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Long-Term Spectroscopic Monitoring of B[e] Stars at the Ondřejov Observatory

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Abstract. We present a project devoted to a systematic spectroscopic monitoring of stars showing the B[e] phenomenon. The observations have been performed during the past thirteen years with the Perek 2 m telescope at the Ondřejov Observatory, Czech Republic. Most of the studied objects are of the FS CMa type. We were able to detect expanding layers, rotating structures in the disk, and signatures of material outflow and inflow. Some of the objects show different behavior in different observation epochs. The amount of obtained material is currently sufficient to allow more detailed studies using numerical modeling.

1. Why Long-Term Observations?

The B[e] stars are covered by a large amount of circumstellar matter. Moreover, the structure of the circumstellar matter is very complicated. A model suitable for the analysis has to combine 3D time-dependent hydrodynamics together with 3D non-LTE radiative transfer in moving media. No such code is currently available. Therefore, the standard analysis can be questionable. The way out of this problem is a long-term monitoring campaign that would at least allow the basic properties and physical effects that take place in the chosen object to be determined.

Spectral lines of B[e] stars, especially of sgB[e], HAeB[e], and FS CMa type stars, are variable on many timescales. Lines forming in the inner parts of the system usually show night-to-night variability. On the other hand, outer regions are more stable and lines forming there vary on timescales from weeks to years. While HAeB[e] stars and sgB[e] are relatively well observed, the data for FS CMa type stars are very poor. Therefore, we devote this paper to these objects.

Night-to-night variability can be detected in the He I $\lambda\lambda$ 5876 and 6678 Å lines. Depending on the object, we observe pure absorption (e.g., MWC 623, Polster et al. 2012), or changes of the profile from a pure absorption to pure emission, P Cygni or inverse P Cygni profiles (FS CMa, Kříček 2013; HD 50138, Pogodin 1997, Borges Fernandes et al. 2012, and Jeřábková et al. 2016; MWC 342, Kučerová et al. 2013). Even a more complicated behavior is observed in the Si II $\lambda\lambda$ 6347 and 6371 Å lines. The night-to-night variability was observed, e.g., in FS CMa (Kříček 2013) and HD 50138 (Jeřábková et al. 2016). However, MWC 342 (Kučerová et al. 2013) and MWC 623 (Polster et al. 2012) show a relatively stable pure emission. To describe the night-to-night variability, a short observing campaign is not sufficient in this case, because the behavior of lines can change over the years (e.g., FS CMa, Kříček 2013).

Most of the spectral lines of the B[e] stars show changes on longer timescales. Even the forbidden lines, the emitting region of which is far from the central object, are variable. Formerly, these outer regions were supposed to be very stable. However, e.g., [O I] lines $\lambda\lambda$ 6300, 6364 Å of MWC 342 (Kučerová et al. 2013), show a strong variability. EW of these lines changed between 2004 and 2010 from -1.5 to -3.3 Å for the [O I] 6300 Å line and from -0.55 to -1.1 Å for the [O I] 6364 Å line. Moreover, the observations of HD 50138 over the last twenty years revealed a clear mutual dependence of the [O I] lines and the Hα variability (Jeřábková et al. 2016).

The description of the long-term variability is critical for the B[e] stars, because they show various periods in different epochs as has been found in photometric observations of MWC 342 (Shevchenko et al. 1993; Mel'nikov 1997; Chkhikvadze et al. 2002). Recently, this behavior was also found in spectroscopic data (Jeřábková et al. 2016) for HD 50138.

In the view of these findings, importance of long-term monitoring of the B[e] stars arises. The found periodicity over a few years could only be a reflection of a real multi-periodicity, quasi-periodicity, or even chaotic behavior of the object (Votruba et al. 2009).

Unfortunately, long-term studies are unfavorable nowadays. There are no fast results and no guaranteed progress. Does it make sense to start a long-term monitoring campaign of these stars? Can we determine physical processes which take place there?

What can be found?

- **proof of binarity**
  Currently, the binary nature is the most crucial question in stars of the FS CMa type. The evolutionary models of a single star are not able to produce such a large amount of matter. On the other hand, an insufficient number of binaries has been detected. This problem is described in detail in, e.g., Miroshnichenko & Zharikov (2015).

- **description of the mass transfer processes**

- **rotating structures**
  The rotating structures are unambiguously detectable in line profiles (e.g., Jeřábková et al. 2016).

- **proof of pulsations**

- **origin of the stellar wind**
  The radiative force in B-type stars is too weak to be able to kick-start a stellar wind by itself. The fast rotation, or pulsations can initialize the material outflow. The determination of the influence of stellar pulsations can be done by analyzing the short-term line-profile changes in different epochs.

- **dynamics of the stellar wind**
  The effects of the wind decoupling and clumping can be studied via this kind of observations.

- **variability of the stellar wind**

- **material infall**
  Some of these stars show permanent signatures of material infall, but for some of them it is a very scarce event. MWC 342 is such an example. The inverse P Cygni profile was observed only once in 102 spectra during seven years (2004 – 2010, Kučerová et al. 2013). When this event is not detected in a short time campaign or restricted data sample, one of the most important physical processes is absent for the modeling of a system.

- **expanding layers**

- **excitation waves**

- **other processes**
  The extreme conditions around the B[e] objects give us the opportunity to study exotic physical processes and rare evolutionary scenarios. Based on observations of globular clusters, de la Fuente et al. (2015) found signatures that FS CMa type stars could be post-merger systems. The collisionless plasma and rotating spiral arms establish good conditions for the transit time damping effect (Suzuki et al. 2006) in the presence of a magnetic field.

Long-term monitoring can point to the basic physical processes that take place in the object. Unfortunately, there are almost no such observations. The most extensive is the work of Merrill (1931). However, in the 1920s the photographic plates were insensitive in the red, therefore, the observations were carried out almost entirely in the Hβ region. Currently, A. Miroshnichenko leads the project of spectroscopic and photometric observations of the B[e] stars of FS CMa type (see Miroshnichenko, this volume). However, only a few professional observatories are involved in this project. The excellent work has been done by amateurs[1]. Unfortunately, most of the objects from Miroshnichenko's list are too faint for small telescopes.

The importance and lack of observations of the B[e] stars were a motivation for starting our own spectroscopic monitoring of the B[e] stars. The project has been running since 2004. During this time, we have obtained more than 560 good-quality spectra appropriate for the analysis.

2. Observation and Analysis

We used the Perek 2 m telescope located at the Ondřejov Observatory, Czech Republic. We took spectra using the Coudé slit spectrograph with the CCD camera placed in the 700 mm focus. To achieve a sufficiently fine temporal resolution, the sample of stars and the spectral region had to be very restricted. We chose the region around the Hα line (from 6265 Å to 6770 Å, see Fig. 1). This spectral interval contains the forbidden

[1] http://basebe.obspm.fr/basebe/MenuIntro.php

emission lines [O I] $\lambda\lambda$ 6300, 6364 Å that form in the outer parts of the envelope; the Si II $\lambda\lambda$ 6347, 6371 Å and He I 6678 Å lines that originate in the inner parts; and the Hα line that forms over a large range of distances from the star. Therefore, starlight can be affected by a range of phenomena as it passes through the entire envelope. The resolving power in this spectral region is $R \sim 12\,500$.

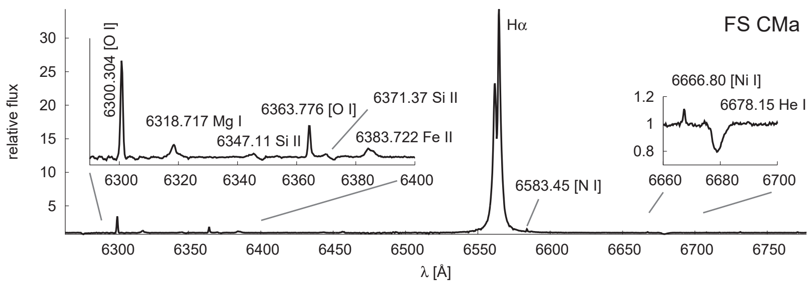

Figure 1. The most frequently used spectral interval.

The most significant limitation was the restriction of the stellar sample. It was reasonable to include only three winter and four summer stars in the program (see Table 1). Later, it was possible to extend the list of the observed stars thanks to the cooperation with two other observatories: Three College Observatory (near Greensboro, North Carolina, USA; A. Miroshnichenko) and Observatorio Astronómico Nacional San Pedro Mártir (Mexico; S. Zharikov).

Table 1. List of observed stars

object	V [mag]	group	published results
FS CMa (MWC 142)	8.5	prototype of the B[e] subgroup	R. Kříček – Bc., Master Thesis in preparation
V743 Mon (HD 50138)	6.6	FS CMa type	Jeřábková et al. (2016)
OY Gem	11.1	compact planetary nebula	in preparation
V431 Sct (MWC 300)	10.5	supergiant	
V2028 Cyg (MWC 623)	10.5	FS CMa type	Polster et al. (2012)
V1972 Cyg (MWC 342)	10.6	FS CMa type	Kučerová et al. (2013)
IRAS 17449+2320	10.0	FS CMa type	in preparation
MWC 728	9.8	FS CMa type	Miroshnichenko et al. (2015)
AS 116	10.4	FS CMa type	
IRAS 00470+6429	11.5	FS CMa type	
MWC 645	12.5	FS CMa type	
V669 Cep	12.5	FS CMa type	

Table 2. The scale of the variability of selected stars.

Period	object	quantity
(4.3 ± 0.1) yrs	MWC 342	*rv* of the Hα central depression
(8.3 ± 1.4) ∧ (14 ± 3) yrs	HD 50138	*EW* of the Hα and [O I] 6300 Å
		rv of the violet peak
(300 ± 50) d	HD 50138	*EW* of the Hα after the global trend subtraction
(600 ± 50) ∧ (50 ± 10) d	HD 50138	V/R of the Hα ($P \sim 50$ d also Doazan 1965)
∼ 34 d	HD 50138	*rv* of the Hα red peak and Hβ central depression
		($P \sim 30$ d also Merrill 1931)
∼ 4.5 yrs	MWC 623	radial velocity of the Hα peak

The data were reduced in `IRAF`[2] without the optimal extraction, and for cleaning of cosmic rays the program `dcr` (Pych 2004) was used. Special attention is devoted to the extraction of night-sky lines and spectra normalization. The technique of spectrum normalization has to reflect the character of the individual stellar spectra.

The properties of individual spectral features have to be taken into account in the measurements of radial velocity (*rv*), equivalent width (*EW*), and peak intensities (F). Depending on the shape of the spectral lines, polynomial fitting, Gaussian/Voigt function fitting, or cross-correlation were used. Special attention was given to the error estimates, which are critical for the further analysis of the temporal variability. The spectral properties and their variability of individual stars were so different that the specific technique for the analysis was required for every star.

3. Results and Conclusion

Our main purpose is to analyze the obtained spectra without the assumption of some models, without using theoretical spectra. This requirement is not typical, especially today. But, this kind of basic analysis has not been done for the chosen stars. Considering that the standard theoretical spectra do not reflect geometry and physical conditions in the envelopes of these objects, such a first step is critical for the analysis of the FS CMa stars. Leaving the standard technique, one must have something which provides the determination of the underlying physical effects. Such information is hidden in variations of *rv*, *EW*, line bisectors, V/R changes, and correlations between the individual quantities.

We already published results of the analysis of MWC 623 (Polster et al. 2012), MWC 342 (Kučerová et al. 2013), and HD 50138 (Jeřábková et al. 2016). MWC 623 shows variations in F, *EW*, and width of the Hα line on a timescale of about 4.5 years. The variability of the Hα bisectors offers a good base for further modeling (Polster, in preparation). We found signatures of expanding layers together with evidence of the material infall in MWC 342. While the inverse P Cygni profile is very rare in the MWC 342 spectra, HD 50138 shows material inflow simultaneously with outflow.

[2] `IRAF` is distributed by the National Optical Astronomy Observatories, operated by the Association of Universities for Research in Astronomy, Inc., under contract to the National Science Foundation of the United States.

Moreover, we detected rotating structures in the circumstellar media of HD 50138. This star supports the previously suggested idea about the different behavior of these objects in different epochs. We found no distinctive period. The spectral features show the different scales of variability (see Table 2), which is quasi-periodic rather than regularly periodic.

The spectral properties and the scale and size of the variability of selected FS CMa type stars are so dissimilar that every star requires a special technique for the analysis. The amount of the observed material is currently sufficient to allow the construction of a model of individual systems, which was the main goal of the project.

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