A Study of the B[e] Star AS 160

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Abstract:

We present the results of our study of the poorly known B[e] star AS 160 = IRAS 07370– 2438. The high-resolution spectrum obtained with the 6-m BTA telescope exhibits strong emission in the Hα line with a two-component profile, indicating that the gaseous envelope of the star is non-spherical. Previously nonanalyzed photometric data suggest the presence of a compact dust envelope. The fundamental parameters of the star (log $L/L_\odot = 4.4 \pm 0.2$, $v \sin i = 200$ km s^{-1}) and its distance (3.5 ± 0.5 kpc) have been determined for the first time and are in agreement with published estimates of the MK spectral type of the object (B1.5 V:). Analysis of the object’s properties leads us to suggest that this is a binary system that belongs to our recently identified type of Be stars with warm dust.

Keywords: *stars—properties, classification.*

Article:

INTRODUCTION

B[e] stars represent a group of B-type stars whose spectra exhibit emission lines (including forbidden ones) along with large near-infrared (1–5 μm) continuum excesses. Sixty-five such objects were first identified by Allen and Swings (1976) in the Milky Way. They noted a correlation between the presence of forbidden lines and the presence of infrared excesses and offered three possible explanations of this phenomenon: the formation of a planetary nebula, the interaction of a hot star with a late-type companion, and direct mass ejection from a massive star. Subsequent studies of B[e] stars indicated that objects at known and well-studied evolutionary stages (young Herbig Ae/Be stars, luminous blue variables (LBVs), symbiotic stars, protoplanetary and planetary nebulae (Miroshnichenko 1998a)) constitute almost half of the initial list. However, until recently about 30 B[e] stars have been studied inadequately and their evolutionary status has been unclear.

We began to investigate individual B[e] stars with an uncertain status in the mid-1980s by using longterm series of multicolor photometric observations (Bergner *et al.* 1995) and low-resolution spectra (Miroshnichenko 1995). These investigations revealed photometric variability in most of the objects studied and no photospheric lines in their spectra. In addition, we found that a large group of B[e] stars with very strong emission-line spectra occupies an unusual position in the IRAS color–color diagram. Such colors ($-0.5 \leq \log(F_{25}/F_{12}) \leq 0.1$, $-1.1 \leq \log(F_{60}/F_{25}) \leq -0.3$, where F_{12}, F_{25}, and F_{60} are the fluxes from the object in the IRAS photometric bands at 12, 25, and 60 μm, respectively) are typical of dust envelopes around cool stars or envelopes without dust hotter than ~200 K. Our subsequent studies of stars from this group (which presently contains 19 objects and which we call Be stars with warm dust) have led us to conclude that these are fairly evolved objects most of which are interacting binaries. The latter accounts for the presence of a large amount of circumstellar matter (see Miroshnichenko *et al.* 2002a). Although these objects share common properties, each of them is individual. Therefore, we present the results of our investigation either for individual objects or for small groups of them.

In this paper, which is a continuation of our series of papers including Miroshnichenko *et al.* (2000, 2001, 2002b, 2002c), we present our photometric and spectroscopic observations of the B[e] star AS 160 from the list of Allen and Swings (1976). An emission-line spectrum of the star was discovered during a spectroscopic survey of the sky at the Mount Wilson observatory (Merrill and Burwell 1950). *UBV* and *HKL* photometry was obtained by Drilling (1991) and Allen (1973), respectively. Infrared radiation from the object was detected by the IRAS and MSX satellites. Based on data published by then, Lamers *et al.* (1998) concluded that the evolutionary status of AS 160 could not yet be determined. Cidale *et al.* (2001) provided spectrophotometry of the star in the wavelength range 3500–4600 Å. They found its spectral type from the Balmer discontinuity to be B1, while its luminosity class (V) was determined unreliably, which does not add information on the nature of the object. The IRAS colors ($\log(F_{25}/F_{12}) = -0.09$, $\log(F_{60}/F_{25}) = -0.71$) allow us to include AS 160 in the group of Be stars with warm dust in their envelopes.

Table 1. The IRTF infrared photometry for AS 160

HJD	*K*	*L*	*M*	*N*
2451599.92	7.54 ± 0.02	5.84 ± 0.02	5.50 ± 0.05	2.88 ± 0.02

OBSERVATIONS

Infrared *KLMN* photometry of AS 160 was obtained on February 24–25, 2000, with a germanium– gallium bolometer attached to the 3-m IRTF NASA telescope (Mauna Kea, Hawaiian Islands, USA). The observations were carried out with a 10″ aperture; the background was subtracted at a distance of 15″ in the north–south direction with a frequency of 11 Hz. Four 20-s exposures were taken in each photometric band. The results were reduced to Johnson's broadband photometric system using standard stars from the IRTF list (HR 2574, HR 2943, HR 3314, and HR 3903).

Spectroscopy of the star was obtained on the night of November 30/December 1, 2001, with the LYNX echellè spectrometer (Panchuk *et al.*, 1999) attached to the 6-m BTA telescope in the wavelength range λ5030–6680 Å with a resolution of $\lambda/\Delta\lambda = 25\,000$. Two 53-min exposures were taken sequentially to reliably remove cosmic-ray particle hits. Observations of this star with such a resolution have been obtained for the first time. The mean signal-to-noise ratio in the continuum is close to 50.

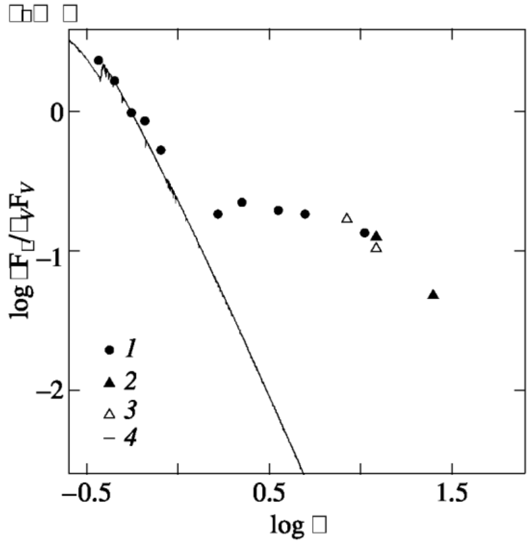

Fig. 1. The spectral energy distribution of AS 160 corrected for reddening: *1*—ground-based photometry; *2*—IRAS data; *3*—MSX data; *4*—theoretical SED for $T_{\rm eff} = 20\,000$ K and $\log g = 4.0$ (Kurucz 1994).

RESULTS

Our infrared photometry for the star (see Table 1) confirms the presence of a large infrared excess, which was discovered by Allen (1973) in the early 1970s. The excess is clearly variable, because, while the results match in the *L* band, our magnitude estimate in the *K* band is 25% fainter than Allen's estimate, which significantly exceeds the accuracy of the two measurements (~2%). The flux at λ = 12 μm measured by the IRAS satellite in 1983 exceeds the flux measured by the MSX satellite in 1996 by roughly the same amount (see Fig. 1). On the other hand, our result for the *N* (10.4 μm) band is in excellent agreement with the IRAS data. Since only two infrared magnitude estimates at different wavelengths are available for the object, we cannot discuss the causes of its variability. We can only say that this picture is typical of other Be stars with warm dust (Miroshnichenko *et al.* 2002b), as is the spectral energy distribution (SED) of AS 160 in general (Fig. 1). In particular, its SED is almost identical to the SED of Hen 3–1398, one of the hottest stars in this group (Miroshnichenko *et al.* 2001). The large infrared excess of AS 160 cannot be explained by the free–free emission from circumstellar gas alone. ISO spectroscopic observations indicate that circumstellar dust is present in the envelopes of such objects (Waters *et al.* 1998). At the same time, the rapid decrease in the observed flux toward longer wavelengths, starting from λ = 10 μm, suggests that the dust envelope is compact. It may have formed recently.

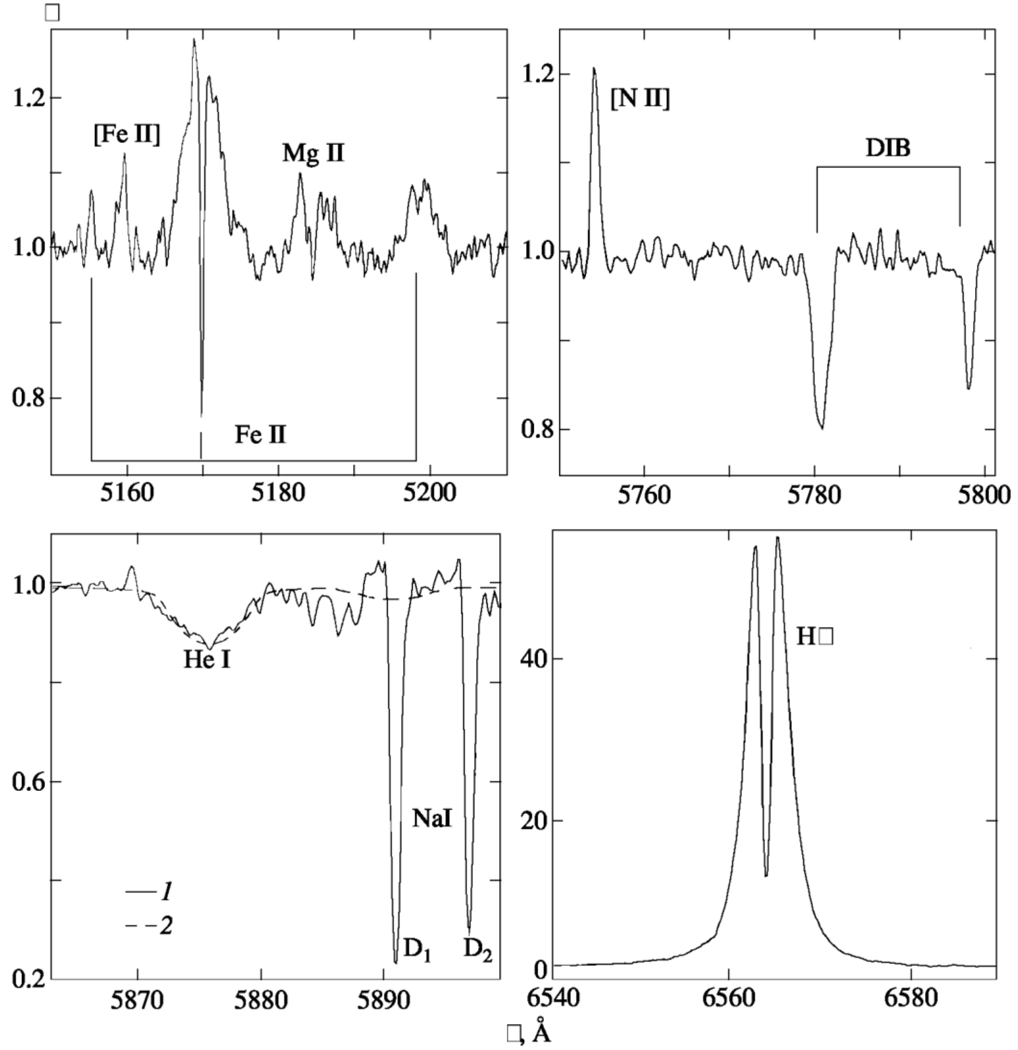

Fig. 2. Portions of the spectrum for AS 160: (*1*) the observed spectrum reduced to the local continuum; and (*2*) the theoretical spectrum computed with the SYNSPEC code (Hubeny *et al.* 1995) for $T_{\rm eff} = 20\,000$ K, $\log g = 4.0$, and $v \sin i = 200$ km s^{-1}. The shallow absorption features in the spectrum with the He I and Na I D$_{1,2}$ lines are telluric.

The lines that we identified in our high-resolution spectrum of AS 160 are listed in Table 2. The spectrum contains mostly permitted and forbidden emission lines of singly ionized iron and diffuse interstellar bands (DIBs). The Balmer spectrum is represented by a strong Hα line. The only detected line of neutral helium, λ5876 Å, has a purely absorption profile. No lines of ionized helium, for example, λ5412 Å, were detected. The state of the helium lines indicates that the spectral type of the object is not earlier than B1, because neutral helium in hotter B[e] stars is usually observed in emission. The observed absorption profile of the λ5876 Å line agrees with its theoretical profile for an effective temperature $T_{\rm eff}$ = 20 000 K, log *g* = 4.0, and *v* sin *i* = 200 km s^{-1} (see Fig. 2). Since there are no other photospheric lines in the observed spectral range, we cannot estimate the fundamental parameters of the star more accurately. However, the result presented above agrees with previously published data (Drilling 1991; Cidale *et al.* 2001).

The optical photometry of AS 160 obtained by Drilling (1991) and its spectrophotometry by Cidale *et al.* (2001) suggest that this is a moderately reddened early-B star. Assuming that the reddening is mainly interstellar (see the discussion below), we can estimate its value from the observed color index B — $V = 0^{m}.48$ (Drilling 1991) and the normal color B — $V = -0^{m}.25$ for the corresponding spectral type (Strajzhys 1977), $AV = 2^{m}.3$. Approximately the same value, $AV = 2^{m}.5 + 0^{m}.3$, can be obtained from the intensities of the DIBs observed in the object's spectrum (Herbig 1993).

The kinematic distance to AS 160 can be estimated from the mean iron-line velocity (+62.0 ± 2.5 km s^{-1}), which is commonly taken as the center-of-mass velocity of the star–envelope system (Humphreys *et al.* 1989), by using the calibration of Dubath *et al.* (1988). The result 3.5 ± 0.2 kpc agrees with the object's position in the Carina arm and gives an estimate of the visual absolute magnitude, $M_V = -4^{m}.1 \pm 0^{m}.1$, for the observed visual magnitude of the star $V = 10^{m}.94$ (Drilling 1991) and $AV = 2^{m}.3$. The derived luminosity corresponds to the MK spectral type B 1.5 III–IV (Strajzhys and Kuriliene 1981), which is in agreement with the remaining data on the star given above. Taking the bolometric correction $BC = -2^{m}.2$ (Miroshnichenko 1998b), we obtain the luminosity $\log L/L_\odot = 4.4 \pm 0.1$. The interstellar reddening law toward AS 160 determined by Neckel and Klare (1980) indicates a linear and slow increase in A_V to ~1^{m} as the distance from the Sun increases to ~3 kpc followed by its sharp increase at distances of 3–3.5 kpc, which is consistent with our kinematic distance estimate.

Table 2. The lines identified in the spectrum of AS 160

Line	λ, Å	I/I_c	RV_{em}, km s^{-1}	RV_{abs}, km s^{-1}	EW, Å
Fe II (35)	5154.50	1.05	67.1	–	0.07
[Fe II] (19F)	5158.81	1.14	60.7	–	0.10
Fe II (42)	5169.03	1.28	63.0	62.9	1.43
Mg I (2)	5183.60	1.10	62.2	68.0	0.29
Fe II (49)	5234.62	1.17	63.5	63.5	0.44
Fe II (48)	5316.78	1.37	52.5	58.3	2.68
[Fe II] (19F)	5333.65	1.09	59.9	–	0.06
[Fe II] (34F)	5746.96	1.07	63.0	–	0.04
[N II] (3F)	5754.80	1.23	52.6	–	0.22
DIB	5780.41	0.80	–	47.7	0.45
DIB	5797.03	0.83	–	50.2	0.17
DIB	5849.80	0.93	–	48.4	0.06
He I (11)	5875.63	0.88	–	6.4	0.75
Na I (1)	5889.95	0.25	–	47.1	0.75
Na I (1)	5889.95	0.18	–	60.9	
Na I (1)	5895.92	0.23	–	47.6	0.66
Na I (1)	5895.92	0.33	–	60.4	
DIB	6195.96	0.90	–	42.8	0.07
DIB	6203.08	0.94	–	37.9	0.10
DIB	6269.73	0.93	–	47.7	0.08
DIB	6283.85	0.82	–	46.2	0.76
[O I] (1F)	6300.30	2.72	61.4	–	1.90
Fe II ()	6317.99	1.15	59.3	–	0.40
Si II (2)	6347.10	1.12	59.6	–	0.57
[O I] (1F)	6363.78	1.52	60.5	–	0.63
Si II (2)	6371.36	1.08	63.2	–	0.04
DIB	6379.29	0.81		45.8	0.27

H (1)	6562.82	55.70	63.0	53.2	235.30
[N II] (1F)	6583.45	1.23	61.3		0.20
DIB	6613.56	0.79		52.9	0.30

Note. ***The chemical element (with an indication of the multiplet number) or the interstellar band with which a given spectral feature is identified are listed in column 1; the laboratory wavelengths are listed in column 2; the intensities, in units of the adjacent continuum, are listed in column 3; the heliocentric radial velocities of the emission and absorption line components are listed in columns 4 and 5, respectively (measured by matching the erect and inverted profiles in velocity space); and the equivalent widths are listed in column 6 (measured for the line as a whole).***

The deep sodium lines (λ5889 and 5895 Å) split up into two components with radial velocities of +47 and +61 km s^{-1}. This splitting is almost invisible on the scale of Fig. 2, because the components are close. The position of the blue component coincides with the mean DIB radial velocity, while the position of the red component is close to the mean radial velocity of the emission lines in the spectrum. The blue component probably originates in the Carina spiral arm, suggesting that the object is far from the Sun, while the red component originates in the circumstellar medium. The absence of the component associated with the local spiral arm can be explained by the low density of the interstellar medium, which is confirmed by a small increase in the reddening of stars with distance in this direction up to the Carina arm (Neckel and Klare 1980).

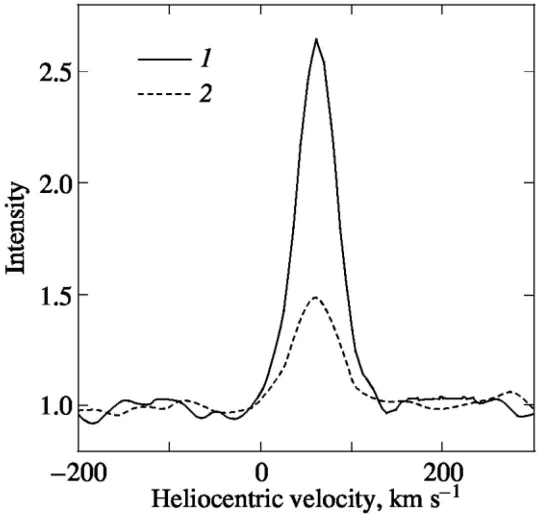

Fig. 3. Profiles of the oxygen forbidden lines in the spectrum of AS 160 at λ6300 Å (*1*) and 6363 Å (*2*). The velocities are given on the heliocentric scale; the intensities were reduced to the local continuum.

DISCUSSION

We determined the kinematic distance to AS 160 and its error by assuming that the metal-line velocities reflect the object’s velocity in its Galactic orbit (in other words, the peculiar velocity is low) and that the Galactic rotation curve toward the object has no significant systematic errors. The above distance dependence of interstellar reddening determined by Neckel and Klare (1980) indicates that these assumptions are valid. It shows that the lower limit of the distance to AS 160 cannot be less than 3 kpc. Otherwise, much of the object’s reddening would be circumstellar. Below, we show that this is unlikely. In addition, since the object is close to the Galactic plane ($b = -1°.4$), the reddening will be higher than the observed one when it is farther (~4 kpc or more). This will give rise to new components in interstellar lines that are unobservable in the object’s spectrum. These considerations allow a more realistic distance estimate of 3.5 ± 0.5 kpc to be obtained, which also slightly increases the error in the luminosity estimate, $\log L/L_{\odot} = 4.4 \pm 0.2$. The equal velocities of the emission and absorption components in metal lines (and forbidden lines), indicating that both the emission and absorption features originate in the envelope, confirm the interpretation of their mean velocity as the velocity of the system. In addition, the kinematic distances estimated for other similar objects observed in different directions under this assumption are generally in good agreement with the distances calculated from their spectroscopic parallaxes (Humphreys *et al.* 1989; Miroshnichenko *et al.* 2000, 2001, 2002b).

The above distance estimate for AS 160 agrees with the interstellar reddening estimate provided that the circumstellar reddening is low. It can be shown that the effect of the object's gas–dust envelope on its optical SED is actually small. The emission-line profiles in the spectrum of AS 160 have either one or two peaks. In the latter case, the peaks are separated by a distinct absorption component. Such profiles are characteristic of nonspherical gaseous envelopes in the shape of highly flattened disks (Hummel and Vrancken 2000). In this case, the symmetry plane of the AS 160 envelope is inclined to the line of sight in such a way that we see it almost edge-on, but the optical depth on the line of sight is small. This orientation is evidenced by the absence of completely absorption Fe II line profiles and by the fact that only one line exhibits an absorption component with the minimum intensity below the continuum level (Fig. 2).

The symmetric emission profiles of the optically thin oxygen forbidden lines (Fig. 3) also indicate that the envelope is highly flattened. Theoretical calculations in terms of the model of an axisymmetric constant-velocity polar wind (Edwards *et al.* 1987) predict such profiles for winds with strong focusing (the wind cone angle is no more than 30°) and with an inclination of the symmetry axis no less than 60° to the line of sight. We do not see double-peaked profiles of these lines, because the spectral resolution of our observations is insufficient. The presence of strong oxygen forbidden lines and weak nitrogen lines (λ6583 Å) makes it possible to estimate the matter density in the formation region of these lines. At a temperature of 10^4 K typical of this region in B[e] stars (Lamers *et al.* 1998), the maximum density at which the collisional and radiative processes become balanced is ~10^6 cm^{-3} for the [O I] λ6300 Å line and ~10^5 cm^{-3} for the [N II] λ6583 Å line (Osterbrock 1989). Thus, the sought-for density must be slightly below 10^5 cm^{-3}.

The absence of an emission or absorption band in the object's spectrum near $\lambda = 10\ \mu$m indicates that the dust envelope is also nonspherical. The flat infrared spectrum in this wavelength range suggests either a large optical depth ($100 \leq \tau \leq 10$), if the envelope consists of silicate grains (Yorke and Shustov 1981), or the presence of predominantly amorphous carbon in the envelope. In the latter case, the optical depth can take on any value, because amorphous carbon has no spectral features near λ10 μm. However, this chemical composition of the envelope suggests that the object has strongly evolved off the main sequence (MS) and that the carbon produced by nuclear reactions in the stellar core has already reached the stellar surface. Since the spectrum of AS 160 contains no lines characteristic of such evolved stars, it would be natural to assume that the circumstellar dust has a nearly interstellar composition. The envelope is then most likely optically thick and nonspherical, with a symmetry axis that does not pass through the line of sight. The infrared excess at wavelengths up to 60 μm accounts for about 1% of the stellar luminosity and is a lower limit for the amount of energy reradiated by the circumstellar dust. This estimate is consistent with the assumption that the dust envelope is optically thick only if it is highly flattened.

The velocity of the He I λ5876 Å line (+6 km s^{-1}) differs greatly from the velocities of the remaining lines and may suggest that the stellar velocity is peculiar. In particular, this difference may result from orbital motion in the binary system. We observed a change in the velocity of this line, while the positions of the emission lines were stable, in other members of the group of Be stars with warm dust (e.g., MWC 657; Miroshnichenko *et al.* 2000), together with other evidence of the binary nature. For example, lines of the late-type star are observed along with emission lines of the hot component in such members of the group as MWC 623 (Zickgraf and Stahl 1989), AS 381 (Miroshnichenko *et al.* 2002b), and V669 Cep (Miroshnichenko *et al.* 2002c). No lines that could be attributed to the secondary stellar component of the system were detected in the spectrum of AS 160.

Assuming that the velocity difference between the helium and metal lines ($\Delta V_r = 57$ km s^{-1}) is comparable to the half-amplitude of the radial-velocity curve for the primary component due to orbital motion, we can roughly estimate the parameters of the possible secondary component. It follows from the derived luminosity and temperature of the primary component (25 000 K; Cidale *et al.* 2001) that its radius is ~10 $R_\odot$. It thus follows that the minimum orbital period of the binary system is ~10 days. With this orbital period, the primary component fills its Roche lobe and the binary component mass ratio is ~3. In this case, distinct eclipses would be observed at the above orbital inclination. In addition, such close (Algol-type) binary systems do not exhibit strong emission-line spectra, because the intrasystem region is too small to accumulate a large amount of circumstellar matter. The eclipsing binary RY Sct with a period of ~12 days and an infrared excess similar to that observed in AS 160 (Smith *et al.* 2002) serves as an example. Therefore, the orbital period of the binary must be longer (possibly, of the order of several months) and the mass ratio must be closer to unity (~2 for a period of two months). Systematic spectroscopic observations for one year could significantly refine the estimates obtained.

The large near-infrared (λ2–10 μm) excess, together with the sharp decrease in the infrared flux toward longer wavelengths, imposes constraints on the possible evolutionary status of the object. For example, AS 160 cannot be at a pre-MS evolutionary stage, because the infrared SEDs for such objects are much flatter and the hot dust emitting in the near infrared dissipates earlier than the cold dust as they evolve toward the MS (Miroshnichenko *et al.* 1996). AS 160 cannot be at a post-AGB evolutionary stage either; i.e., it cannot be a protoplanetary nebula for the following reasons. First, the dust envelopes in such objects are formed at a previous evolutionary stage and their dust temperature is below ~100 K. Second, the luminosity of AS 160 is close to the upper luminosity limit for planetary nebulae (Blöcker 1995). Such objects are rare, because they traverse the entire path from a red giant to a planetary nebula in several tens of years. We have no evidence of any change in the brightness or temperature of AS 160 in the 50 years elapsed since its discovery. In addition, the rotational velocities for objects at such an advanced evolutionary stage are low because of the loss of angular momentum.

The luminosity of AS 160 also indicates that this star is not a supergiant, which can intensely lose its mass at a critical evolutionary stage, showing a strong emission-line spectrum (e.g., LBV-type stars). Nor can it be a Wolf–Rayet star, because its spectrum exhibits no characteristic emission lines of CNO-group elements. For a single star that is not far from the MS, a strong mass outflow is not typical at a relatively low rotational velocity (see above). Classical Be stars are the objects that are most similar to AS 160 in observed properties (Harmanec 2000). However, while the latter have a higher mean rotational velocity, their emission-line spectra are weaker than those of AS 160. In addition, more and more data suggesting that many Be stars (particularly those with strong emission-line spectra) are binary systems have recently appeared (Gies 2000).

Thus, in our opinion, the most plausible explanation for the combination of the object's low luminosity and its strong emission-line spectrum can be mass transfer in a high-mass binary system (Van den Heuvel 1994). The more massive components of such binaries do not go far from the main sequence, whereas their secondary components can have a much lower mass (and/or brightness), with their temperature range being wide. Indeed, among binary Be stars with warm dust, the secondary components are generally fainter than the primary components (B type stars) by 2^m–3^m. At the same time, the secondary components are detected in objects whose envelopes are inclined at a large angle to the line of sight. For example, the plane of the MWC 623 envelope is seen nearly face-on, while the narrow and mainly single- component emission-line profiles of AS 381 and V669 Cep suggest a large inclination of their envelope planes to the line of sight. Thus, it will apparently be difficult to detect secondary lines in the spectrum of AS 160 even at a higher spectral resolution and a higher signal-to-noise ratio. However, the amplitude of the radial-velocity variations due to orbital motion for the observed envelope orientation, which usually coincides with the orbital plane, must be larger for AS 160 than that for the binaries mentioned above.

Modeling the observed characteristics of AS 160 is beyond the scope of our study because of uncertainties in the parameters of the binary system in general (characteristics of the possible secondary component) and its envelope in particular (details of the geometry, sizes, etc.). To address this problem requires further observations, including multicolor photometry, spectroscopy with a higher resolution and a higher signal-to-noise ratio, speckle interferometry, and polarimetry.

CONCLUSIONS

Our new high-resolution spectroscopic observations of the B[e] star AS 160 have allowed its luminosity and distance from the Sun to be reliably determined for the first time. These results agree with previous photometric data and spectrophotometric estimates of the MK type of the object. Our infrared photometry of AS 160 and analysis of (IRAS and MSX) satellite data show that its brightness in the wavelength range λ2–10 μm varied within no more than 20–25% compared to the 1970s–1980s data. The strong emission-line spectrum of the object, together with its peculiar infrared SED (a rapid decrease in the flux toward longer wavelengths from λ = 10 μm), allow us to put AS 160 in the group of Be stars with warm dust that has recently been identified and described by Miroshnichenko *et al.* (2002a). This group is among the few groups of early-type stars that show evidence of circumstellar dust in their envelopes. Our working hypothesis about the nature of such objects is that most of their observed properties can be explained by mass transfer in a binary system. However, the secondary components are difficult to detect because of the large magnitude difference between the components (2^m–3^m). A further study of AS 160 primarily requires spectroscopic observations with a time resolution from several weeks to several months, which can impose constraints on the probable orbital period of the binary system. In addition, a comprehensive investigation using various observing techniques will make it possible to refine the parameters of the circumstellar medium.

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