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FS CMa Type Objects – Products of Intermediate-Mass Non-Conservative Evolution

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Abstract. The group of FS CMa type objects was formed nearly 10 years ago based on previously unclassified objects with the B[e] phenomenon. The main observational features of the group objects include strong emission-line spectra, typical of hot stars, and infrared excesses due to radiation of mostly hot circumstellar dust. Nearly one third of the group objects exhibit various signs of a cool stellar component that indicates a binary nature. The hot components have been shown to have nearly main sequence luminosities. However, mass loss rates that are much higher than those expected from single hot stars in this region of the Hertzsprung-Russell diagram are required to explain the observed emission-line strengths. Nevertheless, spectroscopic orbits have been determined only in two cases. The evolutionary state of the FS CMa objects is still not well constrained, although several possibilities, such as pre-main-sequence stars or protoplanetary nebulae, have been eliminated. I will review typical properties of the FS CMa objects and focus on a few well-studied examples. Possible evolutionary scenarios leading to the observed features will be discussed. Searching strategies for finding more group objects as well as their predecessor and successor objects will be outlined.

1. Motivation to Study Unclassified B[e] Objects

The history of studies of objects with the B[e] phenomenon has been summarized several times now at the Vlieland conference (e.g., Swings 2006; Zickgraf 2006) and here in Prague (see Swings and Oudmaijer & Miroshnichenko, this volume). The main goal of this talk is to describe the evolution of our views at probably the least understood group of B[e] objects, the FS CMa group. The group emerged from what Lamers et al. (1998) called unclassified objects with the B[e] phenomenon (unclB[e]), i.e., the objects with properties of more than one group or not enough information to determine their fundamental parameters.

My collaborators and I started to look at objects with the B[e] phenomenon already in the middle of 1980's in an attempt to enlarge the group of pre-main-sequence Herbig Ae/Be stars (HAeBes) and study their properties with simultaneous multicolor (optical and near-IR) photometry. This project has resulted in a number of studies of individual objects (e.g., Bergner et al. 1988, 1990; Miroshnichenko 1995) as well as in two catalogs of multicolor photometry of HAeBes (Bergner et al. 1993) and unclB[e] stars (Bergner et al. 1995). In the course of this program, we noticed that a number of unclB[e] objects exhibit a steep decrease of the IR flux toward longer wavelength at $\lambda \geq 10\mu$m. Examples of such spectral energy distributions (SED) are shown in Arkharov et al. and Kuratova et al. (this volume). This feature is unusual in HAeBes which are hot stars with large dusty disks and, as a result, typically have flat SEDs in this wavelength range.

We made an initial suggestion that the unclB[e] objects with the declining IR flux were evolved at least to the end of main-sequence and recently formed their own circumstellar dust. The first small list of 11 such objects, four of which have been found to be supergiants (MWC 300, HD 327083, CPD−52°9243, and CPD−57°2874) and luminosity of the other seven were more uncertain, was published by Sheikina, Miroshnichenko, & Corporon (2000). The group was initially called "Be stars with warm dust" (BeWD). The name turned out to be somewhat misleading, as it has not mentioned forbidden lines and was reminiscent of white dwarfs.

The reasons for the lack of far-IR emission, relation to classical Be stars, role of binarity in creation of this particular phenomenon, and rarity of these objects were very unclear at that time. At the same time, only a few of them have been studied well enough to determine their intrinsic properties (i.e., stellar fundamental parameters and evolutionary stages, distribution of the circumstellar gas and dust, distances, etc.). All these problems have prompted us to study these objects closely and search for more candidates in existing all-sky surveys (see Kuratova et al., this volume).

2. The FS CMa Group and Its General Properties

At the Vlieland conference, the new group was renamed to FS CMa type objects following the suggestion by Swings (2006) that the star FS CMa = HD 45677 was a good prototype object for the B[e] phenomenon. The name change was finalized by Miroshnichenko (2007), who defined typical features of these objects and presented a list of 23 of those that were most likely not supergiants, HAeBes, or symbiotic binaries. The features, which have been quoted in many papers now (see, e.g., de la Fuente, Najarro, & Garcia, this volume), include a range of spectral types from early B to early A; a luminosity range of $2.5 \lesssim \log(L/L_\odot) \lesssim 4.5$); the IR flux drop at $\lambda \geq 10\mu$m mentioned above; and location outside of star forming regions.

Ten new FS CMa objects were reported by Miroshnichenko et al. (2007) and 16 more candidates found using purely photometric criteria (see Kuratova et al., this volume) were added by Miroshnichenko et al. (2011). The latter have been studied spectroscopically along with more recently found ones (see Miroshnichenko, Rossi, Polcaro, et al., this volume). Currently the FS CMa group comprises nearly 70 members and candidates.

Emission-line spectra of the FS CMa objects are typically very strong (see, e.g., Fig. 1). Miroshnichenko (2008) found that equivalent widths of the Hα line in their spectra are typically a factor of 10 or more larger than those classical Be stars of the same B-subtype. Based on this result and later studies of individual group objects (e.g., Carciofi, Miroshnichenko, & Bjorkman 2010) as well as on comparison with theoretical predictions for mass loss from single stars (Vink, de Koter, & Lamers 2001), it has been concluded that single B-type stars of the above mentioned luminosity range cannot produce so much circumstellar matter to explain the observed emission-line strengths and IR excesses. Therefore, Miroshnichenko (2007) suggested that most of the FS CMa objects are binary systems which underwent periods of non-conservative mass transfer that resulted in creation of a gaseous disk around the B–type component and a gaseous-and-dusty circumbinary envelope.

The projectional distribution of the group members in the Galaxy is shown in Fig 2. It is seen that most objects are located near the galactic plane. Those found noticeably beyond the $b = \pm 5°$ zone marked by the solid lines are typically not far from the Sun (e.g., HD 50138 at ~300 pc and FS CMa at ~500 pc). The most puzzling is the location of FBS 0022–021 at $b = -64°$ (see Zharikov, Miroshnichenko, Towmassian, et al., this volume). The distance distribution shown in Fig. 6 of Miroshnichenko (2006)

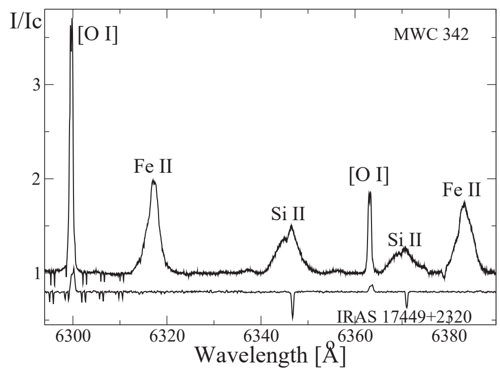

Figure 1. High-resolution spectra of two FS CMa group members with a very different strength of emission-line spectra. MWC 342 with very strong emission lines is an early B–type star from the original list of Allen & Swings (1976) with no clear detection of lines from the star's atmosphere. IRAS 17449+2320 is one of the coolest stars of the group from a recent list by Miroshnichenko et al. (2007) with easily detectable atmospheric lines. Both spectra were taken with the spectropolarimeter ESPaDoNs Donati et al. (1997) at the 3.6 m CFHT ($R \sim 65000$). The spectra are normalized to the local continuum. Double absorption lines around the [O I] 6300 Å emission line are telluric.

did not change much for the last 10 years. Several new distance estimates (e.g., ~1.0 kpc for MWC 728 Miroshnichenko et al. 2015) added more points beyond 1 kpc from the Sun, but no more closer objects have been found. It still remains puzzling why there are not many bright FS CMa objects, although the numbers of binary systems with a Be component and Algols (these two groups may be evolutionary connected to the FS CMa objects) in the vicinity of the Sun is not small.

The apparent brightness distribution in the optical (*V*–band) and near-IR (*K*–band) is shown in Fig. 3. The former peaks at $V \sim 12$ mag, and the latter peaks at $K \sim 8$ mag. This makes possible photometric monitoring of most of the group objects at small telescopes. It has been shown that some group objects are significantly variable in both mentioned spectral regions (e.g., MWC 342 shows variations on the order of 1 mag, Bergner et al. 1995). Recent results of the near-IR photometric monitoring are reported by Arkharov et al. (this volume).

The location of the FS CMa group objects on the *IRAS* color-color diagrams (log F_{25}/F_{12} versus log F_{60}/F_{25}, where F_{12}, F_{25}, and F_{60} are fluxes in the corresponding *IRAS* bands) is shown in Fig. 1 of Miroshnichenko (2006) and for a larger selection of comparison objects in Fig. 1 of Miroshnichenko (2007). The FS CMa objects are located together with such cool star dominated systems as symbiotic binaries and VV Cep binaries and noticeably separated from the region of objects surrounded by circumstellar dust, which is either just cold (Vega-type stars with debris disks) or has a wider range of temperatures (HAeBes).

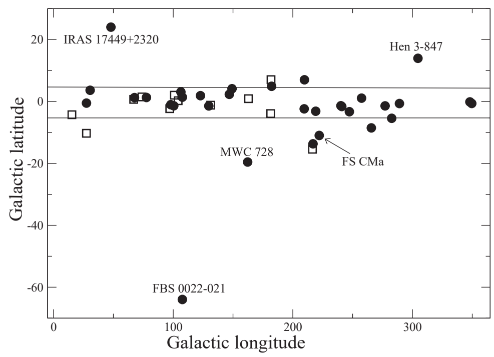

Figure 2. Projectional distribution of FS CMa type objects in the Milky Way. Filled circles show objects from Miroshnichenko (2007) and Miroshnichenko et al. (2007) and open squares show recently found objects with a steep decrease of the IR flux (see Miroshnichenko et al., this volume). Galactic coordinates are shown in degrees. The solid lines mark a ±5° zone around the Galactic equator.

The location of 12 FS CMa type objects, whose fundamental parameters have been determined or estimated reasonably well, in the Hertzsprung-Russell diagram (HRD) is shown in Fig. 2 of Miroshnichenko (2007). Parallaxes were measured by *HIPPARCOS* mission for only the two brightest objects of the group (HD 50138 and FS CMa), while distances of the other 10 were determined by measuring radial velocities of various spectral lines (e.g., Fe II) and comparing them with models of the Galactic rotation curve. Since that time, parameters of several objects have been updated and those of a few more have been measured (e.g., MWC 728, Miroshnichenko et al. 2015). An updated distribution of the FS CMa objects in the HRD is shown in Fig. 4. With a recent luminosity determination for IRAS 17449+2320 using a parallax measured by *GAIA* (GAIA Collaboration 2016, the lowest luminosity object shown in Fig. 4, see also Sestito et al., this volume), the above mentioned luminosity range for the FS CMa group extends to $2.0 \lesssim \log(L/L_\odot) \lesssim 4.5$. This implies that the FS CMa objects are even more common in the Milky Way.

3. Survey of the FS CMa Group Members

The FS CMa group objects whose properties have been studied in reasonable details include FS CMa (Muratorio, Rossi, & Fredjung 2006), HD 50138 (Bjorkman et al. 1998; Jeřabková et al. 2016; Kluska et al. 2016), MWC 342 (Miroshnichenko & Corporon 1999; Kučerová et al. 2013), MWC 623 (Zickgraf 2001; Polster et al. 2012), IRAS 00470+6429 (Miroshnichenko et al. 2009; Carciofi, Miroshnichenko, & Bjorkman 2010), MWC 728 (Miroshnichenko et al. 2015). Regular variations of both optical brightness and radial velocity of absorption features have been detected only for GG Car (Gossett et al. 1985; Marchiano et al. 2012; Kraus et al. 2013), which has still a controversial classification as either a sgB[e] or a FS CMa object. Regular radial velocity variations only have been detected in CI Cam (Barsukova et al. 2006) and MWC 728 (Miroshnichenko et al. 2015). Ten other FS CMa objects were suspected in binarity by either detection of absorption lines of neutral metals (e.g., Li I 6708 Å) or by spectro-astrometry (e.g., Baines et al. 2006). A recent review of the binary FS CMa objects was published by Miroshnichenko & Zharikov (2015).

Initial studies of some other FS CMa group members published before it was defined include AS 78 and MWC 657 (Miroshnichenko et al. 2000), HD 85567 and Hen 3–140 (Miroshnichenko et al. 2001), AS 160 (Miroshnichenko, Klochkova, & Bjorkman 2003), and AS 119 (Miroshnichenko et al. 2006). Along with more recent studies (e.g., Miroshnichenko et al. 2015, and Khokhlov et al., this volume), the above mentioned papers provided a good foundation for solving the problem of the nature and evolutionary status of the FS CMa group.

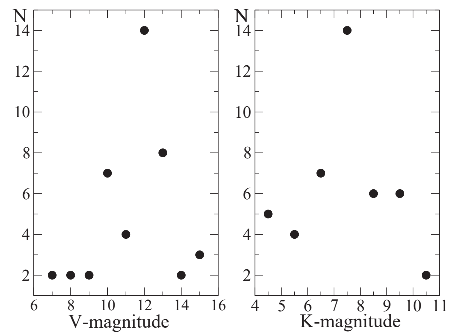

Figure 3. Apparent brightness distribution of FS CMa type objects in the V- and K-bands. The same set of objects as in Fig. 1 is shown here. The number of objects within a 1-mag bin is shown versus the mean brightness.

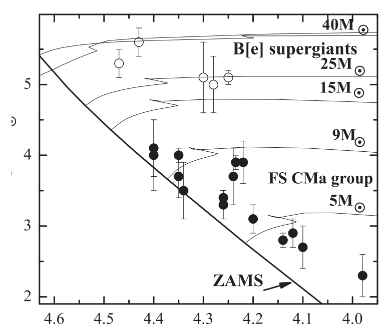

Figure 4. HRD with positions of some FS CMa type objects and B[e] supergiants. The solid lines show the zero-age main-sequence and evolutionary tracks for rotating single stars with the solar composition from Ekström et al. (2012) with the initial masses indicated.

Regular high-resolution (R = 10000 − 65000) spectroscopic observations of many group members have been carried out at a number of observatories, mostly at the Observatorio Astronómico Nacional San Pedro Martir (OAN SPM, Mexico), CFHT and McDonald (USA), Ondřejov (Czech Republic), but also at Complejo Astronómico El Leoncito Argentina), CTIO (Chile), and the Three College Observatory operated by the University of North Carolina at Greensboro (USA). Low-resolution (R = 700 − 6000) optical and near-IR spectroscopy of fainter or recently selected group candidates has been taken at the Asiago Observatory (Italy), OAN SPM, and Lick Observatory (USA).

Multicolor photometric observations in the optical (*UBVRI*) and near-IR (*JHK*) region have been taken at a set of robotic 0.4–0.6 m telescopes (PROMPT, Reichart et al. 2005), Campo Imperatore (Italy), OAN SPM, and the Tien-Shan Astronomical Observatory (Kazakhstan). IR spectra of nearly 30 group members were obtained with the Spitzer Space Observatory, and their initial analysis was reported in (Miroshnichenko et al. 2011). The ground-based monitoring continues, and new results will be published soon (e.g., on HD 85567, Khokhlov et al. 2017).

4. Evolutionary Scenarios

Until recently, two main hypotheses about the origin of the FS CMa objects were considered: intermediate-mass binary systems which underwent a phase of non-conservative mass transfer in the past and a stage of evolution of proto-planetary nebulae before the nebulae become detectable in the optical region (Miroshnichenko 2007). de la Fuente et al. (2015, and this volume) added a merger hypothesis by finding two seemingly FS CMa objects in relatively young Galactic clusters with narrow-band photometry and near-IR spectroscopy. At the same time, non-detection of a secondary component features in a limited set of data does not prove it is not present. Observational criteria based on possible consequence of a merger need to be established to distinguish a merger from a binary with a large brightness difference between the components.

Many binary systems at the proto-planetary evolutionary stage exhibit IR excesses, similar to those of the FS CMa objects, but weaker emission-line spectra. They also contain primary components of later spectral types and have longer orbital periods (over 100 days, see Van Winckel, this volume) compared to those measured for several FS CMa objects (typically a few weeks). It cannot be excluded that some FS CMa objects can represent a more advanced stage of evolution of the proto-planetary binaries. However, no objects with a strong emission-line spectrum and a strong, declining toward longer wavelengths IR excess have been found among proto-planetary nebulae that are powered by a B- or an A-type star (70 such objects are listed in a catalog by Szczerba et al. 2007).

Therefore, the most probable scenario for producing FS CMa objects supported by existing data is evolution of a close binary system, which undergoes a strong mass transfer resulting in a loss of some of this mass into the circumbinary space and formation of a dusty envelope or disk. It was found applicable to the case of MWC 728 (Miroshnichenko et al. 2015). Evolution of intermediate-mass binary systems has been studied theoretically in several papers (e.g., van Rensbergen et al. 2008; Deschamps et al. 2015). According to some of these models, the mass transfer phase occurs when the more massive (primary) component fills its Roche lobe. It results in the component's mass ratio reversal that makes the former primary much less massive and cooler (down to a K-type star by the end of this phase); acceleration of the evolution of the former secondary which becomes a B-type star; and the brightness ratio reversal, so that the B-type star gets several magnitudes brighter than the former primary.

Our observations show evidence for some of these processes in all FS CMa objects with detected signatures of a cool component (e.g., Miroshnichenko & Zharikov 2015). The objects' mid–IR spectra show broad silicate features at 9.7 μm and other bands in emission which suggest that the circumstellar dust was not formed very recently, and processing by stellar radiation resulted in forming crystalline structures in dusty particles. Also, neither known FS CMa binary shows signs of ongoing mass transfer.

The remaining case of CI Cam may also fit within the above scenario. This system seems to contain more massive components but can also be even more complicated (see Goranskij et al., this volume). Some of the hottest group members may be similar to CI Cam (e.g., MWC 342 which has a close X-ray source detected in the 1970's with a low positional accuracy, Bergner et al. 1990). It is worthwhile taking X-ray observations of early B-type FS CMa objects with strong emission-line spectra, such as MWC 17, MWC 645, MWC 1051, MWC 1055, and V669 Cep.

5. Summary and Conclusions

Our extensive search for candidates to the FS CMa group in large data bases of precise positions and photometry and follow up photometric and spectroscopic observations resulted in constraining their basic properties and discovering some previously unnoticed features. In particular, it has been found that nearly 30% of them are binary systems with a brighter B-type primary and a 2–4 magnitude fainter G- or K-type secondary component. The B-type stars have luminosity in a range from about 100 to $5\,10^4$ $L_\odot$. The luminosity typically contains no correction for the circumstellar extinction, which may be noticeable for the hottest objects with the strongest emission-line spectra but is expected to be within a factor of ~2 (e.g., Carciofi, Miroshnichenko, & Bjorkman 2010). The circumstellar gas is present around the B–type stars and has a disk-like geometry that is deduced from mostly double-peaked lines profiles. The strong IR-excess that usually peaks at $\lambda \sim 10\mu$m indicates that the circumstellar dust is distributed compactly, not being extended far from the sublimation distance.

One of the recently discovered features is the presence of the Li I 6708 Å line in the spectra of all FS CMa binaries with a cool secondary component which was initially detected only in the spectrum of MWC 623 (Zickgraf 2001). The existence of neutral lithium, which is easily destroyable in stellar interiors, in the atmospheres of evolved stars has not been unambiguously explained but may lead to important clues to revealing process accompanying the systems evolution.

The other feature that we put in our focus recently is a fast variability of the Balmer emission lines. It did not get much attention earlier because of infrequent spectroscopic observations of the FS CMa objects that is mostly due to their relative faintness. Examples of such variations have been observed in the spectra of HD 50138, MWC 728, and HD 85567 where peak intensity ratios of the Balmer line profiles on a time scale of a few days (e.g., Miroshnichenko et al. 2015; Miroshnichenko & Zharikov 2015; Khokhlov et al. 2017). The variations may be due to varying contributions of the stellar wind and the gaseous disk to the line profiles and need further attention with modeling to understand better the relationship between the disk and wind. At the same time, they can also be partly explained by orbital motion of the system components (see Fig. 4 by Van Winckel in this volume). We have found no clear connection between these variations and the orbital phase in the spectral variation of the only confirmed binary (MWC 728) in this set of three objects.

There is a number of questions that need to be answered to reveal the nature and processes in the FS CMa objects. They include finding precursors and successors of the group objects, constraining the time of the dust formation onset and its duration, finding reasons for the lack of nearby objects, searching for more group candidates affected by a stronger reddening, etc. Another important question is how stable the circumstellar disks of the FS CMa objects are. Unlike those of classical Be stars which disappear from time to time and get renewed within a few years (e.g., Bjorkman et al. 2002), the circumstellar matter around FS CMa objects seems to be more stable. No observation of the line emission or IR-excess disappearance in any of the group objects has been reported for over a century.

Strong photometric variations have been reported for several FS CMa objects. MWC 342 shows both optical and near-IR (ΔV and $\Delta K \sim 1$ mag) brightness variations on a time scale of a few years (Bergner et al. 1995). FS CMa showed a slow fading from $V \sim 6.5 - 7.0$ mag in the end of 1960s to $V \sim 8.8$ mag in the end of 1980s and has not reached the pre-fading brightness level yet (Miroshnichenko 1998). This phenomenon has only been explained by a proto-comet evaporation, assuming the object was a pre-main-sequence star (Sitko et al. 1994). MWC 17 shows variations of the near-R brightness with an amplitude of $\Delta K \sim 1$ mag (see Arkharov et al., this volume). These are just a few remarkable phenomena that await explanation.

Despite all the above mentioned questions, it has become clear that evolution of binary systems with non-conservative mass transfer plays a crucial role in creation of the B[e] phenomenon in FS CMa type objects. There can be several groups of such binaries that go through this stage of evolution. The luminosity range of the group objects spans over two orders of magnitude suggesting that many more such objects should exist in our Galaxy as well as in others. Analysis of their IR-excesses allows to suggest the presence of large amounts of circumstellar dust around the FS CMa objects and their important, but still unaccounted role as dust producers in galaxies.

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