Detection of the spectral binary (SB2) nature of BD$-$6$^\circ$1178

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Abstract BD$-$6$^\circ$1178 identified with the infrared source IRAS 05238$-$0626 is shown for the first time to be a spectroscopic binary (SB2) by analyzing the high-resolution spectra taken with the NES echelle spectrograph of the 6-m telescope. The components of the binary have close spectral types and luminosity classes: F5 IV–III and F3 V. The heliocentric radial velocities are measured for both components at four observing moments in 2004–2005. Both stars have close rotation velocities, which are equal to 24 and 19 km/s. We do not confirm the classification of BD$-$6$^\circ$1178 as a supergiant in the transition stage of becoming a planetary nebula. BD$-$6$^\circ$1178 probably is a young pre-MS stars. It is possibly a member of the 1c subgroup of the Ori OB1 association.

1. Introduction

In this paper we continue to publish the results of our spectroscopy of stars with IR excesses (see [1] [2] [3] [4] [5] and references therein for the main results). BD$-$6$^\circ$1178 is an optical component of the infrared source IRAS 05238$-$0626 (with galactic coordinates l=208.9$^\circ$, b=21.8$^\circ$). This object is considered to be a candidate to protoplanetary nebula (PPN) according to the observed excess of radiation in the 12–60 $\mu$m wavelength region and its position on the IR colour–colour diagram [6] [7] [8]. Recall that according to modern concepts (see, e.g., [9]), objects observed at the short-lived evolutionary stage of a young planetary (protoplanetary) nebula are intermediate-mass stars evolving away from the asymptotic giant branch (AGB) toward the stage of a planetary nebula. The initial main-sequence (MS) masses of these stars lie in the 3–8 $M_\odot$ mass interval. During the AGB stage these stars have lost much mass in the form of a powerful stellar wind, and as a result, at the PPN stage the stars have the form of degenerate carbon-oxygen nuclei with typical masses of about 0.6 $M_\odot$ surrounded by expanding gas-and-dust shell. The astronomers are interested in studying PPNs, first because they allow one to study stellar-wind driven
mass loss and second, because they offer a unique opportunity of observing the result of the stellar nucleosynthesis, mixing, and dredge-up of products of nuclear reactions that occurred during the preceding evolution of the star.

About a dozen objects overabundant in heavy metals synthesized via neutronization of iron nuclei under the conditions of low neutron density (s-process) have been found among the PPN-candidate studied. An analysis of the properties of PPNs showed that the expected overabundances of s-process elements are observed only the atmospheres of C-rich stars whose IR spectra contain an emission at 21 µm \[1, 5, 10, 11\]. However, the overwhelming majority of PPNs exhibit neither carbon (O-rich stars) nor heavy-element overabundance (see, e.g., \[1, 12, 13\]). The correlation found between the excess of heavy elements in the star’s atmosphere and the peculiarity of the IR spectrum of the envelope of the star remains unexplained and hence a further increase of the sample of PPN objects studied is needed.

Currently, we know little about BD−6°1178. Its sky coordinates for the epoch of 2000 are: \(\alpha=05^\text{h}26^\text{m}19.8^\text{s}, \delta=−6°23'57''\). The \(V\)- and \(B\)-band apparent magnitudes are equal to \(V=10.52^m\) and \(B=10.96^m\) \[8\]. Some evidence for the photometric variability of the star was found: according to the NSVS catalog \[14\], the mean magnitude of the star in a close-to-\(R\)-filter passband varies in the interval 10.78–10.87\(^m\) and its standard deviation is about 0.01\(^m\). Modeling of the spectral energy distribution based on the multicolor photometry in the visual and near IR yields effective-temperature values \(T_{\text{eff}}\) ranging from 8000 K \[6\] to 7400 K \[8\], which corresponds to late A — early F-subclasses.

As for spectroscopic observations, only low-resolution (≈5 Å/pixel) spectra have been published so far for BD−6°1178. These spectra yielded the following estimates for the spectral type: F2II \[7\], F4 \[15\], and F5 \[16\]. In view of the aforesaid, it becomes evident from these results that further detailed study of the optical spectrum of the star is needed. In this paper we report the results of our numerous high-resolution spectroscopic observations of BD−6°1178 made with the 6-m telescope of the Special Astrophysical Observatory of the Russian Academy of Sciences (SAO RAS). The aim of this study is to perform two-dimensional spectral classification, search for spectroscopic variability, analyze the velocity field in the star’s atmosphere and envelope, and refine its evolutionary status. In Section 2 the methods of observation and reduction are described; in Section 3 we present and analyze the observational data obtained, and in Section 4 we briefly sums up the main results.

2. Observations and analysis of the spectra

We obtained our spectral material for BD−6°1178 using NES echelle spectrograph \[17\] mounted in the Nasmyth focus of the 6-m telescope of the SAO RAS. Observations were performed with a large-format 2048 × 2048 CCD and with an image slicer \[17\]. The spectroscopic resolution is equal to 60000. We use the modified \[18\] ECHELLE context of MIDAS package to extract the data from two-dimensional echelle spectra. We remove cosmic-ray hits using median averaging over two spec-
tra taken in succession. Wavelength calibration is performed using the spectra of a hollow-cathode Th-Ar lamp. We computed the radial and rotational velocities obtained from these spectra by superimposing direct and mirror-reflected line profiles and listed them in Table 1. We controlled the instrumental mismatch between the spectra of the star and those of the hollow-cathode lamp by the O$_2$ and H$_2$O telluric lines. Residual systematic errors do not exceed the measurement errors (about 1 km/s for a single line).

3. Results and discussion

3.1. Spectroscopic Binarity

Our main result is that we are the first to find that BD−6°1178 is a spectroscopic binary. This is a double-line spectroscopic binary with narrow and easy-to-separate lines. It is evident from Table 1 that the maximum offset between the spectra of the components we recorded is equal to about 120 km/s, which exceeds the line width at least by a factor of five. The two companions have rather close depths of absorptions in their spectra and hence rather close spectral and luminosity classes. We consider the primary companion to be the star with slightly deeper and wider absorption features (their central depths, widths, and equivalent widths exceed the corresponding parameters of the absorption features of the secondary companion on the average by 8%, 25%, and 35%, respectively). Figure 1 shows the fragments of the spectra in the vicinity of the D2 NaI line for various observational dates. The heliocentric radial velocities of the interstellar components are equal to $V_r = 4$ and 20 km/s.

Differential shifts can be seen only for the H$\beta$ and H$\alpha$ lines. For H$\beta$ the shifts are small and they may be due to the blending of wide components; in the spectrum taken on 24.09.05 the velocities of the H$\beta$ absorption components are equal to 87 and −20 km/s, and the spectrum taken on 13.11.05 the velocity of the core of the unsplitted absorption is equal to 26 km/s. In case of H$\alpha$ splitting disappears — possibly because of the more complex shape of the component profiles. In the spectral interval recorded in our observations it is the only line where emission is possible. Otherwise it is difficult to explain the well-marked difference between the profiles of H$\alpha$ and H$\beta$ (see Fig. 2), which differ little from each other in the spectra of normal F-type stars (as it is evident, e.g., from high-resolution spectral atlases [19, 20].

We have no spectra containing both these lines, but we can compare their profiles in close phases: the H$\alpha$ profile of 9.03.04 and the H$\beta$ profile of 24.09.05. In Fig. 2 the two profiles are superimposed and the vertical line indicates the adopted $\gamma$-velocity of the system ($V_{sys} \approx 25$ km/s). Both components show up conspicuously on the H$\beta$ profile of 24.09.05 and their contribution to the total profile differ more than the corresponding contributions for other lines. The first profile ($V_r = 87$ km/s) is deeper than the second one ($V_r = −20$ km/s) by 22%. The H$\alpha$ profile of 9.03.04 is asymmetric: absorption in its red half is much stronger than in the blue half. Only the first component (its radial velocity is 75 km/s) can be clearly seen, it is
deeper than the corresponding component of H\(\beta\) line; the second component possibly contains emission, which rises to the continuum level at \(V_r \approx -130\ \text{km/s}\).

The two-dimensional spectral classification of F-type stars is rather complex. Our observational material can be used to perform it by comparing the intensities of the lines of neutral metals and their ions. We constructed the calibrating curves for the line pairs (\(\text{FeII} 4731/\text{FeI} 4737, \text{FeII} 4924/\text{FeI} 4921, \text{et al.}\) using the high-resolution spectra from the atlas of Klochkova et al. [20] and of the ELODIE.3 library [21]. Figure 3 shows, by way of an example, the dependence of the ratio of the central depths of absorptions on spectral type and luminosity class for the \(\text{FeII} 4924\) and \(\text{FeI} 4921\) lines pair.

The \(\text{FeII}/\text{FeI}\) absorption depth ratios, like those found in the spectrum of BD\(−6°1178\), are observed in the interval of MK–classes from F4V to G0I. However, the color index of BD\(−6°1178\) (B–V \(\approx 0.44–0.47\)) restricts the spectral type of the star: it cannot be later than F6 V–III or F7 II–I, and therefore the supergiant option has to be rejected. This is also evident from the low-resolution spectrum of BD\(−6°1178\) reported by Reddy and Parthasarathy [7]: the blend of the IR oxygen triplet OI 7774 Å in this spectrum is much weaker than in the spectra of F-type supergiants. Our spectrum taken on 13.11.05 (at a phase close to the conjunction of the components) yields a mean spectral type of F5 IV for the entire system, other spectra yield somewhat later type and higher luminosity for the primary compared to the secondary: F5 IV–III and F3V, respectively. Interstellar extinction is weak, and that’s the case not only for BD\(−6°1178\) (it does not exceed 0.15\(^m\)), but also for the neighboring stars. With interstellar extinction and the binary nature of the star taken into account, its heliocentric distance can be estimated at about 450 pc.

One would expect the spectrum of a post-AGB supergiant to exhibit anomalous equivalent widths for the chemical elements whose abundances are subject to change in the course of stellar evolution. This concerns, first and foremost, elements of the CNO group and heavy metals whose nuclei are synthesized during slow neutron-\(\text{He}^6\)\(\Rightarrow\text{He}^3\)\(\text{He}^3\+\text{n} \Rightarrow\text{He}^4\text{He}^4\)\(\text{He}^4\text{He}^4\)\(\text{He}^4\)\(\text{He}^4\)+n\(\text{He}^4\). However, we found no important differences between the spectrum of BD\(−6°1178\) and those of unevolved stars of similar spectral types. To illustrate this point, in Fig. 3 we compare fragments of the spectra of BD\(−6°1178\) and Procyon (F5 IV–V) containing the BaII \(\lambda 5853\) Å and CI \(\lambda 5380\) Å lines. We thus obtain an additional corroboration for our spectral classification of BD\(−6°1178\) as a system consisting of low-luminosity stars.

3.2. The Evolutionary Status of BD\(−6°1178\)

We already mentioned the scantiness of published data for BD\(−6°1178\). We now also point out the inconsistency of published estimates of the distance to the star and its evolutionary status: Fujii et al. [8] classify BD\(−6°1178\) as a post-AGB star at a distance of about 10 kpc, whereas Suarez et al. [15] classified it as a young star based on optical low-resolution spectra. Our estimate of the distance to this pair—about 450 pc—agrees with the results of Suarez et al. [15].
Garcia-Lario et al. [22] obtained and analyzed near-IR photometry for an extensive sample of 225 sources including IRAS 05238−0626. They found that in the (H-K, J-H) color–color diagram IRAS 05238−0626 lies in a domain populated mostly by post-AGB stars. However, this domain may also contain young stars of the T Tau and Herbig’s Ae/Be types. This result led the above authors to conclude that the evolutionary status of IRAS 05238−0626 is uncertain: it may be either post-AGB or T Tau star.

In Table 4 of Fujii et al. [8], which gives the parameters of 26 candidate to PPN objects, IRAS 05238−0626 source stands out because of its rather high effective temperature and low mass-loss rate. The latter fact is inconsistent with the source’s location in domain IV on the van der Veen-Habing IR color-color diagram [23]. The above authors [23] define this domain as the locus of variable stars with high mass-loss rate and producing a powerful circumstellar shell. Moreover, IRAS 05238−0626 also differs from typical PPN by its low IR flux. The λ12μm flux of this source is F12=0.59 Jy, which is one to one-and-a-half orders of magnitude lower than the corresponding fluxes of such well studied post-AGB objects as IRAS 04296+3429 (F12=12.74 Jy), IRAS 23304+6147 (F12=8.56 Jy), and IRAS 07331+0021 (F12=15.32 Jy).

Reddy and Parthasarathy [7] analyzed a sample of 14 candidate PPN objects including BD−6°1178 and concluded that BD−6°1178 is a highly evolved post-AGB star where a cooled-down remnant of the circumstellar shell can be observed. The above authors adopted a stellar-core mass typical of post-AGB stars—0.6 $M_\odot$—to obtain a high luminosity estimate $\log(L/L_\odot) = 3.79$ and, consequently, large heliocentric distance (7 kpc) for the star. Note that Reddy and Parthasarathy [7] pointed out the absence of sources of molecular emission to be associated with BD−6°1178, whereas post-AGB stars are typically characterized by thermal and maser emission of CO, SiO, H$_2$O, and other molecules (see references in the reviews by Kwok [24] and Klochkova [10]). For example, the IR sources IRAS 04296+3429 and 23304+6147 mentioned above are powerful sources of CO emission [25]. Moreover, the presence of molecular features, which replace each other in the course of evolution of the PPN, allowed Lewis [26] to trace the chronological sequence of molecular spectra in stars at different stages of post-AGB evolution.

In view of the facts mentioned above and the results of our spectral classification, we suggest that the spectral binary BD−6°1178 (F5 IV–III + F3V) may be a young object of the Galactic disk. Note that its coordinates and its heliocentric distance of about 450 pc allow us to suspect that BD−6°1178 may be a member of the Ori OB1 association. According to the list of distances to stellar associations based on Hipparcos data [27], subgroup 1c in the Ori OB1 association is located at a heliocentric distance of 506±37 pc. Note also that the adopted $V_{\text{sys}}$ and measured velocities for the NaI(1) interstellar-line components are consistent with the velocities (15–28 km/s) adopted from the SIMBAD database for 19 stars located within 2.5° of BD−6°1178 within the heliocentric-distance interval 0.2–0.7 kpc.
Earlier Torres et al. [16] while analyzing a sample of candidate to T Tau-type stars included BD−6°1178 to their sample. They analyzed the spectroscopic and photometric data and found a total of 17 and 13 T Tau and Herbig’s He/Be stars, respectively. However, the above authors could not place BD−6°1178 into either of the two groups and classified it as “miscellaneous”-type object. On the whole, we see no reasons to classify BD−6°1178 as a post-AGB star. Note also that the detection of the spectroscopic binarity of SB2-type provides further evidence to doubt the classification of BD−6°1178 as a post-AGB star because there are no SB2-type binaries among the known stars at the evolutionary stage considered. A number of post-AGB stars are SB1-type binaries. The nature of the unseen companion is unknown, because its spectral features do not show up in the spectra of post-AGB binaries. HD 101584 may serve as an example of a well-studied post-AGB binary [28]. This system contains a hot B9 II-type post-AGB star and a low-mass companion of unknown nature. It may be either a white dwarf or a low-mass MS star [28].

4. Conclusions

The results of our quantitative spectral classification of BD−6°1178 led us to conclude that it is a double-line spectroscopic binary. Both components are F-type stars: F5 IV–III + F3V. We measured the heliocentric velocities of both components of the binary at four time moments. We found no grounds to classify BD−6°1178 as a post-AGB star. The coordinates of BD−6°1178 and its heliocentric distance 450 pc allow it to be suspected of a membership in the Ori OB1 association. Thus BD−6°1178 may be a young pre-MS object of the Galactic disk.

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Table 1. Log of the observations of BD−6°1178, average heliocentric radial velocities \( V_r \) for both components; the corresponding rotational velocities \( V \sin i \) are given in parentheses.

| Date       | JD 2453+ | \( \Delta \lambda, \lambda \) | \( V_r (V \sin i), \text{km/s} \) |
|------------|----------|-------------------------------|----------------------------------|
|            |          |                               | 1-component | 2-component                 |
| 9.03.04    | 074.2    | 5300–6770                     | 85 (24)     | −36 (18)                    |
| 18.01.05   | 389.2    | 5300–6770                     | −20 (24)    | 66 (19)                     |
| 24.09.05   | 637.5    | 4190–5520                     | 84 (24)     | −34 (20)                    |
| 13.11.05   | 688.4    | 4560–6010                     | 21 (25:)    | 33: (−)                     |
Figure 1. Comparison of the spectra of BD−6°1178 in the vicinity of the D2 NaI line. The arrow on the spectrum of 18.01.05 indicates a telluric emission feature. The vertical dashed line indicates the adopted systemic velocity, $V_{sys} \approx 25$ km/s.
Figure 2. Profiles of the Hα (9.03.04) and Hβ (24.09.05, the thin line) lines. The vertical dashed line shows the adopted systemic velocity of $V_{\text{sys}} \approx 25 \text{ km/s}$.
Figure 3. Dependence of the ratio of central absorption depths, $R(\text{FeII}4924)/R(\text{FeI}4921)$, on spectral type and luminosity class. The filled circles, open circles, and crosses correspond to luminosity classes V, IV-III, and II-I, respectively. The dashed line shows the depth ratio for BD$−6°1178$ at the phase of component conjunction on 13.11.05.
Figure 4. The BaII $\lambda$5853 Å and CI $\lambda$5380 Å lines in the spectra of BD–6°1178 (13.11.05, thick line) and Procyon (the thin line).