Toward Understanding the Origin of the B[e] phenomenon in FS CMa Type Objects

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Abstract

Large amounts of circumstellar material accompany lives of most stars at different evolutionary stages. Formation mechanisms of these, often disk-like envelopes are not always clear. The B[e] phenomenon includes the presence of permitted and forbidden line emission and strong infrared (IR) excess in radiation observed from stars of the B and early-A types. It is found in several groups of mostly binary systems. The recently defined FS CMa group is thought to have their gas-and-dust disks due to an earlier strong mass-transfer between the binary system components. FS CMa objects seem to possess long-living disks, whose properties have not been studied well. I will be reviewing the group properties and results of a long-term monitoring program of some of its members with a focus on detected variations of the brightness and spectrum.

Keywords: *emission-line stars — circumstellar matter — stellar evolution — binary systems*

1. Introduction

Many stars and stellar systems go through evolutionary stages associated with strong mass loss or transfer that lead to formation of gaseous and/or dusty circumstellar envelopes/disks. The circumstellar material comes from protostellar clouds at early stages of star formation and from stellar wind at later stages in single stars as well as from mass transfer in systems with several components. As a result, the star or the entire stellar system gets partially or fully veiled and such features, as emission lines and continuum distortion are introduced. However, formation mechanisms of these, often disk-like envelopes are not always clear.

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Although many phenomena concerning circumstellar matter have been successfully explained by the theory of stellar evolution, some remain puzzling even with the currently available wealth of data and sophisticated modeling methods. One of them is the B[e] phenomenon that refers to the presence of permitted and forbidden emission lines in the spectra of B–type and early A–type stars (effective temperatures, $T_{\rm eff}$ = 8000–30000 K) and strong IR excess radiation due to the presence of circumstellar dust. It is found in several groups of mostly binary systems, but was originally discovered at the dawn of IR astronomy by Allen & Swings (1976).

The presence of forbidden lines gave the name to the B[e] phenomenon (Conti 1976), although did not mention the IR excess which is also a defining factor of the phenomenon. Lamers et al. (1998) recognized 4 subgroups of B[e] objects with known evolutionary status: pre-main-sequence Herbig Ae/Be stars, symbiotic binaries (a cool giant and a white dwarf or a neutron star), compact Planetary Nebulae, and a small sample of supergiants. They confirmed the conclusion by Allen & Swings (1976) that the B[e] phenomenon is found in objects at very different evolutionary stages but with similar conditions in their circumstellar environments. However, Lamers et al. (1998) were unable to assign about half of the originally selected 65 Galactic B[e] objects to any stellar group with known evolutionary status and suggested to call them "unclassified".

Studies of objects with the B[e] phenomenon have already made substantial contributions to the picture of stellar evolution. In particular, they led to the observational discovery of circumstellar disks around pre-main-sequence intermediate-mass Herbig Ae/Be stars (Mannings & Sargent 1997) and later to a new theoretical approach to the dusty disk modeling and planet formation (e.g., Meijer et al. 2008). Also, investigation of the Luminous Blue Variable binary η Carinae has changed our view of the post-main-sequence evolution of massive stars so much that a special Hubble Space Telescope Treasury Project was devoted to it (Davidson et al. 2003). The circumstellar matter formation and evolution mechanisms are still the least understood in the "unclassified" B[e] objects that led to defining the FS CMa group (Miroshnichenko 2007).

2. Properties of the FS CMa group

Galactic FS CMa objects named after the prototype B[e] star (Swings 2006) and defined by Miroshnichenko (2007) are characterized by a star of spectral types from early B to early A with a nearly main-sequence luminosity surrounded by large amounts of circumstellar gas, which powers low excitation forbidden lines and strong permitted lines, and circumstellar dust, which produces a strong IR excess. The main properties of FS CMa objects include the following. 1) A very strong line emission (Fig. 1, left panel) accompanied by free-free and free-bound radiation, which may produce a strong veiling of the stellar spectra. The circumstellar contribution to the optical brightness can be up to ±1 mag, depending on the system geometry and the tilt to the line of sight (e.g., Miroshnichenko et al. 2005). 2) A steep decrease of the IR flux at $\lambda \geq 10\,\mu$m with a typical slope of $d\log \lambda F_\lambda / d\log \lambda \leq -1.0$ that implies a compact spatial distribution of the dust, as hot stars emit enough high-energy photons to warm it even at a large distance and provide a strong far-IR flux. 3) Location not far from the main-sequence but over a wide luminosity range ($2.0 \leq \log L/L_\odot \leq 4.5$, Fig. 1, right panel) mostly determined spectroscopically. Even with the mentioned circumstellar veiling, the FS CMa objects are much less luminous than B[e] supergiants which have an average $\log L/L_\odot = 5.1$ (Miroshnichenko 2007).

The FS CMa group currently consists of 23 out of 30 original "unclassified" objects (Allen & Swings 1976) and ∼70 others found recently (Miroshnichenko et al. 2007, 2011, 2017a), and the number of the group objects keeps growing. The nature of some "unclassified" objects has been recognized (e.g., MWC 137 was found to be a supergiant, Kraus et al. 2017; MWC 922 was classified as a planetary nebula, Zasowski et al. 2015), but a few of them still remain poorly studied (e.g., MWC 819). In addition to the above mentioned defining features, we detected the presence of absorption lines of neutral metals, which typically include the Li I 6708 Å line, in the spectra of 15 group objects (Miroshnichenko & Zharikov 2015). These lines are due to cool stellar components, and their strengths suggest these components are fainter ($\Delta V \geq 2$ mag) then the hot ones (except MWC 623, Zickgraf 2001). Orbital periods have been constrained only for several group objects. A dozen other objects show radial velocity variations possibly due to orbital motion or were detected by spectro-astrometry (Baines et al. 2006) and interferometry (Millour et al. 2009). Two FS CMa objects are known to have compact secondary components: CI Cam (a white dwarf or a neutron star, Robinson et al. 2002) and AS 386 (probably a black hole, Khokhlov et al. 2018).

3. Recent results for the FS CMa group members

Typically the brightest members of most stellar groups receive more attention, but it does not mean they are better understood. The brightest members of the FS CMa group are HD 50138 ($V \sim 6.6$ mag), FS CMa ($V \sim 6.9 - 8.8$ mag, currently ∼7.5 mag), and HD 85567 ($V \sim 8.6$ mag). Although secondary components were detected in these three objects with the spectroastrometry technique (Baines et al. 2006), no other strong evidence for binarity has not been found for them (e.g., Khokhlov et al. 2017). This might be due to a low mass of the secondary component compared to

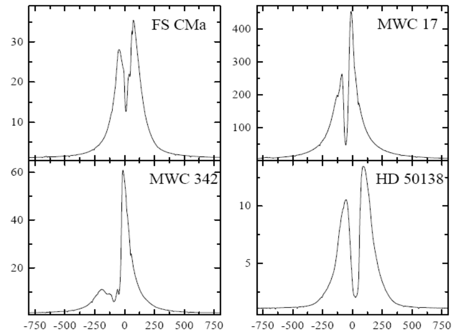

Figure 1: Left panel: Examples of Hα profiles in FS CMa objects, whose equivalent widths reach $\sim$1500 Å. Intensities are continuum normalized and radial velocities are shown in km s^{-1}. **Right panel:** Hertzsprung-Russell diagram for FS CMa objects. Solid lines: the zero-age main-sequence (ZAMS) and evolutionary tracks for single rotating stars (Ekström et al. 2012) with initial masses indicated.

that of the primary, a large orbital eccentricity along with a poor periastron epochs coverage, focus of the previous studies on mostly emission lines, a possibility of merging the secondary components, etc.

Nevertheless, we have recently managed to find orbital periods in two moderately bright FS CMa objects, MWC 728 (period 27.5 days, V $\sim$9.8 mag, Miroshnichenko et al. 2015) and AS 386 (period 131.3 days, V $\sim$10.9 mag, Khokhlov et al. 2018). The former object shows absorption lines of a cool star in the optical spectrum (see Fig. 3). We have measured radial velocity variations of this component but not those of the primary, B–type star. The pair can be resolved with interferometry, as the components' separation is supposed to be 20–30 mas at a distance of 1 kpc suggested by us. At the same time, the recent GAIA measurement of the parallax of MWC 728 (4.3$\pm$1.0 mas, GAIA Collaboration 2018) implies a closer distance which in turn implies a lower than the main-sequence luminosity for the primary component (see Fig. 2). The distance controversy may be reconciled by interferometry, but the GAIA parallax may also be erroneous because of not taking into account the secondary component.

The second object with the measured orbital period is AS 386. It shows spectral features of a lowest-luminosity supergiant (luminosity type Ib), which also contains an unusual number of absorption lines of such species as Ne I, Si II, Al II. Along with non-detection of traces of the secondary component, the latter may be a sign of mass transfer from a more evolved and more massive component. The system mass function, $f(m) = 1.9 \pm 0.3$ M$_\odot$, along with the B–type component mass (7$\pm$1 M$_\odot$) leads to a mass of ≥ 7 M$_\odot$ for the secondary component irrespective of the orbital inclination angle. No regular brightness variations have been detected in the optical range, but only a chaotic variability with an amplitude of $\Delta V \sim 0.15$ mag. Although we have found regular variations of the object's IR brightness with the orbital period, but it was explained by a variable illumination of the inner dusty rim by the B–type component. These results led us to a suggestion that the system contains a black hole as the undetected component. The latter does not reveal itself because of a lack of circumstellar matter in its immediate vicinity. The emission-line spectrum of AS 386 is weak, and an active mass-transfer process is not expected to be present. The GAIA parallax (0.19±0.02 mas) for this system is also inconsistent with our data probably due to the same problem as for MWC 728.

Other recent results from our program include confirmation of the orbital period of the A2/3 Ib[e] object 3 Pup (in prep. for publication), a detection of very small radial velocity variations in HD 85567 (Khokhlov et al. 2017), and revealing a long-term cycle in variations of the emission-line spectrum of HD 50138. We are currently closely monitoring several other objects, whose stellar and circumstellar properties have only been vaguely constrained in the past to increase our collection of well-studied objects and tune up the observing strategy for the rest of the sample.

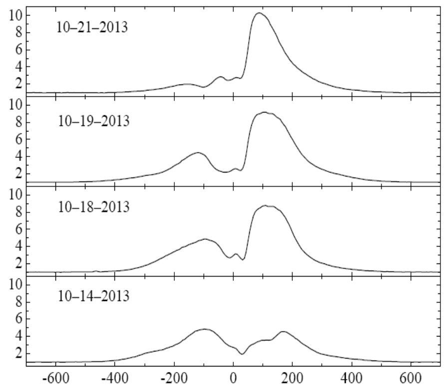

Figure 2: Left panel: Hα line variations in the spectrum of the FS CMa object MWC 728 during a week–long period (Miroshnichenko et al. 2015). The intensity and velocity are in the same units as in Fig. 1. **Right panel:** Evolutionary tracks of 5 $M_\odot$ (solid line) and 2 $M_\odot$ (dotted line) components of a close binary system with non-conservative mass loss (van Rensbergen et al. 2008). The onset of mass transfer is marked with an open circle on the track of the 5 $M_\odot$ star, while the 2 $M_\odot$ star is still near the starting point of its evolution. The tracks are shown until the end of the mass transfer stage. The dashed lines show the zero-age and terminal-age main sequence for rotating single star models (Ekström et al. 2012). The filled circles show the fundamental parameters of the MWC 728 binary components (Miroshnichenko et al. 2015).

4. Evolutionary scenarios for explaining the group properties

We have put some constraints on the evolutionary status of the FS CMa objects. There are only two classes of hot stars surrounded by circumstellar dust in their region of the Hertzsprung-Russell diagram: pre-main-sequence Herbig Ae/Be stars and post-AGB Proto-Planetary nebulae. Pre-main-sequence stars possess larger dusty disks/envelopes, exhibit stronger far-IR excesses, and retain them longer than near-IR ones (e.g., Miroshnichenko et al. 1996a) due to dust photoevaporation (e.g., Gorti & Hollenbach 2009). In contrast, FS CMa objects are not found in star-forming regions and show much weaker far-IR excesses. Post-AGB stars with initial masses of $\geq$5 $M_\odot$ are thought to evolve so fast that spectral changes due to increasing $T_{\rm eff}$ can be detected within a decade (Blöcker 1995, Miller Bertolami 2016), and their IR fluxes typically peak at $\lambda \geq$30 μm. Low-mass ($\sim$1 $M_\odot$) post-AGB stars evolve very slowly and exhibit very weak emission-line spectra. Neither of these properties of post-AGB stars is observed in FS CMa objects (Miroshnichenko 2007). Nevertheless, a thorough comparison of properties of known binary post-AGB objects (Van Winckel 2018) needs to be done to rule out a possibility that the lowest mass FS CMa objects are not currently undergoing this final stage of evolution.

The above results strongly suggest that FS CMa objects are binary systems that have undergone a phase of a strong and non-conservative mass transfer. This hypothesis is supported by our early modeling results that mass loss rates of $\dot{M} \sim 10^{-6} - 10^{-7}$ $M_\odot\,{\rm yr}^{-1}$ are required to explain the Balmer line strengths in most FS CMa objects (Miroshnichenko 2008, Carciofi, Miroshnichenko, & Bjorkman 2010). Such high rates are predicted only for single supergiants with $L \geq 10^5$ $L_\odot$ (Vink et al. 2001), while for single main-sequence early B–type stars they do not exceed $\sim 10^{-9}$ $M_\odot\,{\rm yr}^{-1}$ (Krtička 2014).

We found that neither component of the detected binary systems currently fills its Roche lobes, at least no signs of strong mass transfer have been detected in the spectral line profiles. The circumstellar disks were probably created during the mass transfer phase from the formerly more massive and currently cool or compact component. The observed line profile variations (Fig. 2, left panel) can be qualitatively explained by interaction of the disk material with the wind of the hot component that could result in creation of unusual density distributions.

Matter may also accumulate in the circumbinary area, where its density may be sufficient for dust formation. Theoretical studies of intermediate-mass binaries (e.g., Van Rensbergen et al. 2008) predict periods of strong mass transfer (up to $\sim 10^{-3}$ $M_\odot\,{\rm yr}^{-1}$ due to a Roche lobe overflow), when

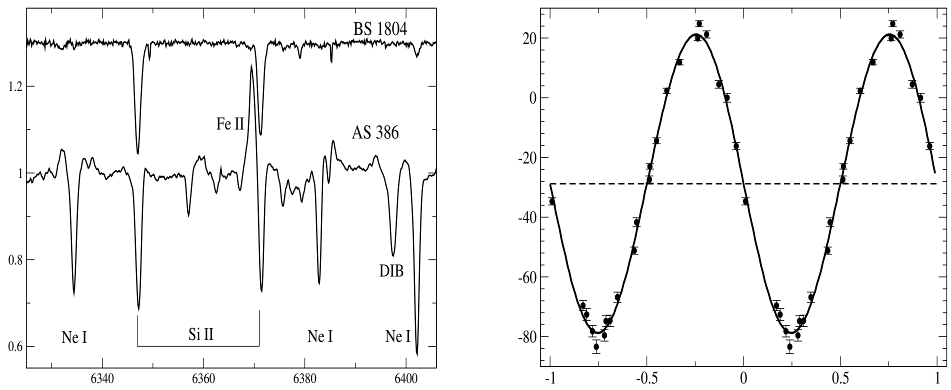

Figure 3: Left panel: Comparison of the spectrum of AS 386 with that of BS 1804 (B9 Ib). The spectra are continuum normalized and shifted with respect to each other along the vertical axis, and the wavelength scale is heliocentric and shown in Angströms. The spectrum of BS 1804 was taken at the 2.1 m telescope of the Observatorio Astronomico Nacional San Pedro Martir (OAN SPM). The shown spectrum of AS 386 is an average from several spectra that were shifted to the same (zero) heliocentric radial velocity. **Right panel:** A radial velocity curve derived from the spectra of AS 386 and folded with the orbital period. The dashed line shows the systemic radial velocity, the solid line represents the best fit to the data. The velocity is shown in km s^{-1} along the Y–axis, and the orbital phase is shown along the X–axis.

the gainer cannot accept all the mass. If this scenario is indeed working in FS CMa type objects, then there is an unaccounted channel for dust production in galaxies. Such objects have not been ever considered as dust producers (e.g., Gehrz 1989).

5. Conclusions and future work

We have defined the FS CMa group of objects with the B[e] phenomenon which most likely different from other four groups showing this phenomenon, found ∼70 new members and candidates, revealed 15 binary systems among the group members, suggested a hypothesis for the group nature and evolutionary status, published studies of 11 group members (e.g., Miroshnichenko et al. 2000, 2002, 2003, 2015, Khokhlov et al. 2017, 2018) and intermediate results of our observing program in the proceedings of the third international conference on studies of objects with the B[e] phenomenon held in 2016 in Prague (Miroshnichenko et al. 2017b), obtained a large collection of observational data, and prepared a set of tools to prove our hypothesis. This hypothesis suggests that the group represents an evolutionary stage of close, mostly intermediate-mass binary systems which have underwent a phase of a strong, non-conservative mass transfer. Part of the mass transferred from the originally more massive star was captured by the originally less massive one, but a noticeable part of this mass settled down in the circumprimary and circumbinary region. This process has most likely spun up the star which accepted the mass and is currently the hot one. The donor star is currently either a cool giant or a stellar remnant, such as a neutron star or a black hole. Evidence for the latter case is currently emerging. It is already clear that the FS CMa group is a new source of interstellar dust. A number of FS CMa objects with cool secondary components show the presence of neutral lithium, a feature that is rare and still awaiting explanation.

Since the beginning of the century, we have been collecting multicolor photometric and high-resolution (spectral resolving power $R = 12000 - 80000$) spectroscopic data for the group members and candidates. To date 50–250 spectra have been taken for the brightest group objects of FS CMa, HD 50138, MWC 342, MWC 728, MWC 623, IRAS17449+2320, and 3 Pup (which has always been classified a B[e] supergiant but may actually be closer to FS CMa objects by both mass and luminosity). Most spectra are being taken at the 2.1 m telescope of OAN SPM (Mexico), 3.6 m CFHT (Hawaii), and 0.81 m telescope of the Three College Observatory (North Carolina, USA). Various samples of the group members are also observed at the 9 m South African Large Telescope (SALT), 3.5 m telescope of the Apache Point Observatory (New Mexico, USA), the 2 m telescope of the Ondřejov Observatory (Czech Republic), 1.5 m telescope of CTIO (Chile), and 2 m Himalayan Chandra Telescope (India). Long-term data sets have also been obtained for such fainter group objects as AS 78, AS 116, AS 160, AS 174, MWC 657, MWC 1055, Hen 3–140, IRAS 07080+0605, IRAS 06341+0159, and a few more ($V = 10 - 12$ mag). The faintest objects ($V \geq 13$ mag) are being observed at a lower spectral resolution at several telescopes including the 2.6 m telescope of the Byurakan Astrophysical Observatory (Armenia), 2.1 m telescope of OAN SPM (Mexico), 1.82 m telescope of the Asiago Observatory (Italy), and the 1.5 m telescope of the Bologna Observatory (Italy).

Photometric observations in the optical spectral range are being taken at a 1 m telescope of the Tien-Shan Astronomical Observatory (near Almaty, Kazakhstan) and a set of robotic telescopes (e.g., PROMPT, Moran & Reichart 2005), while near-IR observations are being taken at 1 m telescope at Campo Imperatore (Italy) and 0.84 m telescope of OAN SPM. Since the objects are complicated, data modeling has only been done for a handful of them (e.g., Carciofi, Miroshnichenko, & Bjorkman 2010). With a better understanding of the group properties, which comes as a result of our observing program, the modeling process will become easier.

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