Stars with the B[e] Phenomenon
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Michaela Kraus and Anatoly S. Miroshnichenko

B[e] Stars with Warm Dust: Revealing the Nature of Unclassified B[e] Stars and Expanding the Family

A. S. Miroshnichenko

Dept. of Physics & Astronomy, University of North Carolina at Greensboro, P.O. Box 26170, Greensboro, NC 27402–6170, USA

S. Bernabei

INAF-Osservatorio Astronomico di Bologna, Via Ranzani 1, 40127 Bologna, Italy

K. S. Bjorkman

Ritter Observatory, University of Toledo, Toledo, OH 43606-3390, USA

E. L. Chentsov, V. G. Klochkova

Special Astrophysical Observatory of the Russian Academy of Sciences, Nizhnyj Arkhyz, 369167, Russia

R. O. Gray

Department of Physics and Astronomy, Appalachian State University, Boone, NC 28608, USA

H. Levato, M. Grosso

Complejo Astronómico El Leoncito (CASLEO) Casilla de Correo 467, 5400 San Juan, Argentina

K. H. Hinkle

National Optical Astronomy Observatory, PO Box 26732, Tucson, AZ 85726, USA

K. S. Kuratov

Fesenkov Astrophysical Institute, Kamenskoe plato, Almaty 480068, Kazakhstan

A. V. Kusakin

Sternberg Astronomical Institute, Universitetskij pr. 13, Moscow, Russia

P. García-Lario, J. V. Perea Calderón

European Space Astronomy Centre, Villafranca del Castillo, Apartado de Correos 50727, E–28080 Madrid, Spain

V. F. Polcaro, R. F. Viotti

Istituto di Astrofisica Spaziale e Fisica Cosmica, INAF, Via del Fosso del Cavaliere 100, 00133, Rome, Italy

L. Norci

School of Physical Sciences, Dublin City University, Glasnevin, Dublin 9, Ireland

N. Manset

CFHT Corporation, 65–1238 Mamalahoa Hwy, Kamuela, HI 96743, USA

A. B. Men'shchikov

Institute for Computational Astrophysics, Saint Mary's University, Halifax, NS B3H 3C3, Canada

R. J. Rudy, D. K. Lynch, C. C. Venturini, S. Mazuk

The Aerospace Corporation, M2/266, P.O. Box 92957, Los Angeles, CA 90009, USA

R. C. Puetter

University of California, San Diego, 9500 Gilman Dr., La Jolla, CA 92093, USA

R. B. Perry

Science Support Office, M/S 160, NASA Langley Research Center, Hampton, VA 23681, USA

T. L. Gandet

Lizard Hollow Observatory, P.O. Box 89175, Tucson, AZ 85752–9175, USA

Abstract. Until recently, unclassified B[e] stars represented half of the entire B[e] group. Our study of these objects with strong emission-line spectra and IRAS fluxes, decreasing toward longer wavelengths, resulted in a suggestion that they currently form dust in their envelopes. The objects have been tentatively called B[e] stars with warm dust (B[e]WD). Their luminosity range (∼3 orders of magnitude) is much larger compared to previous suggestions that dust formation occurs only near very luminous hot stars. A significant fraction of B[e]WD are recognized or suspected binaries. The group has been expanded with both previously detected hot emission-line stars with IR fluxes, typical for confirmed B[e]WD, and new candidates, found in recent all-sky surveys. Currently the number of B[e]WD members and candidates is ∼60 with an opportunity to find more in existing stellar catalogs. Main observational[1] and physical properties of

[1]Partially based on observations obtained at the Canada-France-Hawaii Telescope (CFHT)

B[e]WD and their envelopes are summarized. Our results on newly found group members are presented.

1. Introduction

B[e] stars are known as a heterogeneous group of objects, showing the B[e] phenomenon. This phenomenon refers to emission-line early-type stars that exhibit both forbidden emission lines (e.g., [O I], [Fe II], [N II]) and strong infrared (IR) excesses due to radiation of circumstellar (CS) dust. About half of the original list of B[e] stars (Allen & Swings 1976) belongs to stellar groups with known nature and evolutionary state. These include pre-main-sequence Herbig Ae/Be stars (HAeB[e]), symbiotic binaries (a cool giant primary and a white dwarf or a neutron star secondary, symbB[e]), compact Proto-Planetary Nebulae (PPNe)/Planetary Nebulae (cPNB[e]), and supergiant (sgB[e]). The other half of the original list contains unclassified B[e] (unclB[e]) stars that do not fit into any known stellar group. This classification, suggested by Lamers et al. (1998), indicates that the B[e] phenomenon is associated with objects at very different evolutionary stages, but with similar conditions in their extended gaseous and dusty envelopes.

Lamers et al. (1998) have not included reasons for dust formation in their analysis. It turns out that CS dust in HAeB[e] is protostellar, while in cPNB[e] stars it was left from the previous AGB evolutionary stage. In symbB[e] it is formed in the ejecta of cool giants, as it is in AGB stars. These cases of dust formation are well understood. In sgB[e], which are very luminous objects with extremely dense radiatively-driven winds, dust can be formed due to the presence of heavy elements produced in their interiors, and self-shielding of parts of their winds from UV radiation which otherwise would destroy dust. This is similar to the situation in Wolf-Rayet stars and Luminous Blue Variables. Investigation of dust formation near these 3 types of luminous object began more recently than that in cool stars, but the conditions for the strong mass loss and therefore reasons for dust formation are more or less understood as well.

There are a few main reasons for the existence of unclB[e] stars. They are often very reddened in the optical range, and the reddening removal is uncertain because of the unknown ratio of the CS and interstellar (IS) extinction. In most of unclB[e] stars, photospheric lines have not been detected even in high signal-to-noise ratio spectra. These two reasons make their luminosities and spectral types uncertain. As a result, the location in the Hertzsprung-Russel diagram and, as a consequence, evolutionary state cannot be determined.

Our studies of the unclB[e] prompted us to suggest a new distinct sub-group of $\sim$20 B[e] stars (Miroshnichenko et al. 2002a) with IR colors that imply a lack of dust with temperatures $\geq$150–200 K ($-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 (F_ν) in the IRAS photometric bands centered at 12, 25, and 60 μm, respectively, see Fig. 1). The location of this group, which we called B[e] stars with warm dust (B[e]WD) in the region, mostly occupied by cool dusty stars, suggests that the IR emitting CS dust is distributed close to the underlying hot stars, and therefore their dusty envelopes are compact.

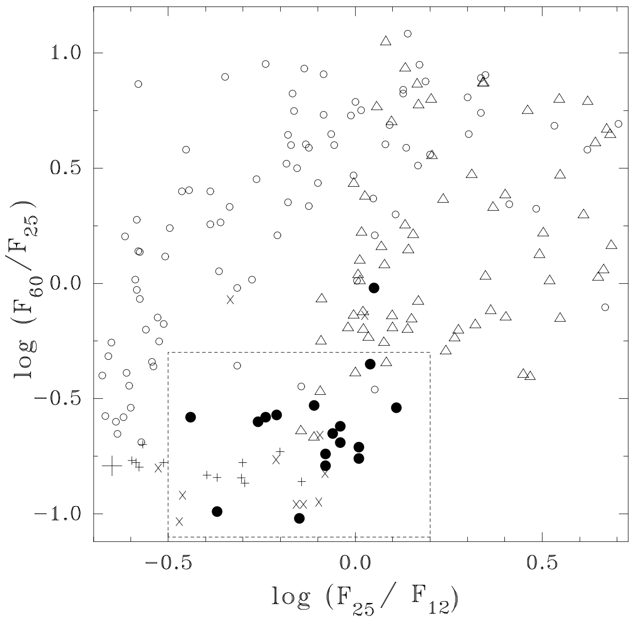

Figure 1. The IRAS color–color diagram for some dusty objects that contain a hot star. Symbols: B[e]WD – filled circles, symbiotic stars – crosses, VV Cep binaries – pluses; HAeBe – triangles; and main-sequence Vega-type stars – open circles. The large cross indicates the photospheric locus. The dash-lined box marks the most probable location of the B[e]WD (from Miroshnichenko et al. 2002a).

We found 9 B[e]WD among the original B[e] stars and recognized 10 more in the list of Dong & Hu (1991), who cross-correlated the IRAS Point Source Catalog (PSC) and the catalog of galactic early-type emission-line stars (Wackerling 1970) to select objects with very strong IR excesses. In particular, fundamental parameters of the underlying hot stars were derived for AS 78 and MWC 657 (Miroshnichenko et al. 2000), HD 85567, Hen 3–140, and Hen 3–1398 (Miroshnichenko et al. 2001), AS 381 (Miroshnichenko et al. 2002b), V 669 Cep (Miroshnichenko et al. 2002c), HDE 327083 (Miroshnichenko et al. 2003), and Hen 3–298 and Hen 3–303 (Miroshnichenko et al. 2005). Direct evidence for the presence of a late-type secondary companion was found in the spectra of AS 381 and V 669 Cep. Spectral lines of an F-type secondary were discovered in HDE 327083 (Miroshnichenko et al. 2003), an object previously considered to be one of the most luminous galactic supergiants ($\log L/L_{\odot} \sim 6$, Machado, Araújo, & Lorenz-Martins 2001).

We showed that B[e]WD are neither pre-main-sequence nor post-AGB objects. Pre-main-sequence stars exhibit much stronger far-IR excesses (due to cold pre-existing dust, Fig. 1) and retain them much longer than the near-IR ones (Miroshnichenko et al. 1996; Malfait, Bogaert, & Waelkens 1998). The only possibility for a pre-main-sequence star to lose the cold dust first is to be exposed to stellar winds from nearby stars in dense star-forming regions (Hollenbach & Adams 2004). In contrast, B[e]WD are isolated objects. Massive post-AGB stars evolve so fast that their spectral changes due to an increase in

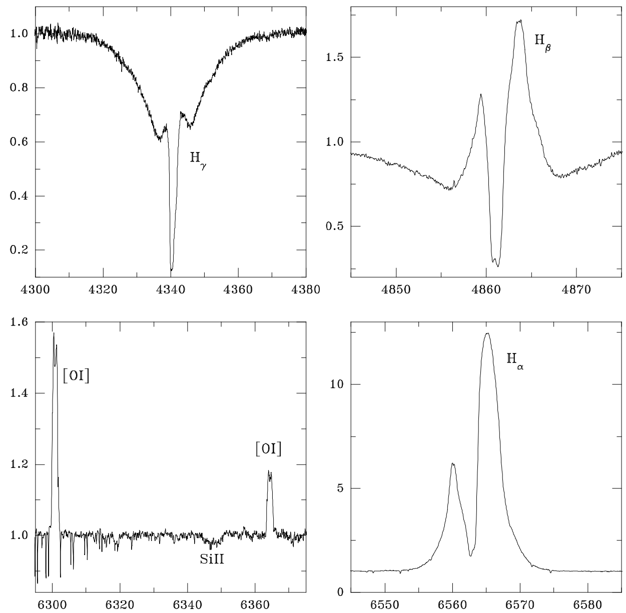

Figure 2. The optical spectrum of IRAS 03421+2935 obtained at CFHT. The object's spectral type is estimated as B8 V. With a brightness of V=10.0 mag and virtually no IS extinction, it would be located at a distance of ~1 kpc. The intensities are in continuum units, and the wavelengths are in Å.

T_{eff} can be detected on a time scale of a decade or so (Blöcker 1995). Their extremely hot photospheres cause strong [O III] emission lines. Neither of these features is seen in the spectra of B[e]WD. Moreover, most early-type post-AGB stars show more pronounced far-IR excesses than those of B[e]WD (see discussion in Miroshnichenko et al. 2000). Low-mass post-AGB stars (known as RV Tau stars) evolve too slow to become hot stars while still retaining hot dust, formed during the AGB phase. Therefore, compactness of the B[e]WD's dusty envelopes is indicative of recent/ongoing CS dust formation.

2. Expanding the Group

The optical brightness of B[e]WD, their IR fluxes (~3–150 Jy at 12–25 μm), and the distances from the Sun (1.5–3.5 kpc) suggest that optically fainter objects could still have been detected by IRAS and MSX. In order to estimate how large the B[e]WD group might be, we cross-correlated the list of IRAS sources with B[e]WD-like colors and recently completed all-sky surveys. We used the USNO–B1.0 optical astrometric survey (Monet et al. 2003) and the 2MASS near-IR survey (Cutri et al. 2003), whose higher positional accuracy ($\sim 1''$ compared with 15–20$''$ of the IRAS) allowed us to unambiguously identify optical counterparts of the IRAS sources.

Analysing different color-color diagrams, we developed photometric criteria for separation of cool and hot dusty stars. It turned out that cool stars with even moderately thick dusty envelopes have the K-band (2.2 μm) flux exceeding the

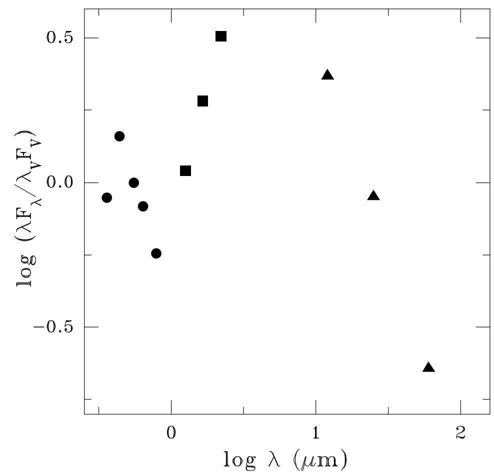

Figure 3. The SED of IRAS 07080+0605. Symbols: our *UBVRI* photometry – circles, 2MASS – squares, IRAS – triangles. The SED is corrected for an IS extinction of A_V=0.6 mag.

IRAS 12–μm band flux. Cool stars with the thickest CS dust have $F_K/F_{12} \leq 1$, but they are much redder ($V-K \geq 8$ mag) than B[e]WD ($V-K \leq 7$ mag). Also, RV Tau stars have smaller near-IR color-indices than known B[e]WD ($J-K \leq$ 1.3 mag, Miroshnichenko et al. 2006).

3. Some Examples of the B[e]WD Group Members

Here I describe a few typical B[e]WD to give you an idea about their properties.

FS CMa. This is a prototype B[e] object, but in a number of studies it is considered to be a HAeBe (e.g., Sitko et al. 1994). Nevertheless, it does not belong to any star forming region and exhibits no reflection or dark nebula. The latter indicates that its CS envelope is more compact than those of pre-main-sequence stars. FS CMa gradually faded by $\Delta V \sim$2 mag between late 1960's and mid 1980's without significant changes in both optical color-indices and the spectral line strength (de Winter & van den Ancker 1997). After reaching the V=8.8 mag level, the brightness has been increasing and is now $V \sim$7.5 mag. The brightness variations show at least 2 cyclic components with periods of 296.5 (Halbedel 1989) and 1594 (Miroshnichenko 1998) days. Although Cidale et al. (2001) did not find traces of the secondary companion in the Balmer jump region, Oudmaijer (2006) reported detection of one using spectroastrometry.

MWC 342 and MWC 623. These objects have very similar optical color-indices ($U-B=-0.2$ mag, $B-V=1.2$ mag, $V-R=1.4$ mag, Bergner et al. 1995). Analysis of their optical spectrophotometry by Arkhipova & Ipatov (1982) resulted in a suggestion that they are both binaries with a hot (B0) and a cool (M0/1) companions. Nevertheless, absorption lines of the cool star are clearly seen only in MWC 623 (Zickgraf & Stahl 1989). Its spectral type is still uncertain being estimated as K2 Ia–II by Zickgraf (2001) and as K7 III by Miroshnichenko (1992). Our recent near-IR spectrum of MWC 623 in combination with a careful removal of the IS extinction and the contribution

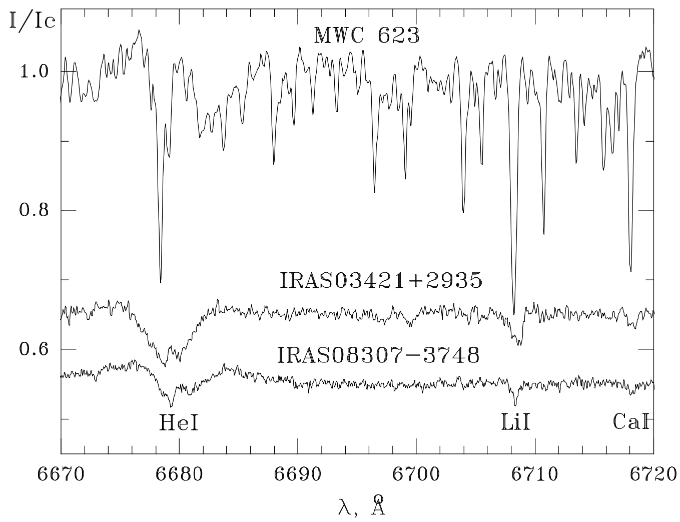

Figure 4. Spectra of some B[e]WD with a cool companion. The spectrum of MWC 623 was obtained at the 2.1-m telescope of the McDonald Observatory, those of the IRAS sources (new B[e]WD) at the CFHT. The spectral resolution is 60000–80000. The intensities are in continuum units, and the wavelengths are in Å.

of the hot primary might clarify the situation. MWC 342 was only suspected in binarity because of its cyclic photometric variations (132 days, Bergner et al. 1990) and a relatively large long-term brightness changes (ΔV ∼0.7 mag, Miroshnichenko & Corporon 1999). Currently this object is almost back to its brightness level in mid 1980's (V ∼10.8 mag) after a high phase in mid 1990's. No traces of its possible secondary have been found.

FBS 0022–021. An interesting object was recently found by Zharikov, Tovmassian, & Costero (2004) among those of the First Byurakan Survey of blue stars in high galactic latitudes. It has a very strong emission-line spectrum, similar to that of η Carinae and B[e]WD, but with such a high luminosity it would be located at a distance of ∼20 kpc. However, its galactic latitude ($b = -64°$) is unusual for population I stars, such as B[e]WD. Even with a typical main-sequence luminosity for this B-type star (no He II line emission detected in the spectrum), it would be at 7.5 kpc from the Sun. Due to its faintness (V=15 mag, K=11 mag), it was not detected by IRAS. Its existence might indicate that more B[e]WD can be expected to be found far from the galactic plane.

Our initial spectroscopic observations[2] of photometrically identified ∼20 B[e] WD candidates showed that they indeed have strong emission-line spectra (Fig. 2). In particular, we found that even the coolest B[e]WD with the least amount of stellar UV radiation, which feeds the dust most efficiently, may have surprisingly strong IR excesses (IRAS 07080+0605, spectral type B9/A0, Fig. 3). We also detected a few new binary systems (Fig. 4).

[2]the CFHT data were reduced using Libre-ESpRIT, Donati et al. (1997)

4. Discussion

The wide luminosity range of B[e]WD (2.5$\leq$ log L/L$_\odot$ $\leq$5.1, see Miroshnichenko et al. 2001) and their location on the Hertzsprung-Russell diagram mostly within the main-sequence indicate that dust formation near hot stars is much more common than previously thought. If they are single, then the main-sequence evolution of intermediate- and high-mass stars may include episodes of rapid mass loss with unknown causes. For binaries, this implies that they are currently undergoing or have recently completed a rapid mass-exchange phase. In either case, these processes have not yet been studied in such objects in detail.

It seems more likely that most B[e]WD are binaries. Ten non-luminous B[e]WD show signatures of a cool (usually K-type, Fig. 3) or a degenerate (neutron star or black hole, CI Cam) companion. A few more objects exhibit radial velocity variations that may be attributed to orbital motion. In all cases but one (MWC 623, Zickgraf 2001), the secondaries are much fainter ($\Delta V \geq 2$ mag) than B-type primaries. No companion in binary B[e]WD seems to fill its Roche lobe, therefore the systems are currently detached.

Also, on average the Balmer lines in B[e]WD are an order of magnitude stronger than in Be stars and even in hot super- and hypergiants. Emission line profiles of most B[e]WD are double-peaked, suggesting that the CS gas distribution is non-spherical. Our calculations show that mass loss rates of $\dot{\rm M}$ $\geq 10^{-6}$ M$_\odot$ yr^{-1} are required to explain the Balmer line strength in B[e]WD. This is consistent with the theoretical predictions for only the most luminous group members (Vink, de Koter, & Lamers 2002). In binaries, CS gas may accumulate in the companions' Roche lobes and/or in the circumbinary area, thus making the CS matter density sufficient for dust formation and requiring smaller, more reasonable, mass loss rates. It is worth noting that the sgB[e] are not the highest IR excess objects (Fig. 5). This is an indirect evidence in favor of the circumbinary matter accumulation.

The distribution of B[e]WD with respect to the galactic plane indicates that most of them are extreme population I stars. There are also very few such objects closer than 1 kpc from the Sun (Fig. 6).

In the evolutionary context, B[e]WD might be transitional objects between binary Be stars, whose secondary companions are also much fainter than the hot primaries, and symbiotic stars, whose cool primaries are much more luminous than the hot secondaries. Recent theoretical studies of intermediate-mass binaries (still conservative, Wellstein, Langer, & Braun 2001) show that there are periods of rapid mass transfer ($\sim 10^{-3}$ M$_\odot$ yr^{-1}), when the mass gainer cannot accept a large fraction of the incoming matter. B[e]WD could be good candidates to verify these results.

Summarizing our findings, we emphasize that B[e]WD is **not the original "zoo"** of emission-line stars with dusty environments, but rather a homogeneous group of possible binaries at a phase of a rapid mass transfer. Homogeneity here refers to certain system parameters (e.g., mass ratios, age range, separations) which we still have to reveal. Their main distinct features are an extreme amount of CS gas, which causes the strong emission-line spectra, and the CS dust distribution, which causes the IR flux to steeply fall towards longer wavelengths beyond 10 μm. We seemed to reveal **a previously unknown critical evolutionary stage of intermediate- and lower-end massive binaries that**

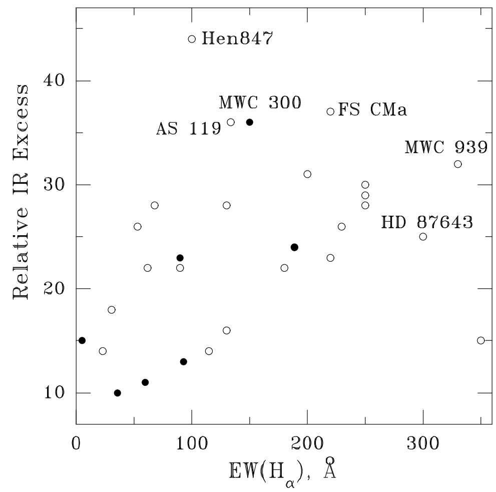

Figure 5. Relationship between the relative IR excess in B[e]WD and some other B[e] stars (calculated as the excess radiation at 10 μm above the photospheric flux in arbitrary units) and the Hα emission line equivalent width. Symbols: filled circles – sgB[e], open circles – lower-luminosity B[e]WD.

is characterized by a significant accumulation of CS material and an ongoing dust formation.

Speaking of the importance of B[e]WD to the galactic evolution, the following arguments can be presented. In general, hot stars are considered to be significant contributors of gas to the IS medium (comparable to supernovae, Castor 1993). Similarly, they could supply a large amount of dust. According to studies of dust formation in the Milky Way, WR stars may account for $\sim$1% of the dust produced in CS environments (Gehrz 1989; Dwek 1998). These studies did not consider B-type stars as dust producers. The large luminosity (and hence mass) range of B[e]WD suggests that they should largely outnumber more massive WR stars, only 24 of which are known to produce dust, and be responsible for at least a few per cent of the galactic CS dust. Also, the dust formation rate in B[e]WD with a moderate IR excess (RY Sct, Men'shchikov & Miroshnichenko 2005) seems to be an order of magnitude higher than in WR stars (Zubko 1998).

Furthermore, both binary (Wellstein, Langer, & Braun 2001) and single star models (Schaller et al. 1992) show that it takes (5–30) 10^6 years for possible precursors of B[e]WD to reach the dust-forming stage. Since conditions near B[e]WD are less "harsh" (less UV radiation due to lower $T_{\rm eff}$) than those near WR stars, where dust can survive for $\sim$100 years (Marchenko et al. 2002), and the dust-forming B[e] stars exist in the lower-metallicity environments of LMC and SMC (Zickgraf et al. 1986), it is reasonable to suggest that B[e]WD might have been important dust producers in the earlier Universe.

5. Conclusions

We have separated a distinct group of B[e] stars, tentatively called the B[e] stars with warm dust. Our initial studies allowed us to enlarge it, so that it is

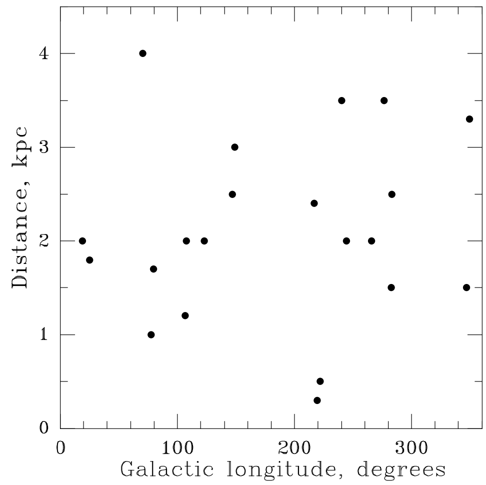

Figure 6. The distribution of 21 B[e]WD with known (mostly kinematical) distances. The only 2 objects closer than 1 kpc are FS CMa and HD 50138.

the largest galactic group of hot stars, which seem to form CS dust. Currently the B[e]WD group contains ∼60 objects, including 33 original B[e] stars, 10 other B[e]WD from Miroshnichenko et al. (2002a), and 16 recently discovered candidates which have been confirmed as hot emission-line stars. The group members span a range of luminosities between log $L/L_{\odot} \sim 2.5$ and 5.1, thus including sgB[e] and unclB[e] stars. I suggest to merge these 2 subgroups of B[e] objects to a single group of dust forming hot stars. They both show a large fraction of binaries, and studying them together may reveal important, but still hidden, clues to understanding the part of the B[e] phenomenon associated with dust formation.

It is not clear yet whether the dust formation in these objects is ongoing or has terminated recently, so that the dust has not been swept away by the stellar winds. Mass loss mechanisms are not clear as well. Future studies of the group should include frequent high-resolution optical spectroscopy, accompanied by contemporaneous multicolor photometry. One of the main immediate goals is a search for the secondary companions. Cross-corellation of more optical (e.g., SDSS) and IR photometric (e.g., 2MASS and DENIS) surveys may result in further group expanding.

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