Publ. Astron. Inst. ASCR 93, 1 – 8 (2005)

Be star research by the HEROS group: results from the past decade

S. Štefl[1,2], Th. Rivinius[3]

[1]*Astronomical Institute, Academy of Sciences of the Czech Republic, Ondřejov*
[2]*European Southern Observatory, Casilla 19001, Santiago 19, Chile; sstefl@eso.org*
[3]*Landessternwarte Königstuhl, 69117 Heidelberg, Germany; triviniu@lsw.uni-heidelberg.de*

The progress in the investigation of Be stars during the past decade was enabled mainly thanks to high-resolution echelle spectrographs. Such instruments made possible to carry out multi-line studies of line profile variations and to search for correlations between photospheric and circumstellar phenomena. The Heros team was one of the most active in this field during the last decade. Here we summarize the most important achievements reached by the group.

Keywords: Spectroscopy, photometry – Be stars

1 Introduction

Data obtained with high-resolution fiber linked echelle spectrographs turned out to be one of the main contributors to our knowledge of Be stars during the last decade. Among the most important ones we can list Heros (Landessternwarte Königstuhl, Heidelberg/ESO), Feros (ESO), Musicos (Haute Province Observatory) or Giraffe (South African Astronomical Observatory). The broad spectral range, for some of the above listed instruments reaching from the atmospheric UV limit up to the near-IR, and at the same time their medium to high spectral resolution permitted to study phenomena on a basis not possible with high-resolution long-slit spectrographs. At least two new main directions were explored:

- Multi-line studies of line-profile variations (*lpv*). After the first monitoring of *lpv* in eighties it was assumed that the variations follow the same variability pattern in all spectral lines. The echelle spectrographs played a decisive role in disproving this assumption and subsequently in explaining the nature of rapid *lpv*.
- Correlations between characteristics of absorption *lpv* and emission-line parameters confirmed a close link between photospeheric processes and the formation of circumstellar disks.

A brief and certainly incomplete list of the most important achievements during the last decade includes:

- ⋆ detection of multi-periodic *lpv* in some Be stars (e.g. Rivinius et al. 1998b, 2003)
- ⋆ correlation between interference of non-radial pulsation (*nrp*) modes of *lpv* and Be star emission outbursts in μ Cen (Rivinius et al. 1998c)
- ⋆ the first successful prediction of the Be star outburst (μ Cen - Rivinius et al. 1998c)
- ⋆ discovery of transient periodicities in rapid *lpv* of Be stars (Štefl et al. 1998)
- ⋆ HST detection of the sdO secondary in the Be star ϕ Per (Gies et al. 1998)
- ⋆ detection of magnetic field in ω Ori (Neiner et al. 2003)
- ⋆ explanation of quasi-emission bumps (Rivinius et al. 1999)
- ⋆ VLT attempt to observe directly *lpv* of Be stars in SMC (Baade et al. 2002)
- ⋆ unified model of rapid *lpv* in Be stars (Rivinius, Baade, Štefl 2003a)

Taking into account the character of the AG splinter meeting we are going to focus this review mainly on results of the German-Czech team “Heros”, which contributed significantly to the Be star research in the given period. For a more complete view, the recent review by Porter and Rivinius (2003) is recommended.

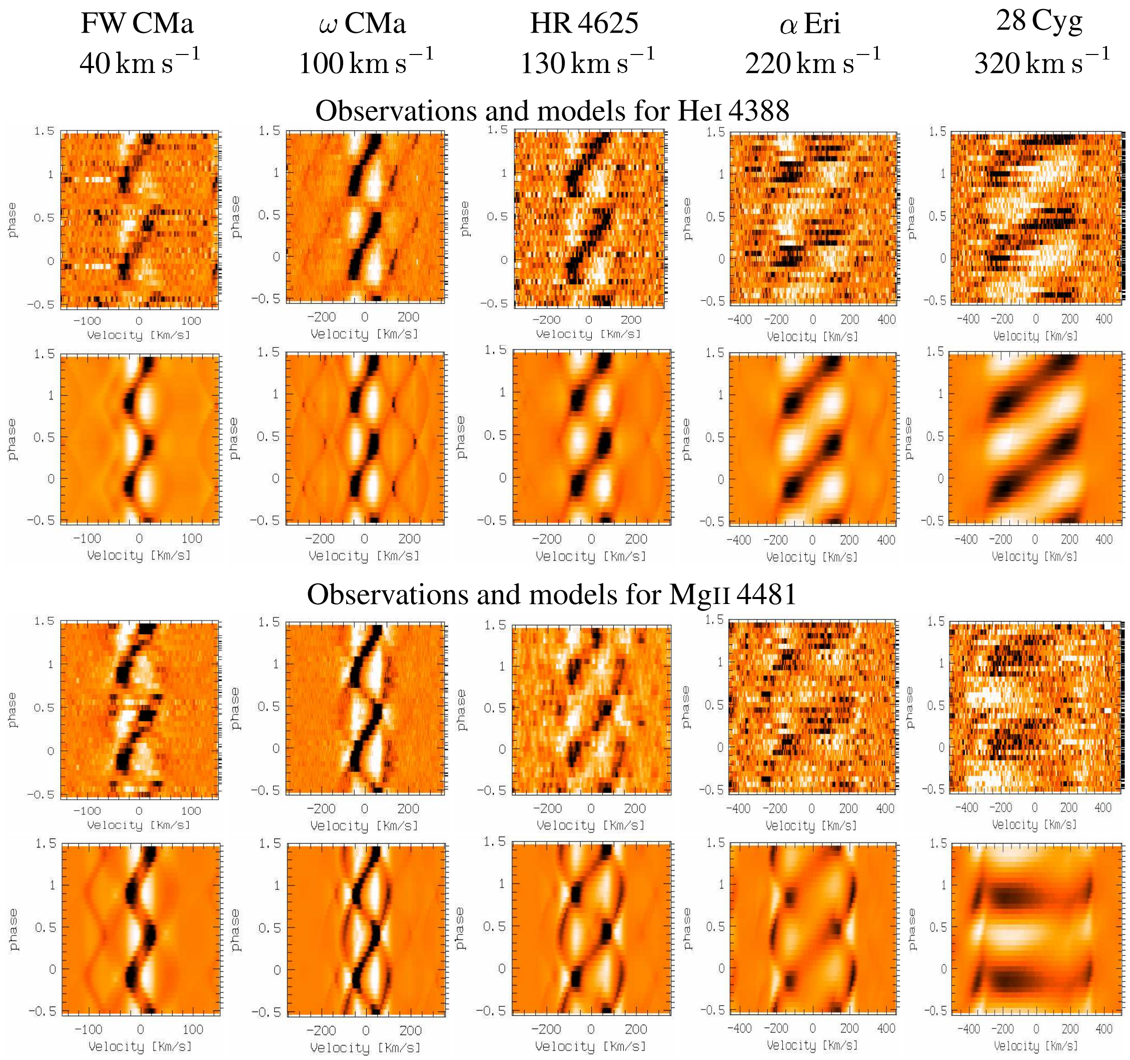

Figure 1: Observed (respective upper rows) and modeled line-profile variations for He I 4388 and Mg II 4481 in stars with different $v \sin i$. From: Rivinius, Baade & Štefl (2003a).

2 Rapid line-profile variations

2.1 Multi-periodicity

The detection of true multi-periodic behaviour situated in photospheric layers can be considered a decisive point in solving the question of the origin of rapid *lpv*. To explain those multi-periodic variations is naturally achieved in the *nrp* model, but requires complicated and improbable modifications to the model of photospheric spots or co-rotating circumstellar structures. However, we must be able to recognize the "true" multi-periodic photospheric variations, as opposed false-detections due to sampling- and other effects. This was the subject of many discussions during last years. Because both spectroscopic and photometric rapid variations can be combined with long- and medium-term trends on time-scales of weeks to months and the photospheric periods may differ only by a few hundreds of days, a monitoring of high spectral and temporal resolution over several seasons is necessary to detect true photospheric multiple periods and distinguish them from transient periods (Sect. 5).

So far the most significant multi-periodic variations were detected for:

- **μ Cen** — the southern prototype B2 IV-Ve star monitored intensively at La Silla between 1992 and 1997. The analyses of mode and line-profile variations (Rivinius et al. 1998) gave six periods. These periods are arranged in two groups around 0.50 and 0.28 day (Tab. 1). Their differ-

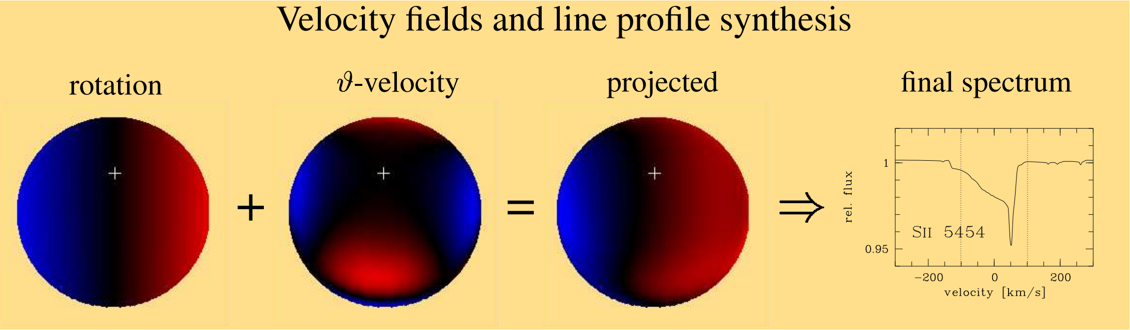

Figure 2: Formation of the absorption spikes and ramps for a pole-on star. The sharp absorption cores (in the red wing) and flat absorption ramps (far blue wing) are formed in phases of extreme line asymmetry as a result of the vector sum of the rotation and pulsation velocity fields. The opposite sign of rotation and pulsation field in the receding part of the stellar disk reduces the combined maximum velocity, and thus a large part of the disk is projected in the narrow velocity range corresponding to the spike. In contrary, close to the approaching limb, the pulsation and rotation velocities co-add constructively and form a velocity plateau extending beyond $v \sin i$. From: Rivinius et al. (2003b).

Table 1: Periods and amplitudes of the modes and rapid line-profile variations of He I 4121, 4168, 4438 of μ Cen.

Period [days]	Amplitude [km/s]
0.502925 ± 0.000006	14.3 ± 1.0
0.507519 ± 0.000009	8.4 ± 0.9
0.494523 ± 0.000011	5.8 ± 0.7
0.516358 ± 0.000015	4.8 ± 0.7
0.281405 ± 0.000005	7.6 ± 0.7
0.279137 ± 0.000008	3,3 ± 0.7

ences probably correspond to *nrp* modes with different “radial” node-numbers n, so that the surface pattern, determined by ℓ and m is the same within each group.

28 Cyg — two close periods of 0.6470 and 0.6249 d were announced by Tubbesing et al. (2000)

η Cen — two close periods of 0.577 and 0.565 d were detected in the preliminary analysis by Rivinius, Baade & Štefl (2003). In a not yet published investigation these periods could be confirmed.

2.2 Modeling the rapid *lpv*

Rivinius, Baade & Štefl (2003a) used the database of more than 3000 echelle spectra obtained with the Heros and Feros spectrographs in the period 1995 – 2003 at the ESO La Silla, Calar Alto, Heidelberg and Ondřejov observatories. 27 Be stars from both the southern and northern hemisphere cover the complete range of projected rotational velocities $v \sin i$. *nrp* modeling was done with the Bruce and Kylie codes by R. Townsend (1997).

As can be seen in Fig. 1, the stellar *lpv* pattern smoothly varies with $v \sin i$. On the basis of an *nrp*-model computed for ω CMa, it is well possible to reproduce this behaviour. Only the inclination of the rotational axes need to be varied to reproduce it, otherwise using the model parameters derived for ω CMa. This does well fit the observed *lpv* variations for about 90 % of the observed stars. The model can even explain peculiar phase dependent *lpv* features, such as spikes and ramps (Fig. 2). Only for 3 *lpv* stars (κ CMa, λ Eri and o And) the $\ell = -m = 2$ *nrp* model does not yield a satisfactory explanation. In these objects other modes like $\ell = -m = 3$ may better fit the observed variations.

3 Spectroscopic outburst description

Analyzing numerous outbursts of μ Cen, Rivinius et al. (1998a) described 4 phases of a typical Be star outburst: quiescence, precursor phase, outburst and relaxation phase. ω CMa (Fig. 3) fits this description in general, but the time scale is longer and some specific differences can be detected particularly during phases of higher brightness.

The outburst phase itself is characterized by a rapid rise and slower decline of circumstellar line emission, the rapid appearance and slow decay of broad emission wings in hydrogen lines, the rapid increase and slow decrease of emission peak separation in optically

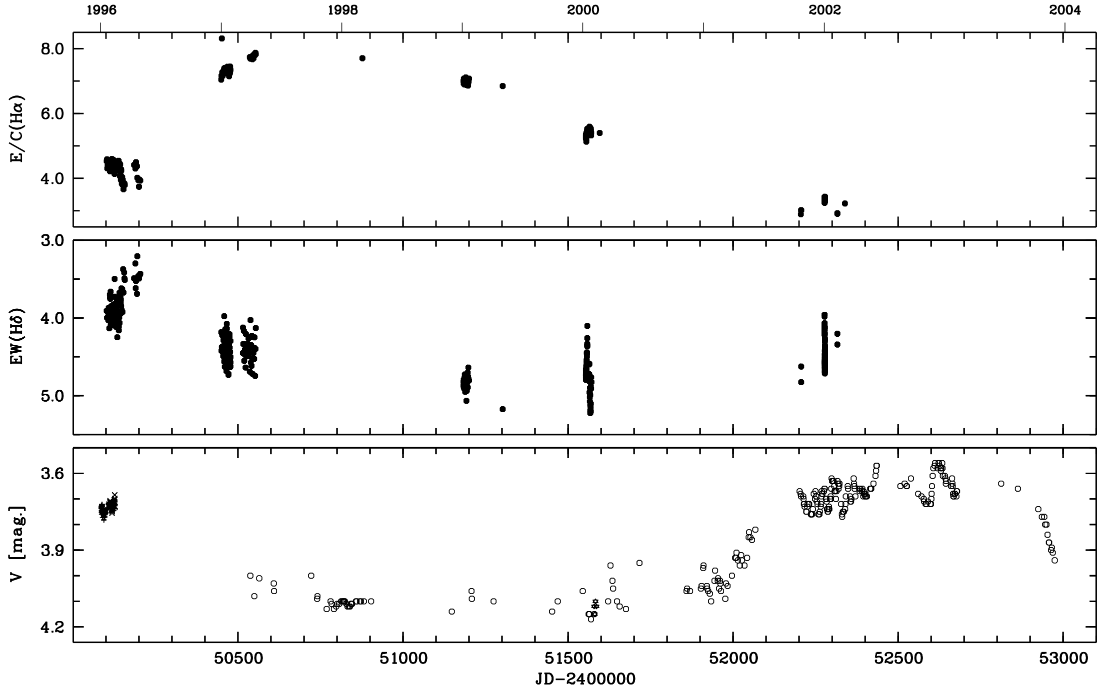

Figure 3: Long-term variability of ω CMa in the period January, 1996 – January, 2003. From bottom to top, V magnitude [visual observations by S. Otero (o) and photoelectric data in *uvby* obtained at the SAAO (Štefl et al. 2000) and Geneva system data obtained at La Silla (x (Štefl et al. 2000)], equivalent width of Hδ and peak height of the Hα emission relative to the ambient continuum flux, E/C, are shown. Assuming a constant photospheric contribution, numerically lower Hδ equivalent widths correspond to increased emission contribution, in particular in the line wings. Spectroscopic data were obtained with the Heros and Feros spectrographs attached to the ESO La Silla 0.5 and 1.5m telescopes, respectively. From Štefl et al. (2003a).

thin lines, and finally by rapid transient V/R variability of the emission peaks. Dynamical spectra of H α and Fe II 5317, presented in Fig. 4, document such a behaviour during the 1996 activity of ω CMa.

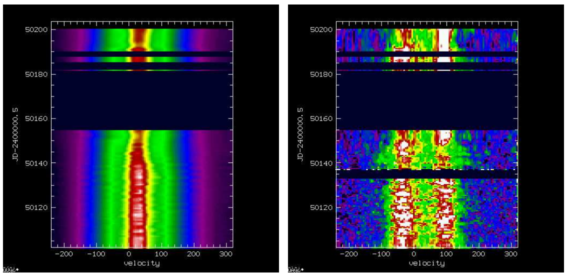

Figure 4: Development of the Hα and Fe II 5317 emission lines during the 1996 activity phase of ω CMa.

4 Linking *lpv* and line emission

Detailed studies of μ Cen and ω CMa show different but clear relations between the characteristics of rapid line-profile variations and formation of the disk giving rise to the line emission. Two types of connection between photospheric and circumstellar processes were described:

μ Cen — Multi-periodicity governs the outburst behaviour. Rivinius et al. (1998c) compared the circumstellar activity, taken from Hδ line strength in 1996 and 1997, to the combined amplitude of the multiperiodic *nrp* modes (Fig. 5). Symbols mark times when two strong modes have phase difference zero. Times of circumstellar disk "refueling" seem to be governed by this multi-periodic long-term beating.

After analyzing the 1995–1996 observations the 1997 June outbursts could be predicted, which was in fact confirmed by observations.

ω CMa — Pulsation–outburst interplay. Variations of modes and line profiles are mono-periodic and fully coherent during the entire 1996 - 2000 period, when there was no outburst (Štefl et al. 2003). This excludes all models of a cyclically or periodically varying period, as it was proposed e.g. by Harmanec (1998). However, *during* outburst the phase is drifting. The radial velocity curves in Fig. 6 show data taken before the 2001 and 1996 outbursts, respectively, and demonstrate significant shifts of the the velocity curves. The present data do not indicate, however, whether the phase glitched or the period temporarily changed during the early phase of the outbursts. Theoretical considerations in the light of nonradial pulsation favor the latter possibility. There are also some other specific phenomena, such as rapid transient V/R variability of the emission peaks, high-velocity absorption components, or cyclic light variations, which occur just during the times of enhanced brightness.

5 Transient periodicities

Secondary periods, as the ones present temporarily during outbursts of ω CMa (Fig. 7), μ Cen and η Cen were discovered by Štefl et al. (1998). These periods co-exist with those of photospheric line-profile variations, and they typically differ from them by about 10 %. The associated profile changes are mainly situated in the wings of lines having contributions from the circumstellar disk and persist for a few days (μ Cen) up to a few months (ω CMa). The transient periods, when observed for several instances, do not re-appear with the same period as at the previous epoch.

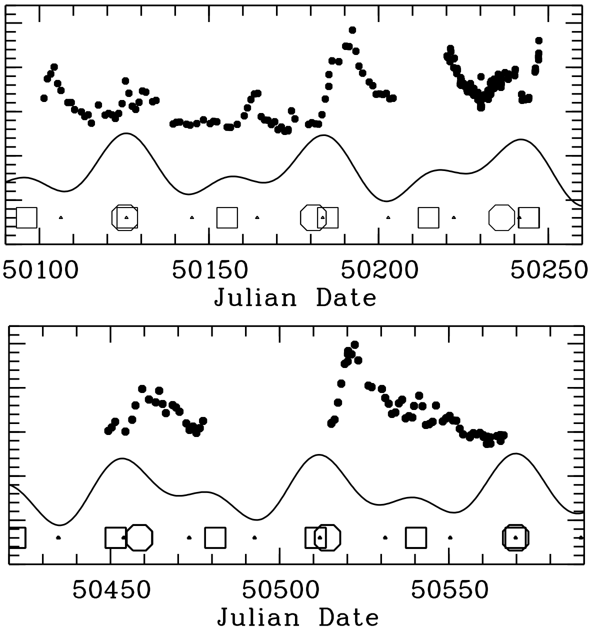

Figure 5: Comparison of the observed and modeled emission activity of μ Cen in the 1996 (top) and 1997 (bottom) seasons. The full line shows the combined amplitude of the 3 strongest *nrp* modes (see Tab. 1), filled circles the observed activity derived from H δ wings and symbols the times, when two strong modes have the phase difference zero. The clear coincidence of times of beatings of *nrp* modes and observed emission events can be seen. This means that an outburst, as measured in Hδ, starts when the combined amplitude, as modeled by the fully drawn line, is highest. From Rivinius et al. (1998c).

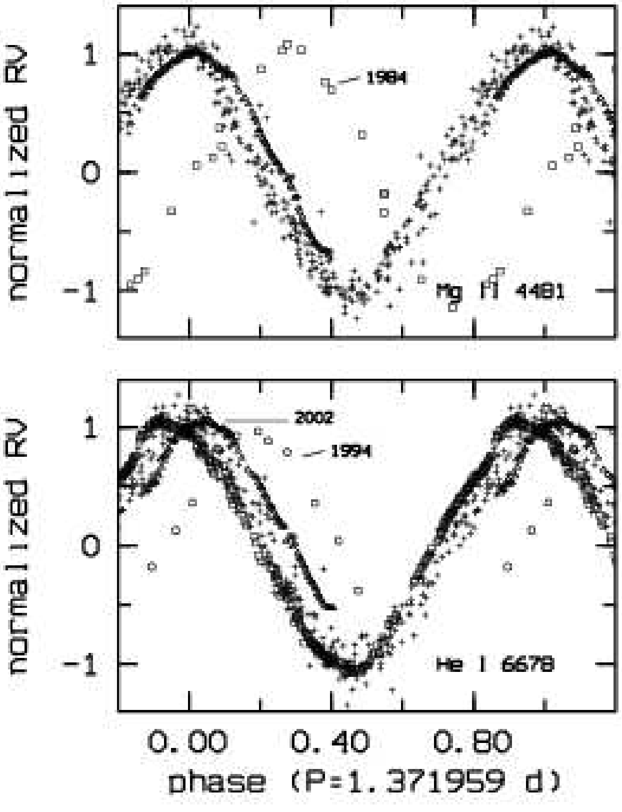

Figure 6: Long-term coherence of ω CMa rapid mode variations between 1996 and 2003. The low scatter in phase diagrams of He I 6678 and Mg II 4481 modes documents a high coherency between 1996 and 2000 (+ symbols). However, a phase shift of the modes in 2002 (dense string of △ symbols identified by 2002) is higher by one order of magnitude than can be expected from the analysis of the 1996-2000 data. Even more conspicuous phase shifts, can be seen for the 1994 published modes of the He I 6678 profiles and 1982 Mg II 4481 data (□ symbols). From Štefl et al. (2003b).

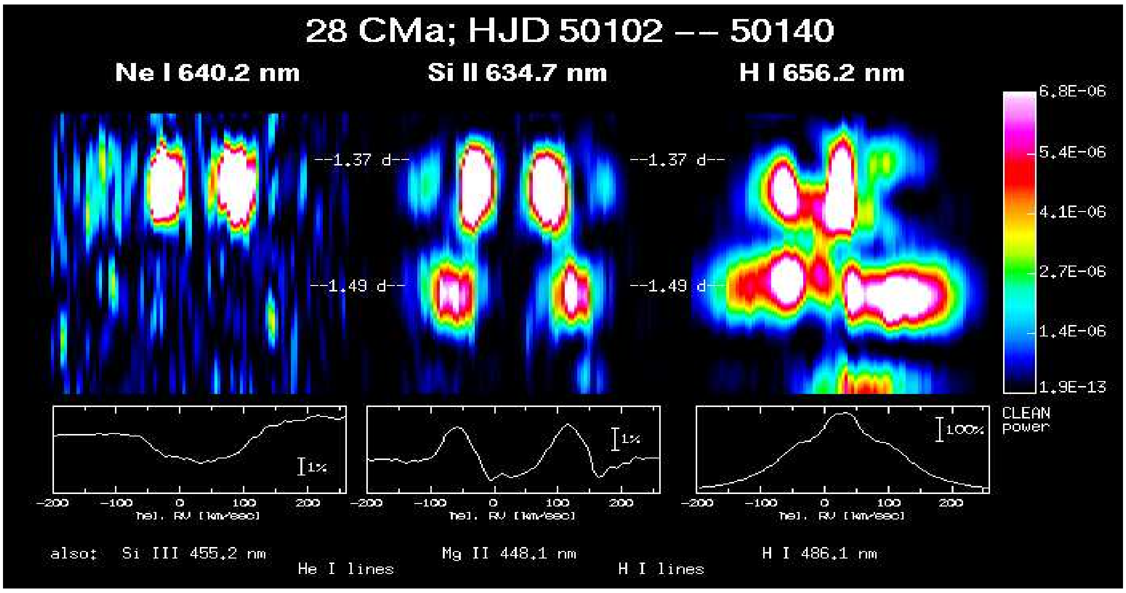

Figure 7: Transient periods, as demonstrated by the two-dimensional Fourier analysis of the 1996 rapid line-profile variations of ω CMa. The x-axis is scaled in radial velocity. Bottom panels show mean profiles in the given HJD interval, while in the upper figures, the frequency increases upwards and the higher brightness corresponds to higher Fourier power. The photospheric absorption profiles, like Si III 4553 and Ne I 6402, only show the photospheric period. However, a satellite transient period of 1.49-day appears temporarily in the wings of Mg II, Si II and some other spectral lines, which have a contribution from the circumstellar disk. The transient period is even dominant in strong emission lines, such as Balmer Hα, Hβ or the Paschen lines.

In μ Cen the transient periodicities excited during different, subsequent outburst fall in an interval ± 10 %, but are in any event longer than the photospheric *lpv*-period. They are either not at all or only weakly detectable in photospheric lines and attain significant strength only in lines formed (also) above the photosphere, i.e. with emission component. This indicates that these periods are connected with processes in the transition area between the photosphere and the disk, but the available data permit not more than to speculate on resonant oscillations being “echoes” of the photospheric pulsation, or clouds of mass ejected from the photosphere and orbiting in the transition region before merging the disk. In fact it is not even clear that the mechanism is the same in different stars.

Whatever the origin of the transient periods is, they do have serious consequences for the time series analysis of rapid line-profile variations of Be stars. Ignoring their potential temporary presence one may draw false conclusions on multiple periods or cyclic period variations.

6 Binaries — application of the Fourier disentangling

Several methods were recently developed for a more efficient analyses of binary spectra, e.g. spectroastrometry (Porter, Oudmaier & Baines (2004) or the Fourier disentangling. The latter method was applied also by the HEROS group.

The decomposition of the observed spectrum into the individual spectra of binary components can be done using the singular value method by Simon & Sturm (1995) or using the Fourier transform (e.g. Hadrava 1995, 1997, 2004). The latter method was developed by Hadrava during last years and his computer code Korel was applied to spectra of several binary systems. In his code, input spectra are transformed into the Fourier space and fitted by the time-dependent Fourier modes. Using this approach the code not only enables to decompose a spectrum of the multiple system into the spectra of individual stars, but as well to remove telluric lines. Fig. 8 illustrates the application of the Korel code to data of the Be binary 66 Oph.

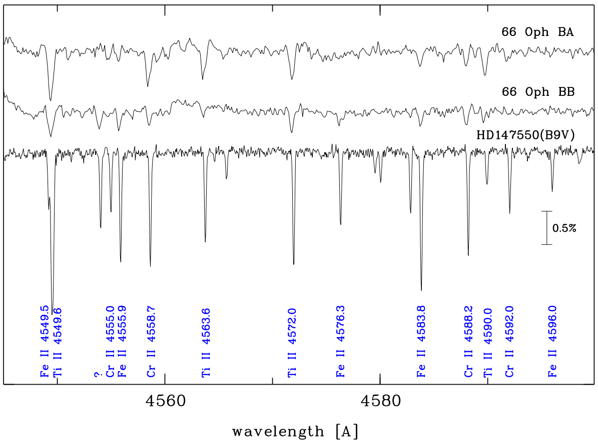

Figure 8: Comparison of decomposed spectra of the 66 Oph BA and BB components, with the reference spectrum of HD 147 550 plotted below. From Štefl et al. (2004).

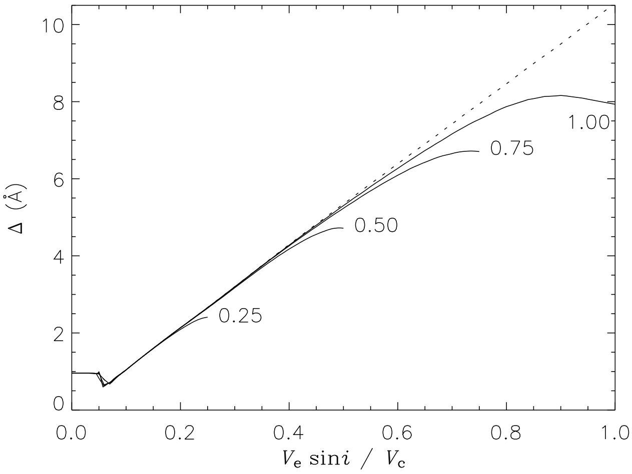

Figure 9: The characteristic width, $\Delta\lambda$, of the He I 4471 line for a model with parameters typical for a B 2 star, plotted as a function of the true $v_{\rm rot}\sin i/v$crit. Individual curves are for four values of *sini*. Because the relation degenerates at approximately 80 % of the critical velocity, classical spectroscopic methods cannot recognize higher rotational velocities. From: Townsend, Owocki & Howarth (2004), used with the permission of the authors.

7 At the limits of spectroscopy

In spite of the remarkable progress in the investigations of Be stars, made thanks to the new powerful observing facilities and more sophisticated methods, there seems to be two principal limitations, which cannot be overcome by classical spectroscopy.

Missing spatial resolution: The observed spectrum arises from a complicated system of the dynamically active photosphere, flattened anisotropic and non-static disks, both possibly interacting with inhomogeneous structures in the disk as blobs or density waves. The geometrical and physical parameters of all these constituents can be hardly separated in the light or line profiles integrated over the entire system.

Extremely fast rotation: Relation between the measured line width and the actual true $v_{\rm rot}\sin i$ degenerates around $v_{\rm rot} = 0.8v_{\rm crit}$ due to gravity darkening (Owocki, 2004; Townsend, Owocki & Howarth, 2004 – Fig. 9). Consequently, the classical spectroscopic approach fails to derive rotational velocities close to the critical one, but rather will yield about 80 % in all those cases. Analysis and modeling of rapid line-profile variations of a pulsating and rapidly rotating star in principal allows to derive the rotational velocities close to critical ones (Rivinius et al. 2005, in preparation), but requires data with an extremely high S/N and its practical application still needs to be tested.

Although a close-to-critical rotation of Be stars makes their modeling rather complicated, it may solve some long-lasting problems of these mysterious objects, like the rotational support of circumstellar disks and the so called Be phenomenon itself. If a Be star approaches critical rotation, any small dynamical instability caused by pulsation, a magnetic field or even turbulence may trigger a mass ejection.

The recent VLTI results indicate that the above sketched limitations can overcome by interferometric or combined interferometric and spectroscopic observations during next years. Following this trend the main interest of the Heros team is shifting to the interferometry.

Acknowledgement

This work was supported by the Deutsche Forschungsgemeinschaft (Wo 296/20-1, 436 TSE 113/18, Ri 1159/1) and the Academy of Sciences and Grant Agency of the Academy of Sciences of the Czech Republic (436 TSE 113/18, A3003001 and A3003403).

References

Baade D., Rivinius Th., Štefl S., Kaufer A.: 2002, A&A 383, L31

Gies D. G., Bagnuolo W. G., Ferrara E. C., et al.: 1998, ApJ 493, 440

Hadrava P.: 1995, A&AS 114, 393

Hadrava P.: 1997, A&AS 122, 581

Hadrava P.: 2004, Publ. Astron. Inst. ASCR 92, 15

Harmanec P.: 1998, A&A 334, 558

Hubert A.-M., Floquet M.: 1998, A&A 335, 565

Neiner C., Henrichs H. F., Floquet M., et al.: 2003, A&A 411, 565

Owocki S. P., 2004, in IAU Symp. 215 *Stellar Rotation*, eds. A. Maeder & P. Eenens, ASP Conf. Ser., p. 515

Porter J. M., Rivinius Th.: 2003, PASP 115, 1153

Porter J. M., Oudmaijer R. D., Baines D.: 2004, A&A 428, 327

Rivinius Th., Baade D., Štefl S., et al.: 1998a, A&A 333, 125

Rivinius Th., Baade D., Štefl S., et al.: 1998b, A&A 336, 177

Rivinius Th., Baade D., Štefl S., et al.: 1998c, in *Cyclical Variability in Stellar Winds*, ESO Astrophysics Symposia, eds. L. Kaper and A. W. Fullerton, Springer, 207

Rivinius Th., Štefl S., Baade D.: 1999, A&A 348, 831

Rivinius Th., Baade D., Štefl S.: 2003a, A&A 411, 229

Rivinius Th., Baade D., Štefl S., et al.: 2003b, The ESO Messenger 108, 20

Simon K. P, Sturm E.: 1994, A&A 281, 286

Štefl S., Baade D., Rivinius Th., Kaufer A., Stahl O., Wolf B.: 1998, in: *A Half Century of Stellar Pulsation Interpretation: A Tribute to Arthur N. Cox*, eds. P. A. Bradley and J. A. Guzik, Astr. Soc. Pacific Conf. Series 135, 348

Štefl S., Balona L. A., Aerts C., et al.: 2000, J. Astron. Data, 6 (on CD-ROM)

Štefl S., Baade D., Rivinius Th., et al.: 2003a, A&A 402, 253

Štefl S., Baade D., Rivinius Th., et al.: 2003b, A&A, 411, 167

Štefl S., Hadrava P., Baade D., et al.: 2004, in IAU Symp. 215 *Stellar Rotation*, eds. A. Maeder & P. Eenens, ASP Conf. Ser., p. 166

Townsend R. H. D.: 1997, MNRAS 284, 839

Townsend R. H. D., Owocki S. P., Howarth I. D.: 2004, MNRAS 350, 189

Tubbesing S., Rivinius Th., Wolf B., et al.: 2000, in IAU Colloq. 175 *The Be Phenomenon in Early Type Stars*, eds. M. A. Smith, H. F. Henrichs, & J. Fabregat, ASP Conf. Ser. 214, p. 232