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B[e] Stars with Warm Dust – A New Type of Intermediate- and High-Mass Interacting binariy?

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Abstract. Dust formation around evolved hot stars requires special conditions, such as very high matter densities or hydrogen deficiency. Only a few groups of hot and luminous stars producing new dust are currently known (Wolf-Rayet stars, B[e] supergiants, and LBVs). Studying unclassified B[e] stars, we have identified another distinct group of ∼20 intermediate luminosity (log $L/L_{\odot}$ =2.5–5.1) hot stars with IRAS fluxes suggestive of a recent CS dust formation process. Our search for optical counterparts of IRAS sources with similar colors in recently released all-sky surveys (2MASS and USNO–B1.0) resulted in finding 40 new candidates to the group. The group properites and recent observational results are discussed.

Stars of almost all masses pass through stages when conditions in their circumstellar (CS) envelopes are favorable for dust formation. Dust formation is only clearly understood around cool stars (e.g., red supergiants and carbon stars, Gail & Seldmayr 1986). They have low surface temperatures ($T_{\rm eff} \leq$3000 K), and so the dust, with a lower sublimation temperature ($\sim$1500–2000 K), can be formed near the stellar surface where the CS matter density is large.

In contrast, hot stars have much higher $T_{\rm eff}$, and dust can form only far away from the star ($\sim$100 $R_\star$ for $T_{\rm eff}$=10000 K), where the CS matter is much less dense, and so the molecule and dust formation process is ineffective. The dust origin in young objects is protostellar; dust can be formed only around evolved stars. An enhanced abundance of heavy elements is observed in the atmospheres and CS environments of many post-main-sequence hot stars, but only a small fraction of them show evidence for the presence of CS dust.

At present, CS dust is known to form near only three types of hot stars: Wolf-Rayet stars, Luminous Blue Variables, and B[e] stars. The first two types contain very luminous objects with extremely dense radiatively-driven winds, and dust could form due to the presence of heavy elements, produced in their interiors, and the self-shielding of parts of their winds from the UV radiation which otherwise would destroy newly formed dust.

In contrast, B[e] stars are a heterogeneous group including objects of mostly B spectral type (10000 K $\leq T_{\rm eff} \leq$30000 K) that show forbidden emission lines in their optical spectra and large IR excesses due to hot CS dust (Allen & Swings 1976). Although a number of B[e] stars have been identified as members of other known stellar groups (e.g., Herbig Ae/Be stars and Proto-Planetary Nebulae) or suggested to have high luminosities (Lamers et al. 1998), nearly half of the originally selected 65 galactic objects remained unclassified until recently.

Our studies of these unclassified objects prompted us to suggest a new distinct sub-group of B[e] stars (tentatively called B[e] stars with Warm Dust or B[e]WD) with IRAS fluxes suggestive of a recent CS dust formation (Miroshnichenko et al. 2002). Analysis of their properties shows that they are neither pre-main-sequence nor post-asymptotic giant branch objects. Furthermore, their wide range of luminosities (2.5$\leq$ log $L/L_\odot$ $\leq$5.1) and location on the Hertzsprung-Russell diagram mostly within the main-sequence suggest that dust formation near hot stars may be much more common than previously thought. Analysing the IRAS data for the originally selected B[e] stars, we noticed that $\sim$20 objects had specific colors ($-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 in the IRAS photometric bands centered at 12, 25, and 60 μm, respectively, Fig. 1, left panel). Such colors are characteristic of late-type stars with CS dust (symbiotic and VV Cep binaries, and Miras) and may indicate either the presence of a cool companion or a compact dusty envelope (a lack of cold dust). The latter could be due to a recent dust formation.

On average, the Balmer lines of B[e]WD are an order of magnitude stronger than in classical 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. They also display numerous Fe II emission lines which might result from an excessive iron abundance in the CS matter, due to rotationally induced mixing of the nuclear products forming in the stellar core. However, available information about the rotational velocities show that even B[e]WD, which are seen almost edge-on, are generally slow rotators with projectional rotational velocities $v \sin i \leq 100$ km s^{-1} (e.g., Israelian et al. 1996).

Only a few B[e]WD have been extensively studied, but with no coherent outcome. For example, HD 45677 and HD 50138 were considered Herbig Be stars (e.g., Pérez & Grady 1997) because of their nebulosities. However, the lack of cold dust in their envelopes and the location outside of star forming regions call into question this interpretation (e.g., Herbig 1994). The far-IR excess is observed even in main-sequence Vega-type stars, descendants of Herbig Ae/Be stars, which show neither line emission nor near-IR excess. It is hard to explain how B[e]WD could have gotten rid of their cold dust if they were young.

The B[e]WD group includes a few high luminosity objects (e.g., MWC 300, CPD$-52°$9243, HDE 327083), similar to B[e] supergiants of the Magellanic Clouds (Zickgraf et al. 1986). The "hybrid" spectra of the latter (P Cyg type spectal line profiles in the UV region in combination with strong double- or single-peaked optical line profiles) have been explained in the framework of a two-component stellar wind model (dense and slow equatorial wind plus less dense and fast polar wind). First attempts have been made to explain dust formation around B[e] supergiants (Kraus & Lamers 2003). Modeling the SED of the LMC B[e] supergiant R126, Bjorkman (1998) showed that the matter density in the outer parts of its strong equatorial wind can be sufficiently high to form dust. However, our recent results show that MWC 300 and HDE 327083 have lower luminosities than was thought earlier (Miroshnichenko et al. 2003, 2004). Thus, B[e] supergiants may be rare in the Milky Way. This emphasizes the importance of investigation of the galactic B[e]WD, which are less luminous and whose CS dust formation has no reasonable explanation yet.

The B[e]WD group is small (19 objects, Miroshnichenko et al. 2002), since only the brightest objects with the strongest line emission have been discovered. Their optical brightnesses ($V \leq$13 mag), IR fluxes ($\sim$3–150 Jy at 12–25 μm), and distances from the Sun (1.5–3.5 kpc) suggest that more distant optically fainter objects could still have been detected by IRAS and MSX. The problem of finding B[e]WD in the Milky Way includes a high interstellar extinction near the galactic plane, where the majority of known such objects are located. Also, global objective prism surveys of the past might have missed objects with $V \geq$12–13 mag and bright emission lines.

Due to the lack of distant cold dust in their CS environments, B[e]WD occupy a well-defined region of the IRAS color-color diagram which contains $\sim$4500 sources with reliably measured fluxes in 3 IRAS bands (at 12, 25, and 60 μm). In order to estimate how large the B[e]WD group might be, we cross-correlated the list of IRAS sources with B[e]WD-like colors and recently completed all-sky surveys in the optical and IR regions (the USNO–B1.0 optical survey and the 2MASS near-IR survey). A much higher positional accuracy ($\sim 1''$) of these surveys, compared to that of 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.

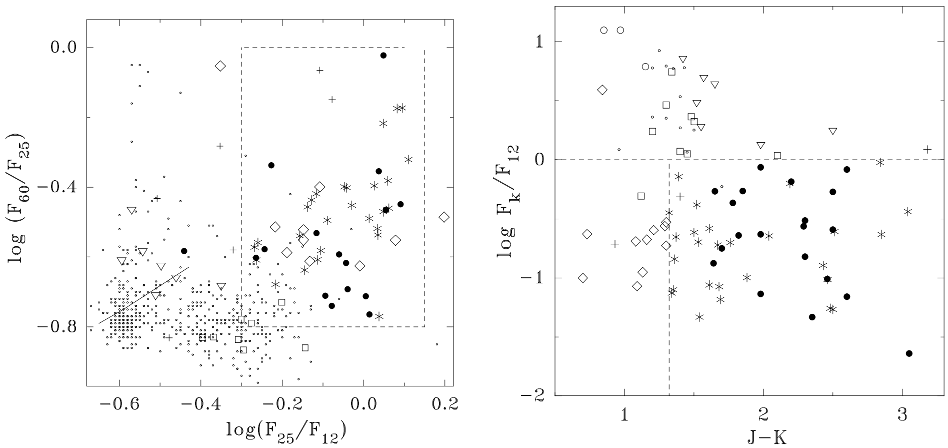

Figure 1. Left panel. A part of the IRAS color–color diagram, where the initial sample of 4500 sources was selected. B[e]WD are shown by filled circles; VV Cep binaries by open squares; Mira stars by upward triangles; carbon stars by downward triangles; optically bright M-type stars by dots; WR stars by pluses; and new B[e]WD candidates by asterisks. The solid line represents IS extinction, starting at the photospheric colors and ending at A_V=20 mag. The most probable location of B[e]WD is shown by the dash-lined box. Young stars have larger amount of cold dust and, hence, more positive IRAS color-indices. Right panel. A color-color diagram which combines data from different catalogs and spectral regions. The symbols represent the same groups of objects as in the left panel. Most of the M-type stars seen in the left panel are out of the range here. They have larger F_K/F_{12} flux ratios.

It turned out that cool stars with even moderately thick dusty envelopes have the K-band flux exceeding the IRAS 12–μm band flux (log $F_K/F_{12} \geq 0$, Fig. 1, right panel). Cool stars with optically thicker CS dust have negative log F_K/F_{12}, but they are much redder ($V-K \geq 8$ mag) than B[e]WD ($V-K \leq 7$ mag) in the optical and near-IR region. Also, RV Tau stars have smaller near-IR color-indices than known B[e]WD (e.g, $J-K \leq 1.3$ mag). Using these criteria, we identified 40 B[e]WD candidates.

We have carried out observations of 12 newly found B[e]WD candidates which show that some of them indeed exhibit strong line emission. We found that IRAS00470+6429 has a very strong Hα emission similar to those of known B[e]WD and a similar overall SED (Fig. 2). Emission in the Hα line was also detected in 8 other objects. Thus, the B[e]WD group becomes the largest among the family of dust-making early-type stars.

The very strong emission-line spectra of the group members indicate either a strong ongoing mass loss or the presence of a large amount of gas in their CS environments. For single objects, this suggests that the main-sequence evolution of intermediate- and high-mass stars may include episodes of rapid mass loss, whose causes are not known. For binaries, this implies that they are currently undergoing or have recently completed a rapid mass-exchange phase. Signatures of secondary companions have been detected in only 10 of the group's objects, but the others have not been studied enough to conclude on their binarity. Overall, the binary hypothesis to explain the objects' properties looks more

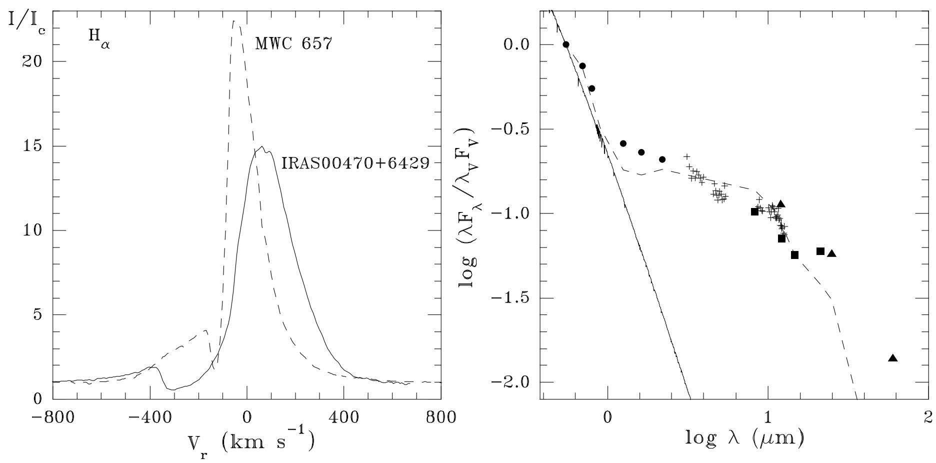

Figure 2. Left panel. The Hα line profiles in the spectra of the B[e]WD MWC 657 (Miroshnichenko et al. 2000) and a newly found B[e]WD candidate IRAS00470+6429 obtained at the 6-meter telescope of the Russian Academy of Sciences. The intensity is in units of the underlying continuum, and the radial velocity (V_r) is in km s^{-1}. Right panel. The de-reddened SED of IRAS 00470+6429 composed of our ground-based (filled circles and pluses) and satellite data (2MASS, MSX, and IRAS). The solid line represents a Kurucz (1993) model atmosphere for T_{eff}=20000 K, log g=3. The dereddened SED of MWC 657 is shown by the dashed line.

attractive and seems to get support from theoretical calculations (e.g., Wellstein, Langer, & Brown 2001).

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