the strengths of the isolated adjacent Paschen lines Pa17, Pa14 and Pa12 and removed from the CaII

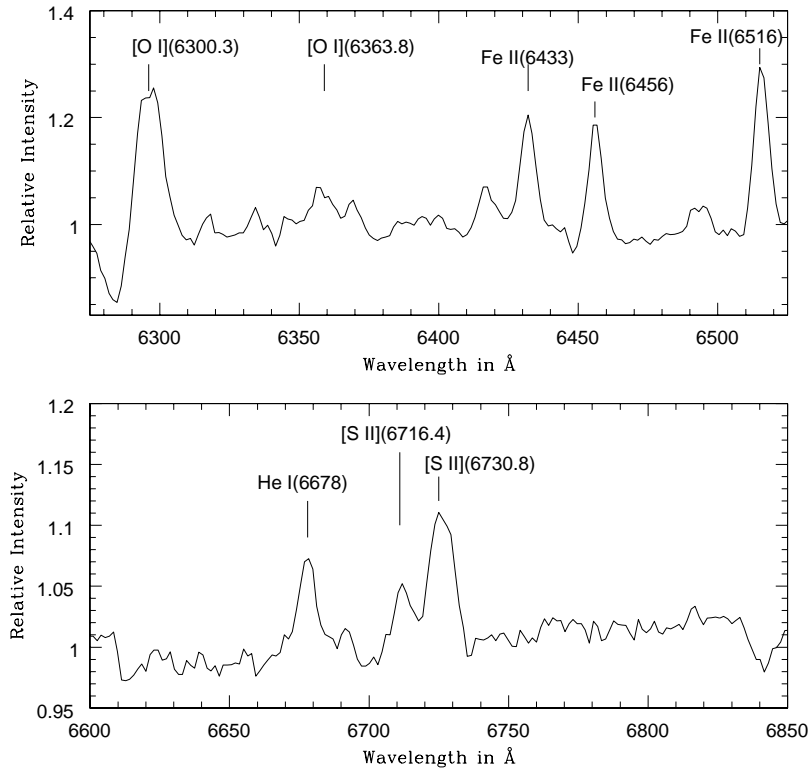


Fig. 3 [O I] $\lambda\lambda$ 6300, 6364 and [S II] $\lambda\lambda$ 6716, 6731 line profiles observed in the object.

triplet line strengths. From these corrected equivalent width values, the relative strength of triplet lines are found to be in the ratio 1.0 : 0.98 : 0.84. This is vastly different from the expected strengths of 1 : 9 : 5, which is the ratio of their respective gf values. This implies that the Ca triplet lines are subject to large optical depth effects. It may be noted that the intensity of the 8498 Å line is greater than the 8542 Å line, which is a unique characteristic of PMS stars (Hamann & Persson 1992).

Could NGC 7380(4) be a symbiotic star? Based on the examples of well-studied and widely accepted symbiotic objects Belczyński et al. (2000) adopted the following spectral criteria to classify an object as a symbiotic star: (i) the presence of absorption features of a late-type giant like TiO, H₂O, CO, CN, or VO bands as well as Ca I, Ca II, Fe I, or Na I absorption lines; (ii) the presence of strong emission lines of H I and He I and either emission lines of ions with ionization potential of at least 35 eV like [O III] or high ionization lines from [Fe VII] $\lambda\lambda$ 5721, 6086, He II $\lambda\lambda$ 4686, 5411 and Ca V λ 6086 (Corradi & Giammanco 2010); (iii) the presence of the Raman scattered 6825 Å emission feature. Schmid (1989) identified Raman scattered O VI lines (6825 Å and 7082 Å) in the spectra of symbiotic binaries, which are not observed in other astrophysical objects. These lines are produced by Raman scattering of the O VI $\lambda\lambda$ 1032/1038 resonance lines by neutral hydrogen. Since none of these criteria are met in the case of NGC 7380(4) it is unlikely to be a symbiotic star. Further, the attributed association of the star with a young cluster whose age is 2 Myr indicates it to be a young object; symbiotic stars are relatively more evolved systems as implied by the presence of a WD as one of the components.

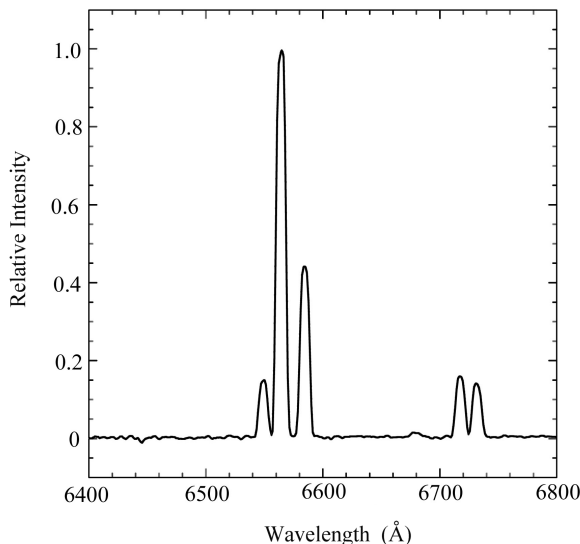


Fig. 4 Spectrum of the nebulosity feature 2 marked in Fig. 1. The prominent lines seen are [NII] $\lambda\lambda$ 6548, 6583; H α and [SII] $\lambda\lambda$ 6716, 6731. HeI λ 6678 is also weakly seen.

A spectrum (5500–9000 Å) of the nebulosity (feature 2 in Fig. 1) was taken with the slit positioned along NS (PA = 0°) and an exposure time of 2400 s. The spectrum is typically nebular with a weak continuum, which barely registers above the dark counts of the detector, with the prominent lines being [NII] $\lambda\lambda$ 6548/6583, H α and [SII] $\lambda\lambda$ 6716/6731. This part of the spectrum is shown in Figure 4. Very few additional lines are seen and these are HeI $\lambda\lambda$ 5876, 6678, [OI] λ 6300 and an unidentified line at 7136 Å (possibly [ArII]). It is possible that this nebulosity could be partially a reflection nebulosity and partially an ionized region. The observed [SII] (6716/6731) ratio of 1.16 in the nebulosity implies an electron density in the range ~ 100 – 150 cm^{-3} assuming a temperature of 10 000 K. It is difficult to be certain whether the region is shock ionized or photo-ionized by the UV flux from DH Cep. In shock ionization, low-ionization lines like [SII] $\lambda\lambda$ 6716/6731 are much stronger with respect to H α than in typical photoionized HII regions (Osterbrock & Ferland 2006; Hartigan et al. 1994; the H α to SII[6717 + 6731] ratio can be around unity). For a representative comparison, Osterbrock & Ferland (2006) listed line intensities in the Orion nebula (photoionized) and a shock ionized filament in Cas A. The observed I(H α)/I(6716) ratio is about 90 in the former and 2.6 in the latter. In our case I(H α)/I(6716) has a value of ~ 6.4 , closer to that expected in a shock-ionized region. Thus a part of the [SII] emission seen in the nebulosity may arise from a shock. However, a deeper study of this region is desirable, to draw firmer conclusions.

3.3 Spectral Energy Distribution

The photometric data spanning the optical to mid-infrared spectral region are presented in Table 3. These data are used to construct the spectral energy distribution (SED), which is shown in Figure 5. It should be noted that the optical, near-IR and mid-IR observations are done at different epochs. The two sets of near-IR measurements separated by ten years do not show noticeable variability. The reddening corrections were done using relations from Rieke & Lebofsky (1985) with $E(B - V) = 0.64$ (Massey et al. 1995). The SED shows a clear IR excess and the IR luminosity is significantly

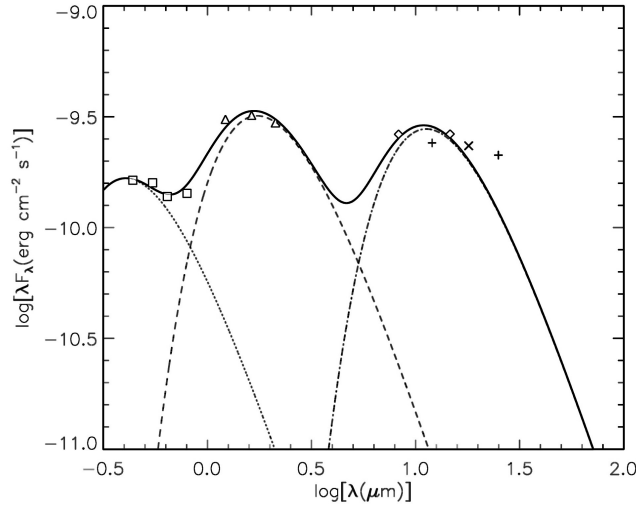


Fig. 5 Spectral energy distribution of the source is shown using the data in Table 3. *BVRI* points are shown in squares, *JHK_s* in triangles, MSX in diamonds, AKARI in crosses and IRAS in ‘+’ symbols. Blackbody fits at temperatures of 9100 K (*dotted* line), 2100 K (*dashed* line) and 300 K (*dot-dashed* line) are shown along with their co-added sum which is shown by a solid line.

Table 3 Available Optical-IR Photometric Measurements

Source	Wavelength/band	Flux/mag
NOMAD	<i>B</i>	15.69
Massey et al. (1995)	<i>V</i>	14.72
IPHAS	<i>R</i>	14.00
	H α	12.85
	<i>I</i>	12.95
2MASS (Mt. Abu)	<i>J</i>	10.80 (10.88)
	<i>H</i>	9.76 (9.71)
	<i>K_s</i>	8.85 (8.75)
MSX6C	8.28 μm	0.73 Jy
	14.65 μm	1.29 Jy
IRAS	12 μm	0.96 Jy
	25 μm	1.77 Jy
AKARI	18 μm	1.40 Jy

larger than the optical luminosity. This is a typical characteristic of HAeBe stars belonging to the Group II class (Hillenbrand et al. 1992). The SED of Group II objects is interpreted in terms of a spherical envelope and regarded as the precursors to HAeBe stars with a circumstellar disk. We have fitted multiple blackbodies to identify different components in the SED. The multiple blackbody fit suggests the presence of a hot component with a temperature of ~ 9100 K and two additional components likely to be associated with dust, with temperature of ~ 2100 K and ~ 300 K respectively. However, the use of an appropriate radiative-transfer code like DUSTY is necessary, which is beyond the scope of this paper, to properly estimate the physical parameters of the dust envelope surrounding the central star.

3.4 HAeBe Nature of the Candidate

Herbig (1960) classified HAeBe stars on the basis of the following criteria: (a) the spectral type is A or earlier, with emission lines, (b) the star lies in an obscured region, and (c) the star illuminates a fairly bright nebulosity in its immediate vicinity. Waters & Waelkens (1998) modified the above definition and removed the constraint of an associated nebulosity by considering the fact that isolated HAeBe stars are also seen, which were identified from the IRAS far-IR all sky survey. Hence they propose the present working definition of HAeBe stars as: (a) spectral type A or B with emission lines, (b) infrared (IR) excess due to hot or cool circumstellar dust or both, and (c) luminosity class III to V. In the following discussion we have analyzed the merits of NGC 7380(4) as an HAeBe candidate.

As explained in Section 3.2, the spectra of NGC 7380(4) show emission lines. The estimation of spectral type from spectroscopy is not possible since absorption lines of hydrogen and helium are absent. Thus, if the spectral class is to be identified even in a very broad sense, we have to take recourse to photometric data. Using several stars in the cluster, Massey et al. (1995) estimated the distance of the cluster to be 3732 pc and also estimated a mean reddening to be $E(B - V) = 0.64$. Using this value of the reddening and an apparent magnitude $m_V = 14.72$ for the object, an absolute magnitude of $M_V = -0.12$ was derived. This would correspond to a B8 – B9 spectral type if it is of luminosity class V and B9 – A0 if it is of luminosity class III (Schmid-Kaler 1982). However, there is likely to be a variation in the intra-cluster reddening as shown by Massey et al. (1995) whose sample of stars showed a variation in $E(B - V)$ between 0.52 to 0.86. Therefore, using the mean value of $E(B - V) = 0.64$ could lead to errors in estimating the absolute magnitude and hence the spectral type of the star. Thus, the photometric data broadly suggest that NGC 7380(4) is a late B or early A type star, which is in line with the requirement for it to be an HAeBe star. From its SED we identified IR excess in this star, which is considered as a defining property of HAeBe stars. The star is also associated with a nebulosity whose presence further strengthens the HAeBe classification of the object. The spectroscopic support for such a classification has already been discussed.

4 SUMMARY

We have presented a study of the object NGC 7380(4) (equivalently 2MASS J22472238+5801214) whose classification was hitherto uncertain. The star is shown to satisfy many of the characteristics of HAeBe stars viz. a similar spectrum, association with a star forming region, an SED showing an infra-red excess that is expected of this category of stars, the presence of a surrounding nebulosity and a suggested young age by virtue of being associated with the young cluster NGC 7380. It is thus strongly suggested that the object is an HAeBe star rather than a D-type symbiotic or a Be star. We find spectroscopic evidence, based on the forbidden lines of [SII] and [OI], for the interesting presence of a $200 \pm 50 \text{ km s}^{-1}$ high velocity outflow originating from the star. From $H\alpha$ imaging, a nebulosity is clearly seen around the object whose principal features consist of a diffuse patch (east of the star) and a bow-shock shaped structure typical of a cometary nebula. The apex of this cometary nebula is seen to point towards the star DH Cep which is believed to be the hot photoionizing source of this region. Such an orientation of the cometary nebula towards the ionizing source is generally seen in other similar objects.

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