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Evolutionary status of isolated B[e] stars

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ABSTRACT

Aims. We study a sample of eight B[e] stars with uncertain evolutionary status to shed light on the origin of their circumstellar dust.

Methods. We performed a diagnostic analysis on the spectral energy distribution beyond infrared wavelengths, and conducted a census of neighboring region of each target to ascertain its evolutionary status.

Results. In comparison to pre-main sequence Herbig stars, these B[e] stars show equally substantial excess emission in the near-infrared, indicative of existence of warm dust, but much reduced excess at longer wavelengths, so the dusty envelopes should be compact in size. Isolation from star-forming regions excludes the possibility of their pre-main sequence status. Six of our targets, including HD 50138, HD 45677, CD−24 5721, CD−49 3441, MWC 623, and HD 85567, have been previously considered as FS CMa stars, whereas HD 181615/6 and HD 98922 are added to the sample by this work. We argue that the circumstellar grains of these isolated B[e] stars, already evolved beyond the pre-main sequence phase, should be formed in situ. This is in contrast to Herbig stars, which inherit large grains from parental molecular clouds. It has been thought that HD 98922, in particular, is a Herbig star because of its large infrared excess, but we propose it being in a more evolved stage. Because dust condenses out of stellar mass loss in an inside-out manner, the dusty envelope is spatially confined, and anisotropic mass flows, or anomalous optical properties of tiny grains, lead to the generally low line-of-sight extinction toward these stars.

Key words. infrared: stars – submillimeter: stars – stars: emission-line, Be – circumstellar matter – stars: evolution

1. Introduction

B-type stars embrace a diversified stellar class. In addition to the main sequence population, which itself covers a wide range of stellar luminosities and masses, some B-type stars exhibit emission lines in the spectra, show rapid rotation, or have gaseous/dusty envelopes. Yet because B-type stars evolve rapidly, it is often challenging to investigate their evolutionary status. B[e] stars, characterized by additional forbidden lines in the spectra, and large near-infrared excess, are particularly elusive. It is believed that their peculiarities originate from latitude-dependent mass loss with dusty disk-like structure (Zickgraf 2003).

The B[e] phenomena are observed in heterogeneous stages of stellar evolution, from pre-main sequence (PMS) Herbig stars to evolved supergiants, compact planetary nebula or symbiotic stars (Lamers et al. 1998). Apart from these B[e] stars with established evolutionary status, there is a subclass still not well known, the unclassified B[e] stars (Lamers et al. 1998), which have dust in their envelopes, yet lack cold dust components (Zickgraf & Schulte-Ladbeck 1989). Sheikina et al. (2000) and Miroshnichenko (2007) proposed that the unclassified B[e] stars with little cold dust, collectively called FS CMa stars, are binary systems undergoing mass transfer. The evolutionary stage of a star is relevant when its circumstellar dust is studied. In Herbig stars, the grains have progressively grown in size since in molecular clouds (old dust around a young star). In contrast, the dust condensed out of the expanding envelope of an evolved star must start with, and grow from, tiny grains (fresh dust around an old star). This paper aims to address the evolutionary status of some of the unclassified B[e] stars.

Diagnostics of stellar maturity may not be always conclusive for single massive stars. Occasionally a star is presumed young on the basis of its large infrared excess alone. While such excess emission manifests existence of dust, it is a necessary, but not sufficient condition for stellar infancy. Spectroscopic detection of enriched elements by nuclear synthesis in advanced stages of stellar evolution may differentiate a post-main sequence star from being in an earlier phase. For example, the ^{13}CO bandhead emission seen in the infrared K Band has been used as indicative of an evolved status for a B[e] star (Kraus 2009). Even though a few FS CMa stars show the ^{13}CO feature, hence should be relatively evolved, some have evolutionary statuses that remain ambiguous.

We started with a sample of nine Be stars with near-infrared excess rivaling to that of Herbig stars. All our targets exhibit forbidden line spectra, therefore are B[e]-type stars, though in the literature, they might have also been classified as FS CMa or Herbig stars. In Sect. 2 we revisit the issue that thermalized dust in the circumstellar envelopes, instead of plasma free-free radiation, is responsible for the elevated infrared excess emission in Be stars. In Sect. 3 we show the spectral energy distributions (SEDs) of our targets extending from mid-infrared to millimeter wavelengths to contrast the compact envelope sizes with those seen in typical Herbig stars. In Sect. 4 we present an elaborative census of each target in order to rule out the possibility of stellar youth for eight B[e] stars, adding support to their evolved status.

Table 1. Parameters of target B[e] stars.

Star name	RA (J2000) h m s	Dec (J2000) ° ′ ″	SpType	$E(B-V)$ (mag)	J^a (mag)	H^a (mag)	${K_s}^a$ (mag)
HD 45677	06 28 17.42	−13 03 11.1	B2[b]	0.2[c]	7.24	6.35	4.78
HD 259431	06 33 05.20	10 19 20.0	O9[d]	0.42[e]	7.45	6.67	5.73
HD 50138	06 51 33.40	−06 57 59.5	B7 III[f]	0.12[e]	5.86	5.09	4.15
CD−24 5721	07 39 06.17	−24 45 04.9	B1.5[g]	0.73[b]	9.24	8.49	7.42
CD−49 3441	08 14 20.50	−50 09 46.5	B7[h]	0.3[h]	8.98	8.22	7.41
HD 85567	09 50 28.53	−60 58 03.0	B2[h]	0.73[h]	7.47	6.68	5.77
HD 98922	11 22 31.67	−53 22 11.4	B9V[i]	0.14[j]	6.00	5.23	4.28
HD 181615/6	19 21 43.63	−15 57 18.2	O9 V+B8p I[k]	0.2[l]	4.15	3.39	2.62
MWC 623	19 56 31.55	31 06 20.2	B4 III+K4 I/II[m]	1.4[c]	7.10	6.10	5.38

References. [(a)] 2MASS, Skrutskie et al. (2006); [(b)] Cidale et al. (2001); [(c)] Sheikina et al. (2000); [(d)] Voroshilov et al. (1985); [(e)] Friedemann (1992); [(f)] Ellerbroek et al. (2015); [(g)] Miroshnichenko et al. (2003); [(h)] Miroshnichenko et al. (2001); [(i)] Caratti o Garatti et al. (2015); [(j)] Malfait et al. (1998); [(k)] Malkov et al. (2006); [(l)] Dyck & Milkey (1972); [(m)] Zickgraf (2001).

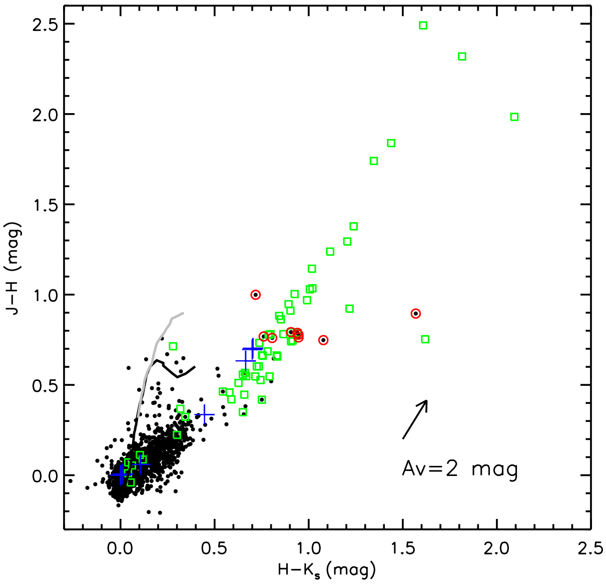

Fig. 1. 2MASS $J-H$ versus $H-K_s$ diagram showing most Be stars (black dots) distinctly separated from Herbig stars (squares), except a few Be stars with very large near-infrared excess (open circles). The sample of Be stars is taken from Zhang et al. (2005), and that of Herbig stars is from de Winter et al. (2001). The crosses indicate the levels of the free-free emission with varying electron number densities and emitting volumes. From bottom left, each cross represents an increase of an order, from 10^0 to 10^8 times in emissivity (see text) surrounding a B0 V star with a gas temperature of 20 000 K. The first three crosses (10^0 to 10^2 times) and the last two crosses (10^7 to 10^8 times), are, respectively, almost overlapped. The gray and black curves are giant and dwarf loci (Bessell & Brett 1988) converted to the 2MASS system. The arrow shows the reddening vector (Rieke & Lebofsky 1985) for an average Galactic total-to-selective extinction (R = 3.1).

In Sect. 5 we discuss the implication of evolutionary status and dust-formation mechanism in isolated B[e]-type stars.

2. Selection of targets

Be stars typically have only moderate infrared excess arising from free-free emission, with the majority being slightly redder than early-type main sequence stars, $J-H \lesssim 0.4$ mag and $H-K_s \lesssim 0.4$ mag (Zhang et al. 2005; Yu et al. 2015), as shown in Fig. 1. Some Be stars, however, exhibit near-infrared excess as large as that of Herbig stars, $H-K \gtrsim 0.7$ mag, so must contain dust in their envelopes (Allen 1973).

Figure 1 also shows the effect on near-infrared colors by adding free-free emission to a B0 V photosphere, assuming an envelope gas temperature T_g = 20 000. The envelope size together with electron number density alters the total emerging infrared flux, and hence also the $J-H$ and $H-K_s$ colors. Adopting typical values of an emitting radius $R_0 = 10^{12}$ cm and electron density $n_0 = 10^{11}$ cm^{-3} (Gehrz et al. 1974; Neto & de Freitas-Pacheco 1982), each cross in the figure represents the free-free intensity in orders from typical $n_0^2 R_0^3$ (bottom left) to $10^8\, n_0^2 R_0^3$ (top right), a value unreasonably large for a Be star. The corresponding $J-H$ and $H-K_s$ colors change from ≈0 mag, to an asymptotic value of ∼0.7 mag, consistent with the results by Allen (1973).

Therefore, we selected among the compilation by Zhang et al. (2005) Be stars with $J-H$ and $H-K_s$ both >0.7. These include HD 45677, HD 259431, HD 50138, CD−24 5721, CD−49 3441, HD 85567, HD 98922, HD 181615 and MWC 623. Note that except HD 181615, all have been listed as Herbig stars (Thé et al. 1994). Moreover, other than HD 181615 and HD 98922, the other six are considered FS CMa stars (Miroshnichenko 2007). Even though not selected by the forbidden line feature, our targets all turn out to be B[e] stars (Miroshnichenko 2007; Acke et al. 2005; Finkenzeller 1985; Kipper & Klochkova 2012). Our sample thus was chosen with no a priori assumption of the evolutionary status. Table 1 summarizes the stellar parameters of our targets, collected from the literature, including the star name, coordinates, spectral type, reddening, and 2MASS J, H, and K_s magnitudes.

3. Spectral energy distributions

The SEDs of our targets have all been presented in the literature (de Winter & van den Ancker 1997; Malfait et al. 1998; Miroshnichenko et al. 2003, 2001; Zickgraf & Schulte-Ladbeck 1989; Netolický et al. 2009; Wheelwright et al. 2013; Kraus et al. 2008b,a; Ellerbroek et al. 2015). At long wavelengths, HD 50138 lacked data, so we observed it at 225.8 GHz with the Submillimeter Array (SMA) on February 13, 2012. The observations were carried out with an extended configuration of baselines ranging from 44 m to 225 m. The radio sources 0530+135 and 0607−085 were used as antenna complex gain calibrators, whereas 3C 84 and Callisto were employed for bandpass and flux calibration, respectively. The typical

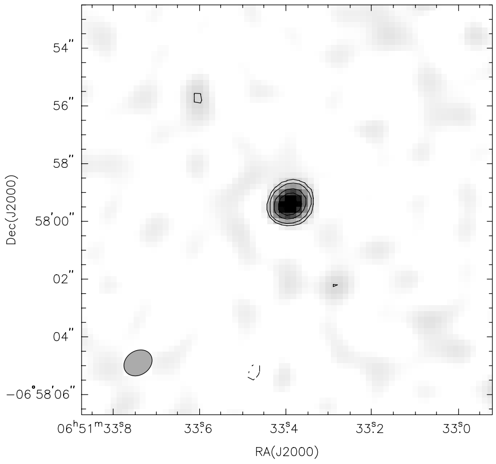

Fig. 2. SMA image of HD 50138 at 225.8 GHz continuum with a 1σ rms 0.9 mjy beam^{-1}. The contours are at −3, 3, 5, 10, 20σ of the sky noise. The lower left *inset* shows the synthesized beam.

uncertainty in the absolute flux scale is 20%. With an on-source integration time of 1.25 h, a total bandwdith of 8 GHz in the double-side-band mode provided by the digital correlator for continuum imaging, and typical system temperatures ranging between 160 K and 250 K, an rms noise of about 0.9 mJy/beam was reached. Figure 2 shows the 1.3 mm continuum image of HD 50138, with the synthesized beam of 1.″03 × 1.″03 obtained with natural weighting. The source was unresolved with a peak flux of 20.75 mJy/beam, yielding an S/N greater than 20.

Figure 3 shows the SEDs of our targets, each typified with a near-infrared excess, followed by a steep decrease toward mid- and far-infrared wavelengths. The only exception is HD 259431, which shows prominent excess emission extending to millimeter wavelengths. For each target, an atmospheric model (Kurucz 1993) reddened by the observed *Av* value (Zhang et al. 2005; Neckel et al. 1980), was used to approximate the stellar photosphere with its adopted spectral class. Two additional components, each of a blackbody radiation, were added to represent the inner and outer edges of the envelope, to approximate each SED at long wavelengths.

4. Census of neighboring regions

Because a Herbig star, unlike a T Tauri star, lacks unambiguous youth discriminant such as the lithium absorption in the spectrum, it is difficult to distinguish a PMS Herbig star from an early-type main sequence star. Nonetheless, the short PMS lifetime, for example, 10 Myr at most for a B-type star (Lejeune & Schaerer 2001), means a runaway Herbig star cannot transverse far from its parental cloud. While an early-type star associated with star formation can already be on the main sequence, one that is isolated from any nebulosity, dark clouds, or young stellar population must have evolved beyond the PMS phase. Therefore, we conducted a thorough neighborhood census of our targets in order to resolve their evolutionary status, in response to the question raised by Herbig (1994) "are there stars which look like Ae/Be's yet are not pre-main-sequence?"

HD 259431: this star, with a known companion ∼3″ away (Baines et al. 2006), is seen near the center of the reflection nebula NGC 2247, with many nearby star formation regions (SFRs) projected within a few deg, for example, NGC 2245, DOG 105, IC 2167, LDN 1607, and NGC 2264. The spectral type reported

Table 2. Photometric data.

Star name	F1565[a] (W/m^2/nm)	F1965[a] (W/m^2/nm)	F2365[a] (W/m^2/nm)	F2740[a] (W/m^2/nm)	U (mag)	B (mag)	V (mag)	R (mag)	I (mag)	L^b (mag)	[12][c] (Jy)	[25][c] (Jy)	[60][c] (Jy)	[100][c] (Jy)
HD 45677	1.26E−13	7.84E−14	6.94E−14	5.43E−14	7.86[b]	8.52[b]	8.5[b]	8.11[d]	8.01[d]	2.15	146.00	143.00	24.80	5.87
HD 259431	2.95E−14	2.56E−14	1.95E−14	1.94E−14	8.48[e]	9.01[e]	8.73[e]	8.72[d]	8.61[d]	4.58	12.54	20.19	109.40	1.13
HD 50138	2.12E−13	1.69E−13	1.20E−13	1.14E−13	6.26[f]	6.66[f]	6.64[f]	6.58[d]	6.59[d]	2.72	70.30	62.50	13.30	2.81
CD−24 5721						11.53[g]	11.04[g]	10.90[h]	10.13[h]	5.86	3.28	2.67	0.49	2.86
CD−49 3441						10.35[d]	10.3[g]	10.30[h]	10.31[h]		5.35	4.67	1.77	3.29
HD 85567	2.97E−14	3.16E−14	1.72E−14	2.03E−14	8.14[f]	8.69[f]	8.57[f]	8.51[d]	8.46[d]		6.39	5.81	1.40	8.84
HD 98922						6.62[i]	6.82[i]	6.78[d]	6.74[d]		40.16	27.24	6.19	7.69
HD 181615/6	2.98E−13	4.10E−13	3.60E−13	2.60E−13	4.18[f]	4.71[f]	4.61[f]	4.54[d]	4.52[d]		137.00	44.20	8.15	2.67
MWC 623						11.99[j]	10.5[j]	10.34[d]	9.79[d]	3.85	9.16	3.85	2.56	3.48

References. [a] Thompson et al. (1978); [b] Morel & Magnenat (1978); [c] Helou & Walker (1988); [d] Monet et al. (2003); [e] Herbst et al. (1982); [f] Mermilliod (1987a,b); [g] Ammons et al. (2006); [h] DENIS Consortium (2005); [i] Myers et al. (2001); [j] Perryman (1997).

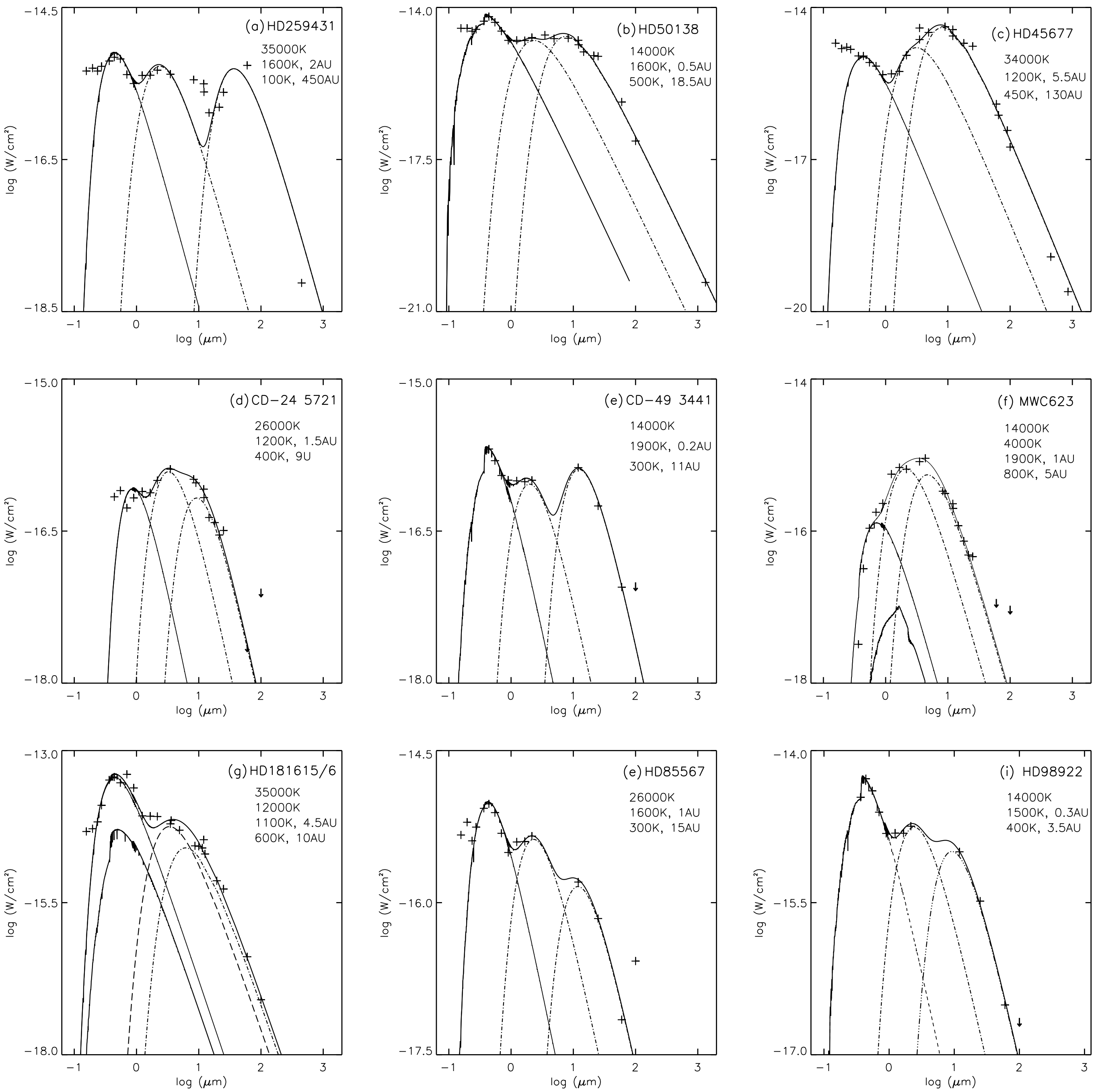

Fig. 3. SEDs of B[e] stars showing large near-infrared excess emission. **a)** The Herbig star HD 259431 has a prominent excess emission not only in near-infrared, but also in far-infrared wavelengths. **b)–i)** The sample of B[e] stars with reduced excess emission in far-infrared and submillimeter. Overlaid for each star are a model stellar photosphere (Kurucz 1993) (solid line), two blackbody curves to present the inner and outer edges of the envelope (dash-dotted lines), and the sum of the three (top solid line). Photometric data sources are summarized in Tables 1 and 2. Additional data include those in **a)** Mannings (1994, 450 μm); **b)** 1.3 mm measurement (this work); in **c)** AKARI/IRC mid-infrared all-sky survey and AKARI/FIS all-sky survey point source catalogs (Yamamura et al. 2010; Ishihara et al. 2010; 9, 18, 65 and 90 μm), COBE DIRBE point source catalog (Smith et al. 2004; 3.5, 4.9 and 12 μm) and (Di Francesco et al. 2008; 450 and 850 μm), and in **g)** (Gehrz et al. 1974; 2.3, 3.6, 4.9, 8.7, 10, 11.4, 12.6 and 19.5 μm).

in the literature ranges from O9 to B6 (Voroshilov et al. 1985; Finkenzeller 1985; Hernández et al. 2004), so its PMS phase, in any case, must be short. Its SED shows copious excess emission leveling to far-infrared, the most prominent, and hence with the most extended outer dust envelope, among our targets. The star has a HIPPARCOS distance of 173 pc (van Leeuwen 2007). The cluster NGC 2247 has a distance 800 pc, estimated by the CO line radial velocity, similar to that of Mon OB1 projected 2 deg away (Oliver et al. 1996). HD 259431 therefore should be in the foreground of NGC 2247. However, given the uncertain distance determination of, and the line-of-sight alignment with, NGC 2247, we cannot rule out the possible association of the star with the nebulosity. HD 259431 may well be a PMS Herbig (Alecian et al. 2013) or a young main sequence star, so is excluded in our final sample of relatively evolved B[e] stars.

We emphasize that our targets were selected on the basis of the level of infrared excess. The Be star sample by Zhang et al. (2005) precludes Herbig stars known at the time, but is not conclusive. That is, Herbig stars may still be included, and some FS CMa stars historically recognized as Herbig stars need further scrutiny. Except HD 259431 just presented, the other eight targets turn out to be isolated B[e] stars. Their neighborhood census follows.

HD 50138: also known as MWC 158, this is a B7 III star (Ellerbroek et al. 2015) at a distance 392 pc measured by HIPPARCOS (van Leeuwen 2007). There are some distant SFRs, projected about one degree away, including the H II regions LBN 1040 and BSF 60, the reflection nebula GN 06.47.6.01, and the T Tauri star J06495854−0738522, all at distances more than 1 kpc (Quireza et al. 2006; Fich & Blitz 1984; Magakian 2003; Vieira et al. 2003). Additional SFRs with no distance information include Paramian 16, Gn 06.54.8.01, Gn 06.54.8.03, and 220.9−2.5A. There are four open clusters, M 50, NGC 2302, NGC 2306 and NGC 2309, within 3 deg and with ages 53 Myr (Loktin & Beshenov 2001), 309 Myr (Kharchenko et al. 2005), 800 Myr (Kharchenko et al. 2005) and 250 Myr (Piatti et al. 2010), respectively. Among these, NGC 2302 is only 8 arcmin off with a heliocentric distance about 1200 pc (Kharchenko et al. 2005), whereas other clusters are all beyond 4.5 deg away and at a distance 1150 pc. The spatially extended CMa OB1 (age 3 Myr, Clariá 1974) is seen about 4.5 deg away and at a distance 1150 pc. We cannot rule out HD 50138 being a possible main sequence member escaped from one of these clusters, given the main sequence lifetime of some five hundred Myr with its spectral type. The star has a measured rotational speed 90 km s^{-1}, and is inferred to have a disk inclined at 56° (Borges Fernandes et al. 2011, 2012). Using the spectrointerferometric technique, Ellerbroek et al. (2015) resolved its au-scale disk with a measured photocenter offset, possibly caused by an asymmetric structure of the disk or a binary companion. These authors favored a post-main sequence status for HD 50138, because of the presence of high transition lines, such as Paschen, Bracket and Pfund series less commonly observed in PMS stars, and because the star is apparently not associated with an SFR, supported by our assessment.

HD 45677: the spectral type reported for this star ranges from B0, B2 IV/V[e] to B3 (Tucker et al. 1983; Cidale et al. 2001; Bohlin et al. 1994). At a distance 279 pc (van Leeuwen 2007), this star has the largest near-infrared excess among our targets. Zickgraf (2003) inferred that HD 45677 is nearly poleon based on the high resolution spectroscopic line profiles. Its infrared spectra indicate existence of not only silicate grains (Molster et al. 2002a,b), but maybe also calcium silicate hydrate, that is, cementitious nano-particles, as suggested by modeling the 10 and 18 μm features by Bilalbegović et al. (2014), rendering evidence of ultra-small particles in the envelope.

Herbig (1994) described this star as "projected upon completely unobscured fields". The nearest SFR WV 340 is projected some 45′ away but with no distance information. Two other SFRs, CMa OB1 and Mon R2, are eight deg away and at distances more than 800 pc (Mel'Nik & Dambis 2009; Herbst 1975), so too far to be related to HD 45677. Besides, both these SFRs are a few Myr old (Clariá 1974; Andersen et al. 2006), too young for such an early-type star to be an escaped member. Hence, HD 45677 should not be a PMS Herbig star. The star, also called FS CMa, characterized by spectral forbidden lines and strong Balmer emission (e.g., de Winter & van den Ancker 1997), is the prototype of the subclass of Be stars studied by Miroshnichenko (2007).

CD−24 5721: this B1.5 V star is at a distance 3.5 kpc (Miroshnichenko et al. 2003). Zickgraf (2003) reported narrow Fe II absorption lines resembling classical Be stars, yet claimed the star as being an unclassified B[e] star because of the presence of P Cygni profiles in Balmer lines and He I line variability. There are only three small clouds, LDN 1668, TGU H1615 and 240.25−1.75 (May et al. 1997), plus one open cluster C 0739−242 (Drilling 1991; Cidale et al. 2001), seen within 1 deg, and a large (~0.4 square degrees) dark cloud LDN 1667 about 2.5 deg to the south-west. None of these have distance information in the literature. The star is some 4 deg away from the large OB association, Pup-CMa (520 pc, Gyulbudaghian & May 1999) and is 1.5 deg away from the open cluster M 93, which is 400 Myr old (Hamdani et al. 2000) and at a distance of 1037 pc (Kharchenko et al. 2005). Another open cluster NGC 2467, with an age 12.6 Myr (Huang & Gies 2006) and at a distance 1355 pc (Kharchenko et al. 2005), is 3.25 deg away. Both these clusters should not be related to CD−24 5721, so the star should not be young.

CD−49 3441: also known as Hen 3−140, this star has an uncertain spectral type. With high resolution spectroscopy, Miroshnichenko et al. (2001) inferred a B7 type in terms of the intensity ratios of He lines, but a B2 type in terms of the Balmer line wings. Based on radial velocity and interstellar extinction, the estimated distance is approximately 2 kpc (Miroshnichenko et al. 2001). Even with a late-B type, the star as a dwarf would be at 1 kpc. There are molecular cloud BHR 31 and reflection nebula BRAN 137, both about 1 deg away at ~400 pc (Henning & Launhardt 1998; Stark & Brand 1989). The open cluster NGC 2547, with an age 38.5 Myr and a distance 361 pc (Naylor & Jeffries 2006), is 1 deg away. All these objects are within the Gum nebula which itself extends about 120 pc in radius at an average distance 400 pc (Sushch et al. 2011), so not related to CD−49 3441.

MWC 623: this is a binary system at ~2 kpc (Zickgraf 2001) with a B4 III star and a K4 I/II companion (Liermann et al. 2014). The binary period is uncertain with long-term radial velocity monitoring (Zickgraf 2001; Polster et al. 2012), and only a minimum period of 25 yr was suggested (Polster et al. 2012). Among our targets, only HD 181615/6 and MWC 623 are known with spectral types for both the primary and secondary. MWC 623 is 1.26 deg above the Galactic plan, with eight unresolved sources within 20 arcmin (Taylor et al. 1996), plus two young stellar objects and one supernova remnant projected within 20−40 arcmin. None of these has a distance estimation except a very rough 7−17 kpc estimated for the supernova remnant (Hui & Becker 2009), but their small sizes suggest likely being more distant than, thus unrelated to, MWC 623.

Additionally, the prominent H II region W 58 and the young stellar object IRAS 19592+3302, both more than 2 deg away, are associated with the Perseus arm or Cygnus arm, which are at 8.3 kpc and 13.38 kpc, respectively (Thompson et al. 2006; Yang et al. 2002), so not related to MWC 623. In addition to SFRs, one old open cluster (about 800 Myr) Kronberger 52 is 24′ away, but is at 3.6 kpc (Szabó et al. 2010), so too far for MWC 623 to be an escaped member. Accordingly, MWC 623 should not be a PMS star. The cool stellar companion should contribute to the near-infrared excess, but in no way could extend beyond mid-infrared. MWC 623 therefore should be a secure case of a non-PMS dusty Be star. The observed extinction of MWC 623, $E(B - V) = 1.4$, the largest among our targets, is almost entirely interstellar (Sheikina et al. 2000), suggesting little circumstellar dust extinction.

HD 181615/6: also known as υ Sgr, this star is an evolved spectroscopic binary (Schoenberner & Drilling 1983; Campbell 1899) consisting of a luminous supergiant and an "invisible" but hotter and more massive dwarf with a binary period 138 d (Wilson 1915) and mass ratio $q = 0.63 \pm 0.01$ (Dudley & Jeffery 1990). The spectral type reported for the supergiant primary ranges from B5 II, A2 Ia to F2 I (Bonneau et al. 2011; Abt et al. 1979; Maury 1925), and for the dwarf secondary from O9 V to B 3V (Malkov et al. 2006; Maury & Pickering 1897). With a close distance of 595 pc (van Leeuwen 2007), the circumbinary geometry of HD 181615 was well determined by the optical and mid-infrared interferometric techniques (Bonneau et al. 2011; Netolický et al. 2009): the radius of the bright companion (20 $R_\odot$), the Hα formation region (12 au), the inner radius of the geometrically thin disk (6 au), the angle of disk inclination (50°) and orientation (position angle 80°). There are no obvious SFRs within 10 deg from the star, with only four small or unresolved radio sources, OV−133, OV−136, PMN J1922−1525 and PMN J1924−1549 (Ehman et al. 1970; Griffith et al. 1994), projected about 0.5 deg away. None of the them have distance estimation in the literature. There is little doubt that this is an evolved system, so the dust should be freshly produced in situ, likely as a result of mass transfer or wind-wind collision.

HD 85567: this B2 star is at a distance 1.5 kpc (Miroshnichenko et al. 2001). Wheelwright et al. (2013) found no indication of close binary within 100 au using near-infrared spectrointerferometry. These authors found the inner radius of the dusty disk to be undersized (∼1 au) given the stellar luminosity, and attributed it to the presence of dense gas in the interior of the disk. Moreover, they suggested the cold dust in the outer disk to have been photoevaporated so its SED shows a strong near-infrared excess but little far-infrared excess. Our SED analysis indeed shows an inner envelope size less than 1 au with a temperature 1600 K, and an outer envelope edge of 15 au at 300 K.

There are two high-velocity clouds (Wakker & van Woerden 1991; Putman et al. 2002) seen within 50′, but they are small in angular sizes so likely in the background and not physically associated with HD 85567. The open cluster NGC 3114, at a distance of 820 pc (González & Lapasset 2001) and with an age of 160 Myr, is some 1.3 deg away, is too old to harbor any Herbig stars. Therefore, HD 85567 is very unlikely to be in the PMS phase.

HD 98922: this star is the most isolated among our targets, with only the compact dark nebula G291.11+7.86 and the reflect nebula BRAN 350 projected 1.4 deg away, neither with distance information. The prominent SRF, the Carina Nebula, projected 7 deg away, is at a distance 2.7 kpc (Tapia et al. 2003).

HD 98922 was considered a Herbig star on the basis of its infrared excess (Thé et al. 1994), which has been allegedly propagated through the literature, with no further evidence of stellar youth. Hales et al. (2014) detected tenuous but extended (more than 600 au across) molecular gas. Little reddening to the star, $E(B-V) \sim 0.07$–0.14 (Malfait et al. 1998; Hales et al. 2014), indicates non-spherical distribution of circumstellar dust. It is puzzling how the star could form out of a completely isolated cloud, keep the surplus gas and dust, and maintain active accretion (Alecian et al. 2013).

We note that the distance determination, 400 or 500 pc, for neither a B9 V nor an A2 III spectral type (Caratti o Garatti et al. 2015; Hales et al. 2014) can reconcile with the HIPPARCOS measurement (1150 pc, van Leeuwen 2007; Alecian et al. 2013). Using high-dispersion spectroscopy, Hales et al. (2014) derived a gravity (log = 3.0) and effective temperature (T_e = 9000 K) that put the star much above even the 1 Myr isochrone in the HR diagram. This inconsistency can be vindicated if this star is in the post-main sequence phase. Adopting the effective temperature and stellar luminosity (Hales et al. 2014) the star is indeed consistent with being a ∼5 $M_\odot$ star along the giant branch, likely a luminosity class II bright giant. In any case, HD 98922 should not be a PMS object.

Apart from positional isolation, our targets should not be associated with any SFRs in terms of space motions. Table 3 lists the heliocentric distances, proper motions, and radial velocities of our targets. The three stars having complete proper motion and radial velocity measurements have Galactic space motions (U, V, W), respectively of (7.0, −1.8, 4.9) for HD 45677, (8.8, 5.3, 4.0) for HD 259431, and (23.8, −0.8, 2.6) for HD 50138, all in km s^{-1}, which are within the range for field disk-population stars.

HD 85567 and CD−49 3441 are intrinsically high-velocity stars. HD 85567 has a relative fast $U \sim 69$ km s^{-1}. Notably, CD−49 3441, with its appreciable proper motion ∼20 mas yr^{-1} (Høg et al. 2000) and a large distance yield a tangential space velocity close to 200 km s^{-1} alone. Plus a radial velocity 33 km s^{-1} (Miroshnichenko et al. 2001), it is therefore not impossible that CD−49 3441 was escaped from one of the regions projected on the sky or along the line of sight.

5. Discussion

Whether a young star can be in isolation from star-forming activity is an open issue. Grady et al. (1993) suggested that the isolated B[e] stars with prominent infrared excess could be in the PMS phase. However, most of the prototypical isolated Herbig stars are actually not far from SFRs. For example, UX Ori is only some 40″ from the nearby luminous cloud NGC 1788 and a group of T Tauri stars. Another well known example, HD 163296 (Thé et al. 1985) is, when a large field was scrutinized, associated with dark clouds as a part of a prominent H II region and cloud complex (Lee & Chen 2011). We note that HD 163296 clearly shows elevated mid-infrared emission, signifying cold dust (see Fig. 4; Kraus et al. 2008a). Even if isolated star formation could have been possible (Grinin et al. 1991; Alecian et al. 2013), a new-born star collapsing out of a molecular core should still keep a distributed dust, warm and cold, in the envelope; this is not the case for our targets. We therefore conclude that the eight stars reported here, namely HD 50138, HD 45677, CD−24 5721, CD−49 3441, MWC 623, HD 181615/6, HD 85567, and HD 98922, represent a well defined FS CMa sample. We note that the two newly identified FS CMa stars reported here, HD 98922 and HD 181615/6, have IRAS colors ([25] − [12], [60] − [25]) = (−0.17, −0.64) and =(−0.49, −0.73), respectively, indeed consistent with the known ranges of this class (Miroshnichenko 2007). Observationally the FS CMa stars show B[e] spectra and prominent excess emission in near-infrared, but only moderate at longer wavelengths. They have evolved beyond the PMS phase, so the dust should not be surplus from star-forming processes.

Hillenbrand et al. (1992) divided Herbig stars into three groups by their level of near- to mid-infrared excess relative to the stellar photospheric emission: Group I (moderate), Group II (prominent), and Group III (weak). Groups I and II show flat or rising SEDs toward mid-infrared, whereas Group III sources have steep flux decrease toward longer wavelengths. These authors classified HD 259431, the only Herbig star in our sample,

Table 3. Distances, proper motions and radial velocities.

Star name	dist (pc)	μ_α mas yr^{-1}	μ_δ mas yr^{-1}	RV km s^{-1}	References
HD 45677	279	2.0 ± 0.9	0.3 ± 0.9	21.6 ± 2.0	1, 2
HD 259431	173	−2.4 ± 1.1	−2.7 ± 0.9	19 ± 4.1	1, 3
HD 50138	392	−3.3 ± 0.6	4.1 ± 0.5	34.2 ± 2.0	1, 4
CD−24 5721	3500	−1.1 ± 2.7	2.0 ± 2.4		5, 6
CD−49 3441	2000	−11.5 ± 1.7	18.0 ± 1.6	33 ± 2	6, 7
HD 85567	1500	−9.3 ± 0.6	6.2 ± 0.5	0 ±2	1, 7
HD 98922	1190	−9.0 ± 0.4	0.8 ± 0.3		1
HD 181615/6	546	−1.3 ± 0.2	−6.3 ± 0.2	8.9 ± 0.9	1, 4
MWC 623	2000	−0.6 ± 2.1	−3.9 ± 2.1		5, 8

References. [1] van Leeuwen (2007); [2] Evans (1967); [3] Gontcharov (2006); [4] Wilson (1953); [5] Miroshnichenko et al. (2003); [6] Høg et al. (2000); [7] Miroshnichenko et al. (2001); [8] Zickgraf (2001).

as a Group I source. In comparison, the eight FS CMa stars we present here have comparable near-infrared excesses as Group I Herbig stars, but with mid-infrared excess clearly even weaker than Group III. In at least two stars in our sample, in HD 45677 (Di Francesco et al. 2008) and HD 50138 (this work), the flux continues to decrease beyond far-infrared. Millimeter measurements of HD 45677, included in the SCUBA legacy catalogues (Di Francesco et al. 2008), indicated an emission size 14″, comparable to the SCUBA resolution *FWHM* ∼ 14″ at 850 μm, that is, the emission was unsolved. For our SMA observations of HD 50138 at 1.3 mm, shown in Fig. 2, with an angular resolution of ∼1″, the emission was unresolved in either the image or the visibility domain. The fall-off of the SEDs toward submillimeter wavelengths suggests a lack of cold grains, thus more compact dusty envelopes in size than those in Herbig stars. Alternatively, photoevaporation would erode the outer parts of a circumstellar disk earlier than the inner part, thereby exacerbating the disk dispersal within timescales of a few Myr (Gorti et al. 2015). The classification scheme for Herbig stars based on infrared excess therefore is not directly applicable to the B[e] stars in our sample because of the different origins of circumstellar grains.

Existence of thermonuclear products would provide a diagnostic of an evolved atmosphere. Kraus (2009) proposed that an evolved B[e] star should have a ^{13}C-enriched equatorial environment because of the disk-forming winds in massive stars, locking the isotope in the form of molecules, for example, ^{13}CO seen in high-dispersion *K*-band spectra. Oksala et al. (2013) and Liermann et al. (2014) found ^{13}CO emission in four FS CMa stars, including MWC 137, HD 327083, GG Car, and Hen 3−298, to justify the stellar seniority. We found related literature only for two stars in our sample. Wheelwright et al. (2013) detected no ^{13}CO emission in HD 85567, but the spectral resolution of the data was not sufficient to dismiss the post-MS status. In MWC 623 ^{13}CO is in absorption, which may be attributable to the cool supergiant companion (Liermann et al. 2014). In any case a sample of FS CMa stars in star clusters would better firm up their evolutionary status. Recently, a few FS CMa candidates were found as members of two young clusters, in Mercer 20 and Mercer 70 (de la Fuente et al. 2015), though uncertainty in mid-infrared fluxes owing to cluster crowding requires further clarification.

Correlation between the level of infrared excess and intensity of Balmer emission lines has been known in Be stars (e.g., Feinstein & Marraco 1981; Neto & de Freitas-Pacheco 1982; Dachs & Wamsteker 1982; Ashok et al. 1984; Goraya & Rautela 1985; Dachs et al. 1988; Kastner & Mazzali 1989; van Kerkwijk et al. 1995; Touhami et al. 2010), in Herbig stars (Corcoran & Ray 1998; Manoj et al. 2006) and in T Tauri stars (Cabrit et al. 1990). For Be stars, those with Hα and Hβ both in emission exhibit large near-infrared excess (Lee et al. 2011). All our targets belong to this group. In comparison, those with Hα in emission, but Hβ and higher Balmer lines in absorption have moderate near-infrared excess, with $J-H$ and $H-K_s$ up to 0.8 mag. The Be stars with Hα and Hβ both in absorption, show little near-infrared excess, with the observed $J-H$ and $H-K_s \lesssim 0.2$.

The correlation between the dust emission and emission lines supports the two-component model for FS CMa stars, one of an enhanced stellar mass loss, and the other of a dusty envelope (Zickgraf 2003). The copious hot plasma produces the prominent Hα emission lines in the vicinity of the stars, and also the forbidden lines in the tenuous regions further away. The expanding gas cools off and condenses to form dust grains, which reprocess starlight to give rise to the excessive infrared emission. Because dust is formed out of stellar mass loss, proceeding inside out to the envelope, it is confined preferentially in the vicinity of the star. This is in contrast to a Herbig star which harbors existing large grains distributed on scales of the parental molecular core.

All isolated B[e] stars in our sample suffer comparatively small intrinsic extinction (Table 1), despite the prominent near-infrared excess signifying existence of warm dust in quantity. Possible explanations include an anisotropic dust distribution or ineffective dust extinction. Dust formation in an asymmetric mass outflow, for example, as a consequence of colliding massive stellar winds, ejection in mass transfer in a binary system, or fast rotation to shed the atmosphere of a single star, results in a dusty region close in to the star and a relatively clear line of sight. The mass loss consequently gives rise to the P Cygni profiles commonly seen in the B[e] spectra.

Alternatively, tiny grains are effective in thermal emission but otherwise not in attenuation of visible light. Freshly condensed grains should be tiny in size. Grain growth in an FS CMa envelope may proceed efficiently, but with ample supplies of tiny grains, such as nanosized particles, which are known to have anomalous specific heat capacity (van de Hulst 1957; Purcell 1976).

It has been suggested that binarity may be responsible for the FS CMa phenomena (Polcaro 2006), and dust is formed as a consequence of binary interaction. Interestingly, among our targets, HD 181615/16 and MWC 623 have ascertained spectral types for both binary components, whereas HD 45677, HD 50138, HD 85567, and HD 98922 are found to be spectro-astrometric binaries, that is, the photocenter of a star is wavelength dependent (Baines et al. 2006).

Dust formed out of stellar mass loss, therefore, has properties distinct from that in the interstellar medium or around a young star. Caution must be taken, then, to derive dust contents in different environments based on interstellar grain properties. The current paradigm is that most cosmic dust is produced in expanding cool atmospheres of post-main sequence stars. Our work supports the notion that FS CMa stars may serve as additional suppliers of dust in space (Miroshnichenko 2007).

6. Conclusion

We present a sample of eight B[e]-type stars that show prominent near-infrared excess, but steep flux drop toward mid-infrared and longer wavelengths, indicating the dusty envelopes being compact in size and lacking cold grains. On the basis of their isolation from star-forming activity or young stellar populations, we argue that these stars have evolved beyond the PMS phase, so the grains must be produced in situ, starting with very tiny sizes. Anisotropic mass loss, or properties of tiny grains, lead to the phenomena observed in our targets. The properties of dust, such as the size, composition, and spatial distribution in these isolated B[e] stars certainly deserve further investigation.

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