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An infrared study of Be stars based on ISO SWS01 spectra *

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Abstract The Infrared Space Observatory (ISO) Short-Wavelength Spectrometer (SWS) spectra of 10 Be stars are presented. It can be seen that the Be stars show a diversity in their ISO SWS01 spectral classifications by Kraemer et al., from naked stars, stars associated with dust, stars with warm dust shells, stars with cool dust shells to very red sources. In addition, the Brα/HI(14-6) line flux ratio derived for the sample stars is compared with that of P Cyg, and it is found that the line ratio of Be stars which were investigated show not only lower values as suggested by Waters et al., but also larger values. Therefore, the line ratio cannot be used to judge whether a star is a Be star or not.

Key words: stars: circumstellar matter — infrared: stars — stars: emission-line, Be

1 INTRODUCTION

Be stars are the B-type stars with emission lines; they are commonly defined as nonsupergiant B-type stars whose spectra have, or had at one time, one or more Balmer lines in emission (Jaschek & Egret 1982; Collins 1987), which originate from the extended circumstellar envelope (usually a disk-like geometry) around Be stars. For a review, see Porter & Rivinius (2003).

The infrared spectrum of Be stars is rich in information that can be used to improve our understanding of the circumstellar environment around Be stars. For example, Zhang et al. (2004) used the Infrared Astronomical Satellite Low-resolution Spectra (IRAS LRS) to study Be stars, and obtained a few valuable results.

ISO SWS01 spectra are the full-scan (scanning mode AOT01) spectra observed by the Short Wavelength Spectrometer (SWS, de Graauw et al. 1996) aboard the Infrared Space Observatory (ISO, Kessler et al. 1996). These spectra cover a greater wavelength range than the IRAS LRS ($2.4 - 45.2\,\mu$m compared to $7.7 - 22.7\,\mu$m) and are at a higher spectral resolution ($> 300 - 200$ vs. $20 - 60$). From these SWS01 spectra, the circumstellar environment of Be stars could be better studied.

This paper is organized as follows: Section 2 presents the sample and data reduction; Section 3 describes the spectral features of the individual sources; Section 4 discusses the line flux ratio Brα/HI14–6 derived for the sample stars; and Section 5 summarizes the results of this study.

2 SAMPLE DATA

The Catalogue of Be stars by Jaschek & Egret (1982, 1995, about 1300 in total) contains almost all known galactic Be stars, based on which, Zhang et al. (2005) ruled out the possibility that those are B[e] stars or non B-type stars and presented a catalogue of Be stars in the 2MASS database (1185 in

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total). In this study, we restrict ourselves to those Be stars listed in the paper by Zhang et al. (2005). The main aims of this paper are to identify the ISO SWS01 associations of these Be stars, to obtain the ISO SWS01 spectra for Be stars which are associated with the Highly Processed Data Products (HPDP) of ISO SWS01 from Sloan et al. (2003), and to discuss some properties and environment of Be stars.

Based on the position information given by Zhang et al. (2005), we use a $5''$ searching circle to search for the counterpart of ISO for those Be stars listed in the paper by Zhang et al. (2005). Finally, we obtained 10 Be stars with ISO SWS01 spectra. It is notable that there are three stars (out of these 10 Be stars with ISO SWS01 spectra) that also appear in the Herbig Ae/Be members and candidate members listed by some authors (e.g. Thé et al. 1994; Vieira et al. 2003; Zhang et al. 2006). Because it is very difficult to determine whether these stars are really Be stars or Herbig Be stars, we will study them as Be stars in this paper. Our 10 Be stars with ISO SWS01 spectra are listed in Table 1. The items in the columns of Table 1 are listed as follows: (1) HD number; (2) IRAS name; (3) TDT number; (4) and (5) the RA and Dec. from ISO at the epoch of 2000, respectively; (6) the distance between the position of the Be star and the position of the related 2MASS source in arcsec; (7) ISO SWS01 infrared spectral classification from Kraemer et al. (2002); 8. IRAS LRS classification from Kwok et al. (1997) and (if any) from the LRS Atlas (1986) in parentheses.

Table 1 Be Stars with ISO SWS01 Spectra

Name	IRAS	TDT	RA. (2000)	Dec. (2000)	r (arcsec)	Group	LRS
HD 5394	00536+6026	24801102	00 56 42.38	60 42 59.6	1.15	1.NE	S (18)
HD 10144	01358–5729	17902503	01 37 42.86	–57 14 12.3	0.4	1.N	S (18)
HD 45677	06259–1301	71101992	06 28 17.50	–13 03 10.5	1.29	3.SE	E (24)
HD 90177	10211–5922	24900215	10 22 53.90	–59 37 28.0	0.46	4.Seep	H (05)
HD 94910	10541–6011	22400153	10 56 11.62	–60 27 13.4	0.55	4.Me	
HD 100546	11312–6955	27601036	11 33 25.27	–70 11 42.2	1.24	4.U/sc	H (82)
HD 104237	11575–7754	10400424	12 00 06.04	–78 11 33.9	2.94	4.SE:	E (24)
HD 105435	12057–5026	07200272	12 08 21.48	–50 43 21.0	0.4	1.NE	F(16)
HD 316285	17450–2759	30101147	17 48 14.01	–28 00 53.4	0.47	2.E	U
HD 200775		33901897	21 01 36.77	68 09 48.7	1.25	5.SE	

3 SPECTRAL FEATURES

ISO SWS01 spectra of our sample are plotted in Figure 1.

Some of the spectra presented here have already been studied in great detail, e.g. γ Cas (=HD 5394) in Hony et al. (2000) and HD 100546 in Waelkens et al. (1996). It should be pointed out that 5 stars in the sample, HD 90177, HD 94910, HD 100546, HD 104237 and HD 105435 have two ISO SWS01 observations; in this study we shall use the better one.

According to Kraemer et al. (2002), sources with ISO SWS01 spectra can be classified into seven groups based on the overall shape of the spectrum and thus the temperature of the dominant emitter. Among them, group 1 shows naked stars; group 2 stars are associated with dust; group 3 are warm dusty objects with little or no stellar contribution; group 4 are cool dusty objects; and group 5 shows sources with red spectra rising to 45 μm. Furthermore, Kraemer et al. (2002) use 1–3 letters to identify the dominant spectral features. Among them, N shows naked stars, no molecular bands; NE naked stars with emission lines; SE oxygen-rich dust emission at $10-12$ μm; Me miscellaneous emission; U unidentified infrared emission features dominate the spectrum; SC crystalline silicate emission, especially at longer wavelengths; and E shows that emission lines are the only significant spectral feature. In this section, based on the ISO SWS01 spectral classification from Kraemer et al. (2002), we discuss the spectral features of the sample.

HD 5394 and HD 105435 are naked stars with emission lines. Numerous hydrogen recombination lines appear in the emission.

HD 10144 is a naked star with no molecular bands in its spectrum.

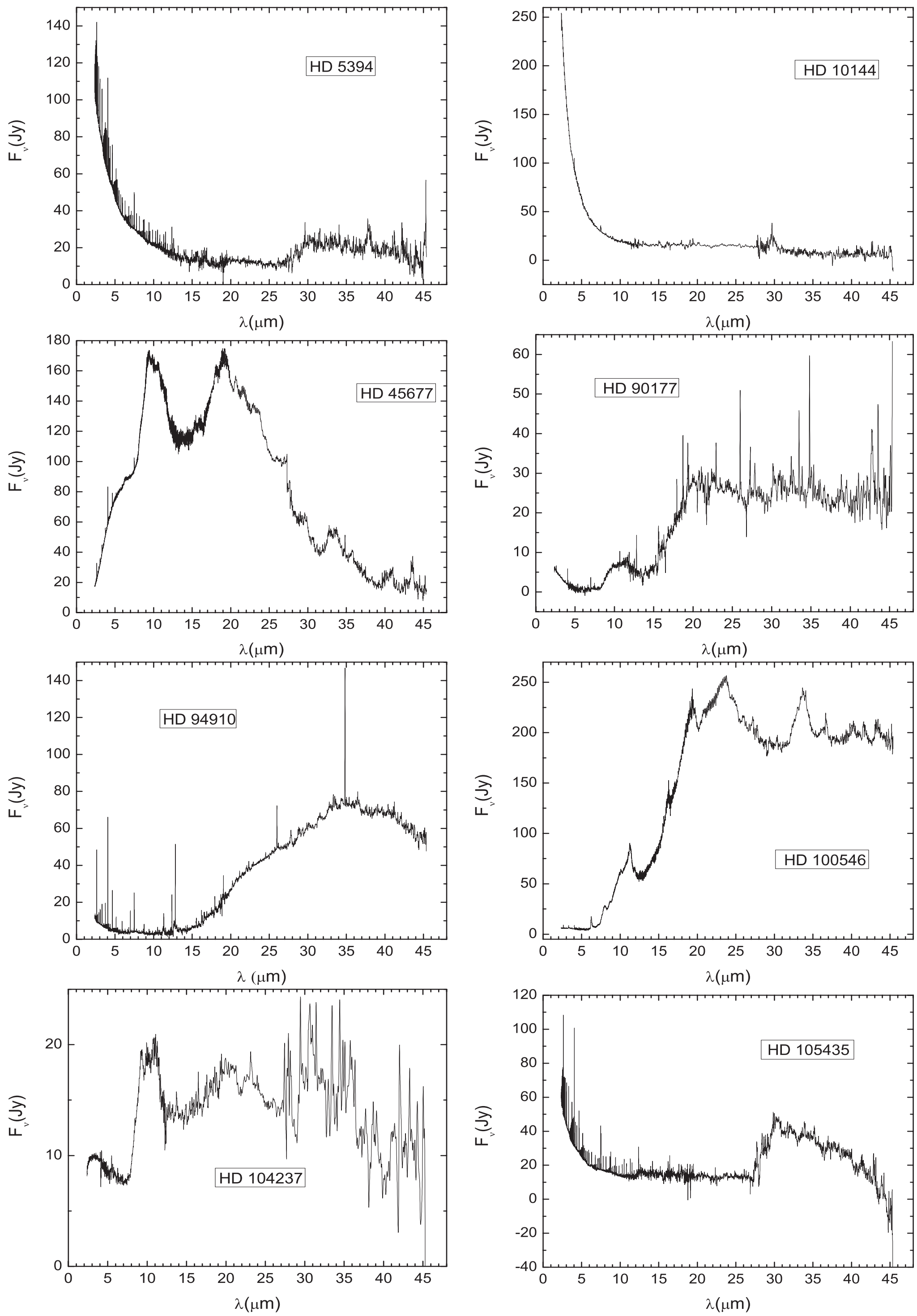

Fig. 1 ISO SWS01 spectra of 10 Be stars.

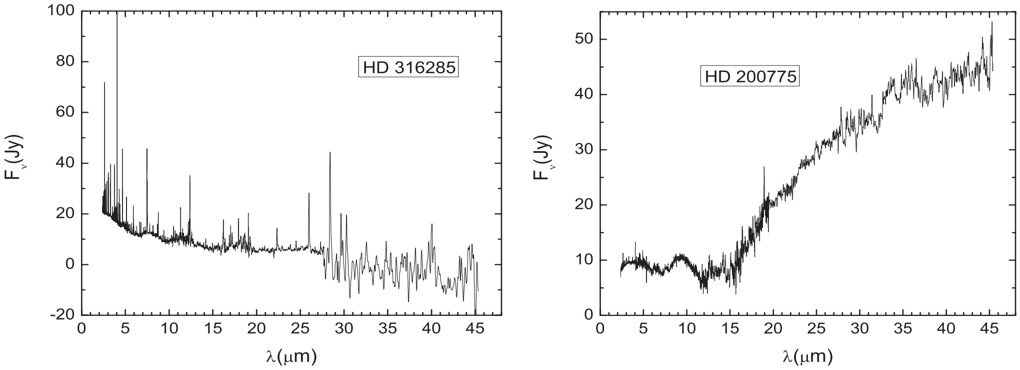

Fig. 1 — *Continued.*

HD 45677 is a warm dusty object with little or no stellar contribution. This star shows silicate or oxygen-rich dust emission at $\sim 10-12\,\mu$m superimposed on the thermal continuum from the dust shell, accompanied by a secondary emission feature at $\sim 18-20\,\mu$m.

HD 90177 and HD 104237 are cool dusty stars. These stars show an emission feature from amorphous silicates (oxygen-rich dust silicate) at $10-12\,\mu$m superimposed on emission from a cool dust shell. Dust emission dominates the spectral energy distribution and the dust temperature is cooler than that in group 3. For HD 90177, the spectrum peaks at $20-25\,\mu$m; for HD 104237, the spectrum peaks near $30\,\mu$m. Furthermore, it seems that the longer part of the spectrum shows a quite flat global shape without clear peaks, suggesting that the emitting dust spans a range of temperatures, e.g. HD 90177 is a luminous blue variable star with a complex circumstellar environment (as shown by Nota et al. 1997).

HD 94910 is a cool dusty star with miscellaneous emission. Voors et al. (2000) studied HD 94910 (=AG Car), based on ground-based imaging and ISO spectroscopy. They concluded that HD 94910 is surrounded by a dust shell with inner and outer radii of 0.37 and 0.81 pc respectively and a total dust mass of 0.25 $M_\odot$.

HD 100546 is a cool dusty star. The unidentified infrared emission features are present and characterize the $2-8\,\mu$m range, but the spectrum is dominated by the dust emission at longer wavelengths. Bouwman et al. (2000) studied HD 100546 (=AB Aur), based on the $2-200\,\mu$m ISO spectrum. They found that the circumstellar dust around HD 100546 shows two distinct regimes in the mass over temperature distributions with temperatures of $\sim 10^3$ and $\sim 10^2$ K.

HD 316285 is a star associated with dust. This star shows emission lines on a photospheric spectral energy distribution.

HD 200775 is a star with a red spectrum rising to 45 μm. This star shows oxygen-rich dust emission at $10-12\,\mu$m.

It can be seen in Table 1 and Figure 1 that three stars, HD 5394, HD 10144 and HD 105435, which occupy 30% of the samples, are in group 1, indicating they are naked stars. One star, HD 316285, is in group 2, indicating it is a dust star. One star, HD 45677, is in group 3, indicating that it has a warm dust shell. Four stars, HD 90177, HD 94910, HD 100546 and HD 104237, which occupy 40% of the sample, are in group 4, indicating that these stars have cool dust shells. One star, HD 200775, is in group 5, indicating it is a very red source. Therefore, Be stars show a diversity in their ISO SWS01 spectral classifications by Kraemer et al. (2002), which is not surprising. It is known that the circumstellar envelop of a Be star can vanish and re-appear in an apparently random fashion (Porter & Rivinius 2003), so Be stars can be expected in different infrared spectral groups.

4 HI LINE FLUX RATIOS

Waters et al. (2000) studied the $3.8-4.1\,\mu$m ISO spectrum of five Be stars and found that for Be stars, the line flux ratio Brα/HI14–6 is much smaller than that of hypergiant P Cyg. Then they suggested that Be stars may be recognized from their infrared spectrum on the basis of HI line ratios. It is noted that star

P Cyg has ISO SWS01 infrared spectral classification 2E, i.e. a dust star with emission lines (Kraemer et al. 2002).

In Figure 2, we plot the ISO SWS01 spectra of our sample in the $3.8 - 4.1\ \mu$m range; the doted line indicates line Brα (4.052 μm) position, the dashed line indicates line HI 14–6 (4.0209 μm) position. All spectra plotted in Figure 2 are taken from Sloan et al. (2003).

In Table 2, we list the calculated line flux ratio Brα/HI14–6 for sources appearing in Figure 2, with the exception of two stars, HD 10144 and HD 104237, because their ISO SWS01 spectra do not show distinct line HI 14–6. It can be seen from Figure 2 and Table 2 that five Be stars have the line flux ratio Brα/HI14–6 smaller than that of P Cyg, just as suggested by Waters et al. (2000), but the other three

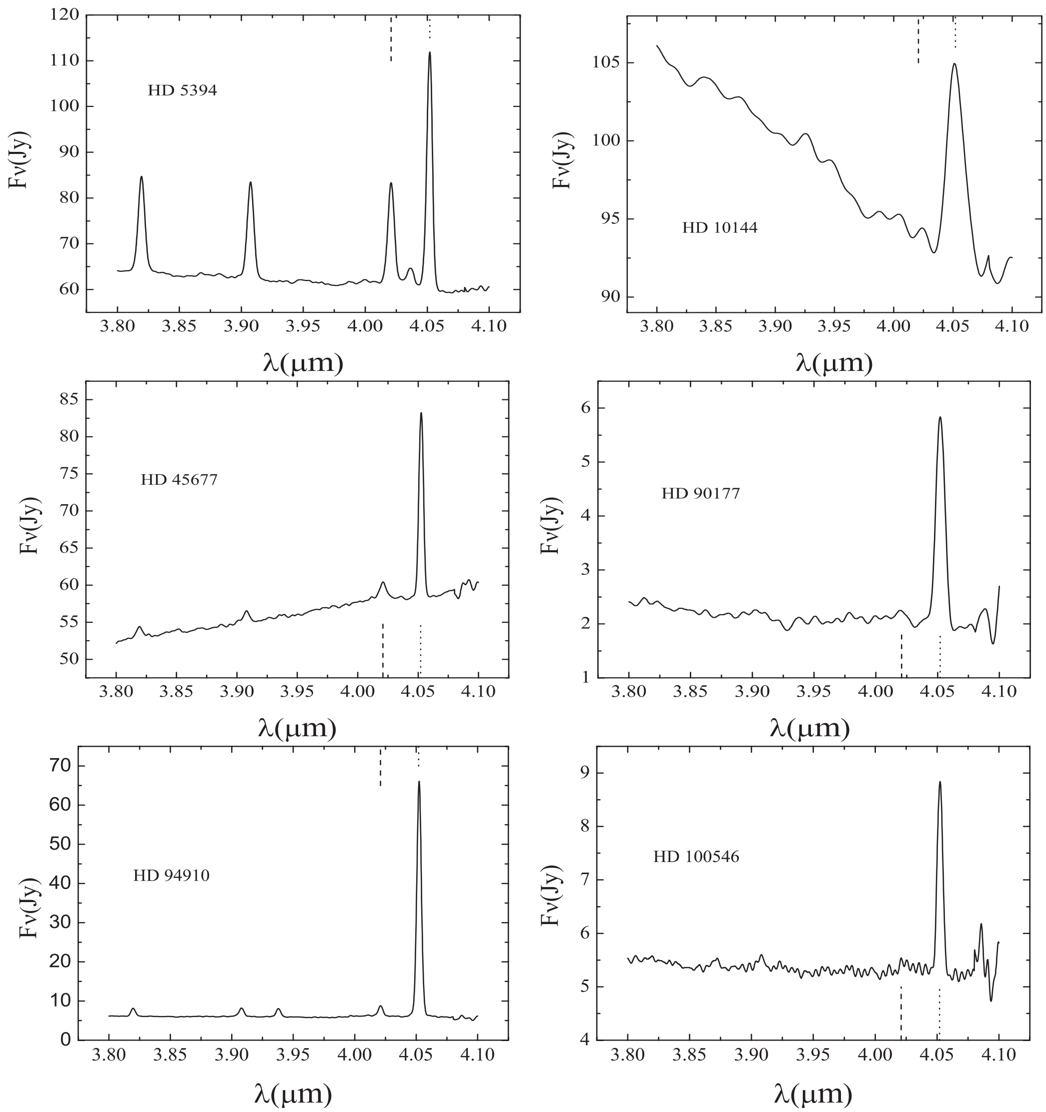

Fig. 2 ISO SWS01 spectra of 10 Be stars in the $3.8 - 4.1\ \mu$m range. The hypergiant P Cyg is shown for comparison. The doted line indicates the position of line Brα (4.052 μm); the dashed line indicates the position of line HI 14–6 (4.0209 μm).

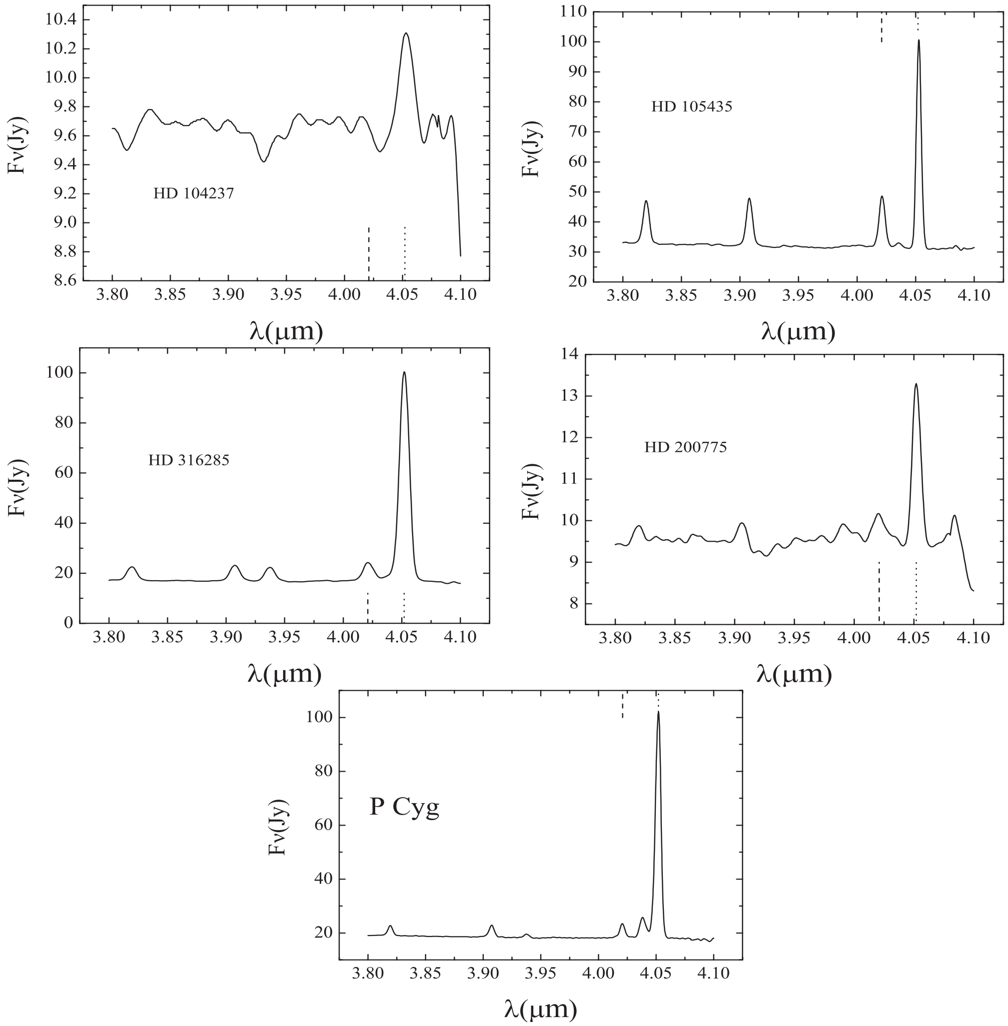

Fig. 2 —*Continued.*

Table 2 Line Flux Ratios of Brα/HI 14–6 for 9 Stars

Star	Ratio	Star	Ratio
HD 5394	2.4	HD 45677	10.2
HD 90177	23.1	HD 94910	22.3
HD 100546	19.0	HD 105435	3.9
HD 316285	12.8	HD 200775	5.9
P Cyg	16.2		

Be stars have the line flux ratio Brα/HI14–6 larger than that of P Cyg. Therefore, our result does not support the argument from Waters et al. (2000).

In addition, Hony et al. (2000) studied the ISO SWS01 spectrum of Be star γ Cas (=HD 5394) in detail. They found the line strengths of the HI emission lines do not follow the Menzel case B recombination line theory (i.e. detailed balance between levels 1 and 2; level 2 is the effective ground level; see Hummer & Storey 1987) and suggested the line fluxes are probably caused by a combination of non Local Thermodynamic Equilibrium and temperature effects. Hony et al. (2000) suggested that HI lines originate from an inner, high-density region with radius 3–5R* and temperature above that of the bulk of the disc material, but line Brα contains a contribution from the outer regions. If this is true, one can expect that there is a correlation between the line flux ratio Brα/HI14–6 and the circumstellar material distribution. It can be seen from Tables 1 and 2 that stars in group 1 have the smallest line flux ratio Brα/HI14–6, stars in group 4 have the largest line flux ratio Brα/HI14–6. The stars in other groups have the line flux ratio Brα/HI14–6 between those in group 1 stars and in group 4 stars. It is noted that groups primarily depend on the temperature of the dominant emitter; five main categories emerge, ranging from the hottest objects such as naked stars (group 1) to the coolest objects such as protostellar cores (group 5) (Kraemer et al. 2002). It can be found that star HD 200775 in group 5 has a much smaller line flux ratio Brα/HI14–6 than those in groups 2, 3 and 4, but similar to those in group 1. This fact would imply that for star HD 200775, line Brα contains little contribution from the outer regions (because of very low temperature).

5 SUMMARY

In this paper, we have searched the ISO SWS01 spectra for those Be stars listed in the paper by Zhang et al. (2005) and found 10 Be stars with ISO SWS01 spectra. Based on the ISO SWS01 spectral classification from Kraemer et al. (2002), we have discussed the spectral features of the sample. It is found that Be stars show a diversity in their ISO SWS01 spectral classifications by Kraemer et al. (2002), from naked stars (3 stars), a star associated with dust (1 star), a star with a warm dust shell (1 star), stars with a cool dust shell (4 stars) to a very red source (1 star). In addition, we have compared the Brα/HI(14–6) line flux ratio derived for the sample stars with that of P Cyg, and it is found that the line ratio of Be stars which we investigated show not only lower values than this ratio, as suggested by Waters et al. (2000), but also larger values. So, the line ratio cannot be used to judge whether a star is a Be star or not.

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