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Tracing Physical Processes Affecting Spectral Formation in the Low-luminosity B[e] Stars of the FS CMa Group

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Abstract. In order to help model the circumstellar environment of FS CMa stars, we summarize the spectral features of these objects and point to physical phenomena that affect the structure of the circumstellar region.

1. Introduction

Nowadays, most stellar groups can be modeled properly and have a well understood evolutionary status. Due to the presence of circumstellar matter, which complicates analysis, and to a lack of observations, FS CMa stars present an exception.

Currently, the second point does not represent such a huge problem as a few years ago. The description of spectroscopic and photometric properties and behaviour is sufficient to develop a model of these stars now. Night-to-night variability of spectral lines has been shown well by Pogodin (1997) for HD 50138. Long-term changes have been described by Polster et al. (2012); Kučerová et al. (2013); Miroshnichenko et al. (2015); Jeřábková et al. (2016). Moreover, the interferometric measurements are now at the disposal. The first interferometric analysis was done by Monnier et al. (2006) for MWC 342. A decade later, Kluska et al. (2016) were able to apply interferometric imaging to HD 50138, not only to reconstruct the structure of the circumstellar matter, but also to show that the morphology of the system changed between years 2010 and 2013.

The usage of standard techniques for the analysis of FS CMa objects is very limited. The amount of circumstellar matter in some cases is so large that it excludes photospheric lines from the analysis. This is a reason of large errors in determination of the stellar parameters. Despite this, HR diagram (Miroshnichenko 2017) shows that FS CMa stars are located near the terminal main sequence or somewhat beyond it.

Another limitation of standard techniques is a lack of sophisticated modelling. Only one detailed calculation of hydrogen line profiles and IR excess for the FS CMa object IRAS 00470+6429 has been done by Carciofi et al. (2010). Usage of the 3D non-LTE Monte-Carlo code `HDUST` allowed determination of the mass-loss rate $\dot{M} \sim (2.5-2.9)\times10^{-7}\ M_{\odot}$/yr. However, IRAS 00470+6429 is among a few FS CMa stars with P Cyg line profiles, while most other group members show double-peaked profiles typical for disks. Up to now, this is the best synthetic spectrum of FS CMa stars. Unfortunately, it is still insufficiently accurate. Hα itself is not an optimal indicator of $\dot{M}$. Even if its line-forming region covers a large portion of the circumstellar region, it does not describe all of it. Another problem is that only hydrogen was included into the calculations by Carciofi et al. (2010). As shown below, coupling with oxygen is important in the environment of FS CMa stars as well as strong absorption by metals in the UV spectral region.

2. Spectral features

One of the features that distinguishes FS CMa stars from classical Be stars lies in the UV region. In contrast to classical Be stars, strong absorption of metals appears in the spectra of FS CMa stars (Fig. 1). It creates a so called *"iron curtain"* observed in classical novae, symbiotic stars, and B[e] supergiants. The appearance of this feature in FS CMa stars is overlooked in the literature, however, it is the key driver for the optical FeII and permitted and forbidden lines. The radiative energy is redistributed in this way into the visual and IR regions, where spectral lines of, e.g., iron are seen in emission or broad emission overlapped on absorption.

Another signature of the ultraviolet radiative effects results from the coincidence of Lβ and the resonance line of neutral oxygen line at 1026 Å. The Lyman emission can also pump OI, which affects a wealth of optical transitions. In particular, a cascade from the upper level of 1026 Å can produce the emission of the [OI] doublet $\lambda\lambda$ 6300, 6364 Å. These lines are taken as tracers of the outer parts of the circumstellar region. However, this effect makes the usage of the [OI] $\lambda\lambda$ 6300, 6364 Å uncertain for this purpose, because collisional and radiative excitation may not produce the OI emission from the same parts of the environment. The strength of this effect can be seen at the temporal variability of the Hα line and [OI] $\lambda\lambda$ 6300, 6364 Å lines (HD 50138; Jeřábková et al. 2016).

The hydrogen lines are also different in the FS CMa stars than classical Be stars. The Balmer series continues to higher members in FS CMa stars, e.g., FS CMa itself shows 42 lines (Kříček 2013). Even extreme Be stars such as 48 Lib do not usually show such high transitions. This provides an estimate of the electron density ($1\cdot10^{11}$ cm^{-3}) and turbulent velocity (< 40 km/s). The higher the member of the Balmer series, the lower the line intensity and the narrower the line is. This behaviour also shows up in

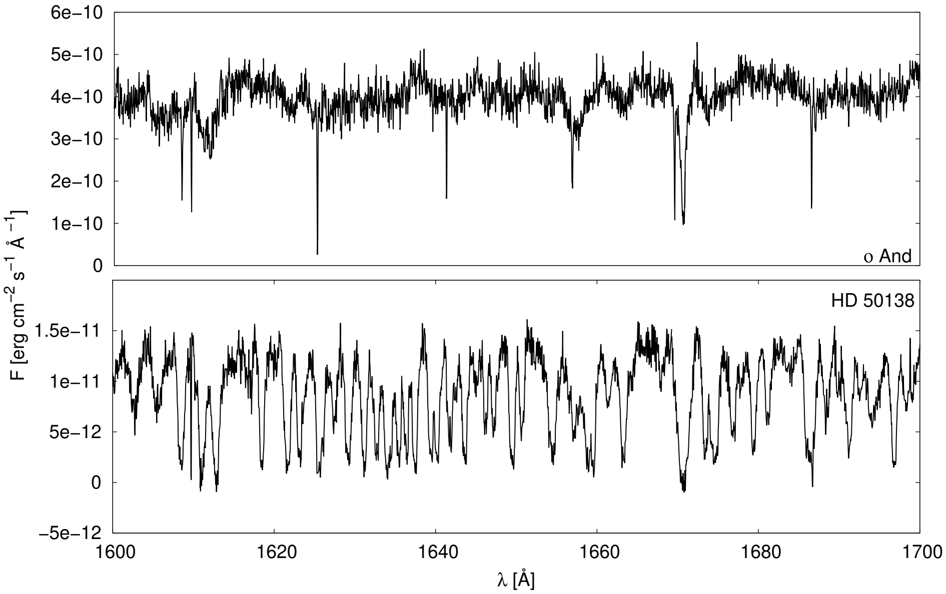

Figure 1. High resolution IUE spectra of a classical Be star (o And) and one of the best representative stars of the FS CMa type (HD 50138).

classical Be stars. The difference between these two types of object is in the intensity of the Balmer lines. The intensity of the Hα line at maximum in a FS CMa star can exceed the continuum level by over a hundred times. Relatively frequently, weak moving absorptions are observed within the Hα line profile. They move sometimes from the red wing to the blue one, suggesting the presence of a rotating structure in the envelope, sometimes their behaviour suggests the presence of expanding layers.

Observations indicate that the appearance of the moving humps is connected with the appearance of discrete components of resonance lines. However, more data are needed to see whether this is purely a coincidence or there is a physical connection. Resonance lines are relatively broad, with a width of about 400 km/s, and usually show a symmetric emission. The resonance lines NaI D1,D2 and CaII H and K have never been observed in absorption. On the other hand, very rarely these lines almost disappear.

We have briefly mentioned problems associated with the [OI] lines $\lambda\lambda$ 6300,-6364 Å, a distinguished signature of almost the entire B[e] class. Forbidden lines in their spectra are not only represented by oxygen. Fortunately, the [SII] $\lambda\lambda$ 6716, 6731 Å lines are usually also observed. This allows the usage of the nebular diagnostic. Another set of forbidden lines appropriate for the analysis are the [NII] $\lambda\lambda$ 6548, 6583 Å lines. Unfortunately, they are very rarely present in these stars, and their intensity is too small for a meaningful analysis. Problematic is also the usage of [FeII] lines. They are usually not sufficiently intense, frequently blended and affected by absorption in the UV region.

The forbidden lines are variable on timescales of months and years. Permitted emission lines also show changes on these timescales, but shorter period variations on a timescale of about a week are observed as well. Absorption lines of metals show a very rapid, night-to-night, variability. A detailed description of this multiperiodic, even

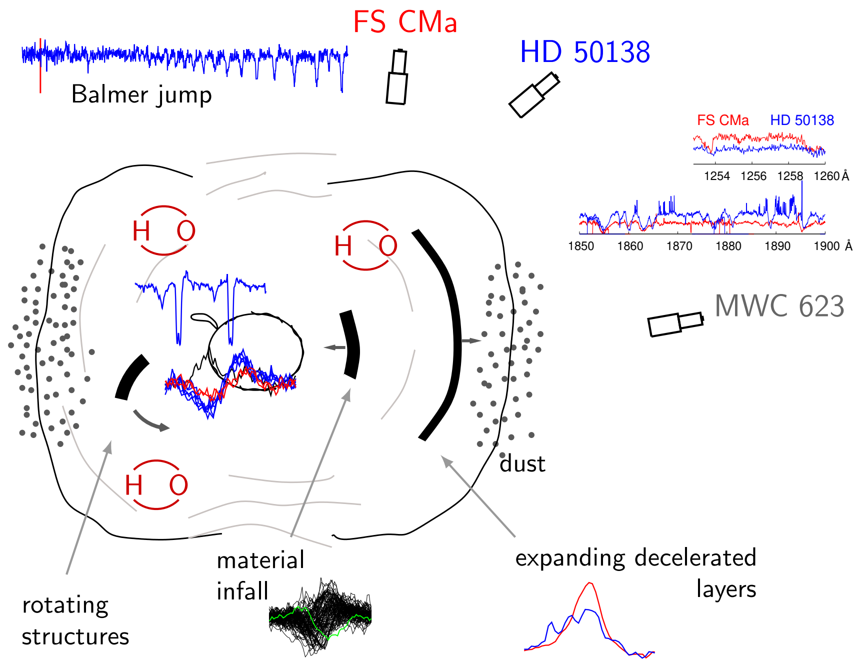

Figure 2. Sketch of the environment around FS CMa stars and their specific spectral features – extended Balmer series, iron curtain in UV, coupling of the oxygen and hydrogen lines. The pulsations of the star are not visible well on this scale.

chaotic behaviour, can be found in Polster et al. (2012); Kučerová et al. (2013); Miroshnichenko et al. (2015); Jeřábková et al. (2016). Such a behaviour, multiperiodicity with variable periods, has also been found in photometric data. The best photometrically monitored FS CMa star is MWC 342 (Introduction in Kučerová et al. 2013). FS CMa stars are also variable in the UV. Considering that the UV radiation plays a crucial role in the line formation, it is very difficult to distinguish radiative transfer effects and real changes of the matter properties from the spectrum itself.

3. Proposed model and concluding remarks

We summarise the described features and phenomena in the sketch (Fig. 2). From the radiative transfer point of view, this figure means 3D, non-LTE, moving media, and inclusion of many elements. Since the expansion velocities are too small, ~ 100 km/s, moving areas decelerate, sometimes until standstill, the Sobolev approximation can not help to simplify the problem in this case. Almost every part of the object is connected with the rest of the region; outer parts with a deep photosphere, equatorial region with the polar ones. This sets the radiative transfer modelling of FS CMa stars as a challenging stellar physics topic.

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