Research Note

Emission line star 3G71: a Herbig Ae/Be star candidate

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Abstract. We present new optical spectral observations of 3G71, the previously suspected optical counterpart of the hard X-ray source 1H2214+589. The spectra of 3G71 exhibit many forbidden lines, unusually intense H-Balmer emission lines and the approximately B5 spectral type. Such spectral features, together with its large IRAS infrared color excess and associated with nebulosity, provide evidences that the star may be a Herbig Ae/Be star candidate rather than the optical counterpart of Be/X-ray source of 1H2214+589.

Key words: stars: individual: 3G71 – stars: pre-main sequence

1. Introduction

Herbig Ae/Be stars are young objects characterized by strong infrared excess, variable brightness, intrinsic polarization and complex spectral line profiles. Almost all these features are due to the presence of equatorially concentrated non-stable winds and exterior cool stable circumstellar shells. Herbig (1960) was the first to realize that the "Be and Ae stars associated with nebulosity" are in fact stars of intermediate mass still in their pre-main sequence phase of evolution (i.e. stars which have lost most of their envelopes of infalling gas and d ust, but are not yet fusing hydrogen into helium and their energy is mainly supplied by gravitational contraction). The criteria for membership of Herbig Ae/Be stars are (The et al. 1994): (1) spectral types earlier than F8; (2) presence of emission lines; (3) presence of IR-excess in the spectral energy distribution; (4) location in or near a probable star formation region.

The X-ray source of 1H2214+589 was detected with the HEAO-1 satellite both with Large Area Sky Survey (LASS) instrument and the Modulation Collimator (Tuohy et al. 1988). The X-ray flux between 2–10 keV was found to be 1.1×10^{-11} ergs cm^{-2} s^{-1}. 3G71 was tentatively identified as the optical counterpart of the X-ray source (Tuohy et al. 1988), primarily due to its early spectral type and the presence of Hα emission line (Wackerling, 1970). It was believed that 3G71/1H2214+589 was a Be/X-ray binary system consisting of a Be star and a neutron star. As an X-ray binary, 1H2214+589 had been collected in

the X-ray Binaries Catalogue compiled by van Paradijs (1993). However, the proof that 3G71 is a classical Be star associated with the X-ray source is not sufficient, and evidences for the binary characteristics, such as the orbital period and correlated behavior between optical and X-ray outbursts, remain undiscovered. In this paper we will present the results of optical spectroscopy of this interesting object and show that 3G71 is a convincing candidate of Herbig Ae/Be stars instead of a classical Be star.

2. Observations and results

Using a CCD spectrograph attached to the Cassegrain focus of the 2.16 m telescope at Xinglong station of Beijing Astronomical Observatory, Academia Sinica, we have made spectroscopic observations of 1H2214+589/3G71 during our long-term monitoring programme for 12 Be/X-ray binaries and 34 classical Be stars since 1992. The spectra of 3G71 obtained on October 15, 1995 (JD 2450006) are shown in Figs. 1 and 2, with a reciprocal dispersion of 50 Åmm^{-1} and spectral resolution of 1.22 Å pixel^{-1}, covering the wavelength range 5500–6750 Å (Fig. 1) and 4300–5500 Å (Fig. 2), respectively. Data reductions were done with the IRAF package on Sun-4 Work Station. The influence of night sky light on the spectra has been eliminated. As one can see from the spectrum in Fig. 1, it is dominated by the extremely strong, single- peaked Hα emission line. In order to show some weak lines clearly, part of Hα emission line has to be truncated in Fig. 1 due to its too large intensity, while a reduced whole spectrum is appended to the upper left of the figure.

Our observations indicated that the Balmer emission of 3G71, though often highly variable, is still extremely strong. In fact, the peak intensity of Hα emission line relative to continuum changed between 15 and 20, and its equivalent width changed between 75 Å on October 15, 1995 and 103 Å on November 5, 1993 during our programme (Hang & Xia, 1997). The maximum equivalent width is larger than those of the 11 Be/X-ray binaries considered in the work by Reig, Fabregat, and Coe (1997) except He 3–640/A 1118–61 (Coe et al. 1994), which may be slightly larger. The H-Balmer lines exhibit obvious photospheric absorption with wide line wing except Hα line, which is completely filled in by its emission. Although Hβ is also seen in strong emission, with its peak intensity relative to the contin-

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Fig. 1. Normalized line profile of 3G71 on 1995 Oct. 15 in red region. Horizontal scale is wavelength in Å

Fig. 2. Same as Fig. 1 but for blue region

uum reaching 2.5 in 1995, it still shows obvious photospheric absorption. We find a strong asymmetry in the Hβ absorption, that can be due either to an asymmetry in the velocity field or to the presence of weak emission features in its blue wing. The full width at zero intensity of Hβ photospheric absorption profile amounts to 60 Å (see Fig. 2), corresponding to a velocity of about 3700 km s^{-1}.

Some weaker lines of He I can be easily detected, such as He I $\lambda\lambda$4471, 4713, 4921, 5876 and 6678. Among them He I λ5876 is the most prominent line and possesses emissions in its absorption wings.

The following multiplets or strong multiplet components of Fe II emission are visible: (37)- λ4629; (38)- λ4583; (42)- $\lambda\lambda$5169, 5018, 4923; (49)- $\lambda\lambda$5316, 5275; (Z^{4}D^0-C^{4}D)- $\lambda\lambda$6318, 6384. Among them the multiplet (42) is the strongest.

Another distinct feature in the spectra is the appearance of a lot of forbidden lines. [O I] λ6300 and [O I] λ6364 are of considerable intensity, although [O I] λ5577 is not present. In

Table 1. IRAS flux densities and magnitudes of 3G71.

Wavelength(μm)	12	25	60	100
Flux density (Jy)	12.04	12.19	8.379	36.92
Magnitude	1.34	-0.27	-1.80	-4.70

addition, [Fe II] $\lambda\lambda$5527, 4889, 4814, 4415, 4359 and 4304 also appear clearly.

The intensity ratio of absorption lines Mg II 4481 and He I 4471 is about 0.7. This ratio is about 0.7 at B5 and about 1 at B8. The spectral type of 3G71 is approximately assigned as B5.

3. Identification of IRAS infrared counterpart

Usually Be stars have considerable infrared color excess (Johnson, 1967). The special behaviors in spectra of 3G71 encourage us to search for its IRAS point source counterpart. The equatorial coordinates of 3G71 at equinox 1950.0 given by Wackerling's Catalog of Early-Type Stars with Emission Lines (Wackerling, 1970) are 22^h 24^m 47.8^s and + 60° 58′ 59″. But at the exact coordinate position, we could not find any candidate. Within $\pm$ 3 arc-minutes region nearby, there are no stars brighter than V = 16 except a V = 12.2 star and a fainter one (V = 14.1). Further observations by one of the authors (QZL) show that the latter is an F-type star so that it could not be 3G71. Considering the coordinates, the magnitude (V $\sim$ 11) and the behavior of hydrogen emission lines of 3G71, we suggest that the V = 12.2 star should be 3G71. The equatorial coordinates of 3G71 at equinox 1950.0 given by the GSC catalogue are 22^h 24^m 53.37^s and + 60° 58′ 13.1″. Examining IRAS Point Source Catalogue (IRAS Explanatory Supplement, 1985), we found an IRAS point source 22248 + 6058 with coordinates 22^h 24^m 53.8^s and + 60° 58′ 15″ at equinox 1950.0. The differences of position between 3G71 and the IRAS point source counterpart are only 0.4^s in right ascension and 2″ in declination, lying in the uncertainty ellipse of major axis 11″ and minor axis 6″ given in IRAS Point Source Catalogue. Within the uncertainty ellipse there are no other stars brighter than V = 16. Thus we associate the IRAS source with 3G71. The flux densities of 22248 + 6058 in various IR bands quoted from IRAS PSC and its converted magnitudes in the corresponding bands (no correction for interstellar reddening) using the IRAS definition for zero-magnitude are listed in Table 1.

The equivalent widths of the Na I D1 and D2 doublet absorption lines are 0.365 and 0.496 Å, respectively. From the empirical formula between the distances and the average equivalent widths of Na I doublet lines (Allen, 1973), a distance of 0.86 kpc can be deduced. We estimate that the reduction of V magnitude due to interstellar extinction is less than 2 magnitude because the average interstellar extinction is about Av = 1.9 mag kpc^{-1}. By comparing the far-infrared magnitudes listed in Table 1 with the visual magnitude (V = 12.2) of 3G71, it is obvious that this star has a very large infrared color excess.

4. Discussion and conclusions

A B[e] stars is a Be star exhibiting forbidden lines in emission (Jaschek & Jaschek, 1987). The most frequently found forbidden emission lines in B[e] stars are those of [Fe II] and [O I]. The spectroscopic characteristics of 3G71 indicate that it must be a B[e] star. Since B[e] stars are defined by spectroscopic criteria alone, a certain superposition exists between B[e] stars and Herbig Ae/Be stars. Finkenzeller and Mundt (1984) noted that among the some 60 Herbig Ae/Be stars discovered at that time, about 30 % are B[e] stars, so we wonder whether 3G71 is also a Herbig Ae/Be star.

As a kind of special stars, an important criterion of Herbig Ae/Be stars is that there must exist nebulosity around the star, as Herbig (1960) first suggested. To confirm our suspicion, we have made a search for a nebulosity in the immediate vicinity of 3G71 by consulting Palomar Sky Survey map and actually found a bright nebula with a diameter about 1 arc-minute, at whose center 3G71 is just located.

Be stars with peculiar infrared excess can be divided into three classes (Hu and Zhou, 1990), that is, classical Be stars, Be stars associated with star formation region, and Herbig Ae/Be stars. Hu and Zhou (1990) found that for classical Be stars the difference between visual magnitude V and 25 μm infrared magnitude [25] of a star is equal to or less than 5, while for Be stars associated with star formation region and Herbig Ae/Be stars the difference V – [25] is equal to or larger than 7. Furthermore, they pointed out that, one can distinguish stars associated with star formation region from Herbig Ae/Be star candidates, only by judging whether the criterion of flux densities $f_{12} < f_{25} < f_{60}$ is satisfied or not. In the infrared color-color diagram, these three types occupy different parts (Hu and Zhou, 1990). Observations demonstrated two stars (HD 100546 and HD 104237), falling in the Herbig Ae/Be stars region in the infrared color-color diagram, turned out to be good candidates (Hu, The, & de Winter, 1989), and are now accepted as Herbig Ae/Be stars (van den Ancker et al. 1997). 3G71 is largely deviated from the classical Be-star region in both Cote & Waters' (1987) and Hu & Zhou's (1990) color-color diagrams, and its V – [25] equals 12.47, which means that it is not a classical Be star. Moreover, the flux densities do not satisfy the criteria given by Hu and Zhou (1990), and from its position in infrared color-color diagram one can predict that 3G71 should be a Herbig Ae/Be star, so the characteristics in infrared region of the star further illustrate that it is a Herbig Ae/Be star candidate.

According to the analyses mentioned above, the fundamental characteristics of 3G71 coincide completely with the criteria for membership of Herbig Ae/Be stars (The et al. 1994), so we can conclude that 3G71 is a Herbig Ae/Be star candidate.

This result implies that 3G71 might not be the optical counterpart of the hard X-ray source 1H2214+589. Previous identification may be wrong and a further identification is needed. So far, none of about 30 Be/X-ray binaries identified has been found to be Herbig Ae/Be stars or B[e] stars.

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