To Be or Not to Be and a 50-cm Post-Mortem Eulogy

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Introduction

Be stars were discovered as early as 1866 by the famous Jesuit astronomer Angelo Secchi. Not only was γ Cas the first known Be star but the first star ever to be seen displaying emission lines. About half-way between then and today, the work by Otto Struve and others led to the picture that Be stars differ from supergiant B-type stars, which also feature emission lines, in that they are much less evolved, rotate extremely rapidly (up to 450 km/s at the equator), and their emission lines arise from a circumstellar disk.

Roughly 1–2% of the 10,000 visually brightest stars belong to this class, and only few other types of stars have been observed so intensively and over a similar period of time. Therefore, every addition to the arsenal of observing tools and facilities resulted in an at least proportional expansion of the empirical knowledge base about Be stars. This made it increasingly clear that the physics of the atmospheres of Be stars does not fundamentally differ from the one of other early-type stars. But various processes are more pronounced and interact with one another more strongly. This renders Be stars attractive laboratories for the exploration of early-type stars in general, which make the largest stellar contribution to the chemical and dynamical evolution of late-type galaxies.

The comparison with a laboratory is appropriate because variability on time-scales of hours to decades is the common theme of virtually all investigations that are based on repeated observations of Be stars. Obviously, the role of actively controlled experiments is to be taken over by observational monitoring. With many modern observing facilities this is getting ever more difficult. Therefore, when the PI of the FLASH/HEROS spectrographs (e.g., Wolf, B., Mandel, H., Stahl, O., et al. 1993, *The Messenger,* No. 74, p. 19), Prof. Bernhard Wolf from Heidelberg, offered the opportunity of a long-term collaboration, we immediately jumped on it.

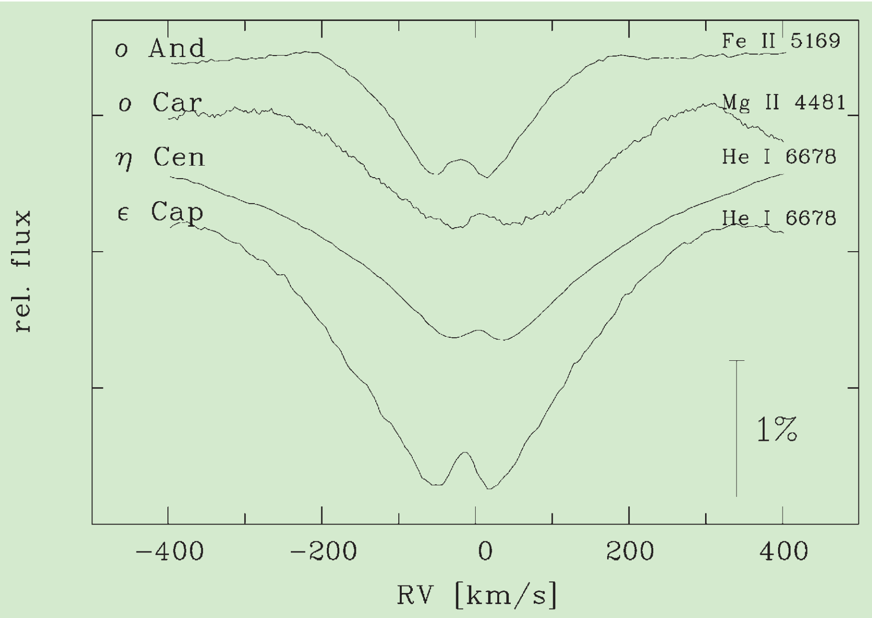


Figure 1: Central quasi-emission components (CQEs) in four different stars. The CQEs themselves are a purely circumstellar, geometric-kinematic phenomenon. The Fe II line is formed only in the disk; the other lines also have some photospheric contribution, which is broader due the rapid stellar rotation. The velocity has been reduced to the heliocentric scale with the CQEs marking the respective systemic velocities.

The wavelength coverage from the near-UV to the near-IR meant that both stellar and circumstellar phenomena could be studied simultaneously. With a CCD as detector, even a 50-cm telescope would suffice to obtain within 30 minutes spectra of 5th-magnitude stars with a signal-to-noise ratio of 100 and a spectral resolving power of 20,000. ESO's Observing Programmes Committee could be convinced to recommend the allocation of the ESO 50-cm telescope on La Silla for several runs of up to 3 months each. The time was to be shared among several projects, of which Be stars formed only one.

This has resulted in an until then unprecedented database of almost 2000 high-quality echelle spectra of three dozen Be stars (some 500 additional ones were obtained from northern-hemisphere observatories). Since meanwhile the ESO 50-cm telescope was de-commissioned in 1997 and after some temporary revival was terminally mothballed in 1999, a summary in *The Messenger* of the many exciting results that could be extracted may be appropriate. Before embarking on the story, we emphasise that the picture of Be stars sketched below is probably not representative of late-type Be stars, which are much more inert. Moreover, it is not complete because, for the sake of brevity, only a minimum of non-HEROS results is mentioned.

The Velocity Law in the Disks

A few broad-lined B stars were noted some years ago to show a weak central reversal, dubbed central quasi-emission (CQE), in some spectral lines (Fig. 1). From the comprehensive HEROS database, two points quickly became apparent: (i) All these stars are actually so-called shell stars, i.e. Be stars whose circumstellar disk ('shell') is intersected by the line of sight, thereby imprinting narrow and often very deep absorption lines onto the stellar spectrum. (ii) CQE's only occur in spectral lines that have also some component due to absorption in the disk. (The latter is cooler than the central star so that the two spectra do not have all spectral lines in common.)

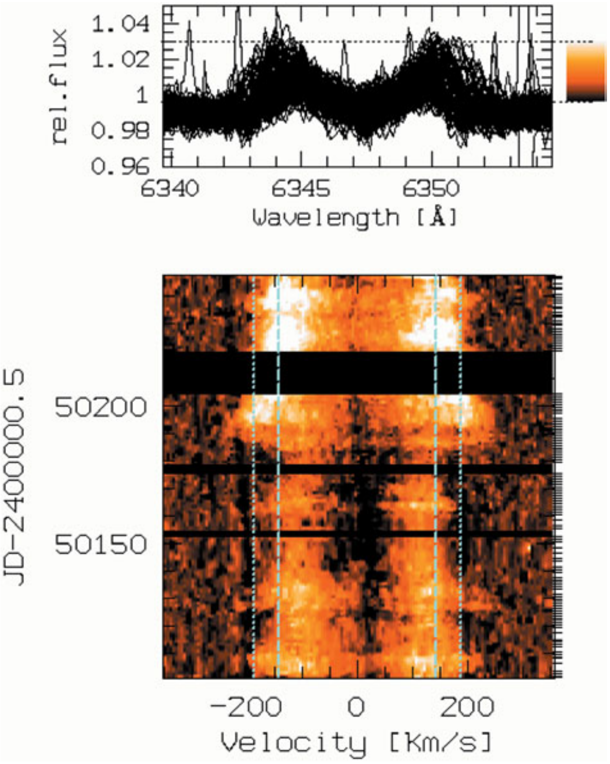


Figure 2: The evolution of the Si II 6347 emission line of μ Cen over an outburst cycle. The left and the right peak respectively form in the approaching and recessing parts of a rotating disk. The blue vertical lines mark the projected rotation velocity of the star (dashed) and the Keplerian velocity at the stellar surface (dotted), respectively. The initial occurrence of line emission at super-Keplerian velocities suggests that some of the matter was moving fast enough to escape the star. The subsequent reduction in separation of the two peaks shows that the ejecta were collected at large distances from the star, where the rotation velocities are lower, and merge with the disk.

Some Be stars erupt relatively mildly every few weeks. Others prefer one major outburst per decade, and there are all kinds of mixed cases. In stars with infrequent outbursts one can observe the incipient demolition of the disk at its inner edge. With time, a cavity eats into the disk, which can be replenished by one or more later outbursts (Fig. 3).

The HEROS spectra have not yet enabled us to elucidate the physical process(es) underlying these mass-loss events. Otto Struve still conjectured that the Be stars are rotationally unstable. Later, quantitative analyses have rendered this picture untenable. Not considering a small number of stars spun up by mass transfer from a companion, the HEROS database did not lead to the identification of stars with more than three quarters of the critical equatorial velocity. It only confirmed that rapid rotation is necessary but not sufficient for a B star to become a Be star.

Periodic Short-Term Variability

The first report about periodic line profile variability in any Be star appeared in *The Messenger* (1979, No. 19, p. 4). Many others have been published since (cf. Fig. 4). For a while, the proximity of the observed periods of 0.5 to 2 days to calculated rotation periods made co-rotating surface structures appear as a possible alternative to the original explanation as non-radial pulsation.

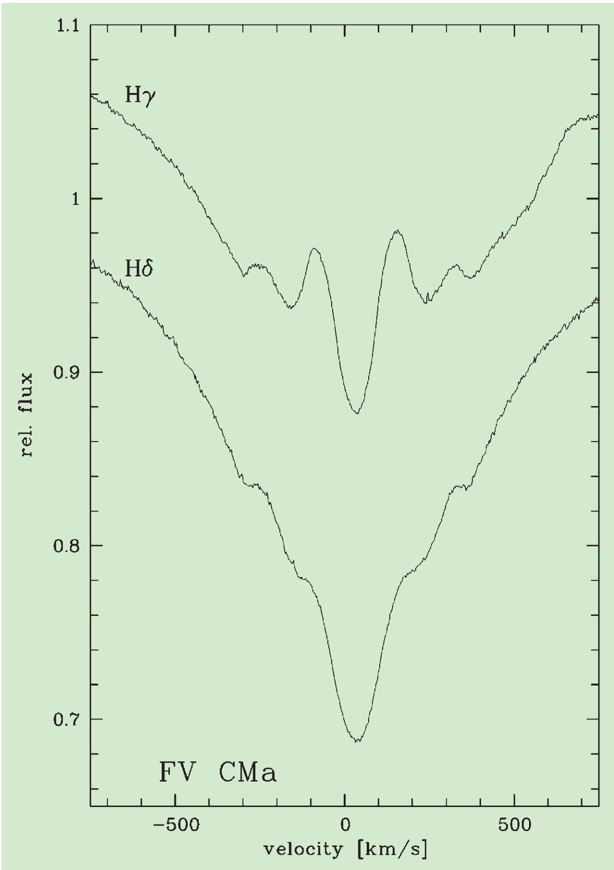
This provided a strong hint that the explanation of CQEs might already be contained in studies of the formation of shell absorption lines. Indeed, calculations by R. Hanuschik (1995, *A&A*, 295, 423) have shown that apparent central reversals arise from disks provided there is no significant radial motion. Because only quasi-Keplerian rotation can plausibly achieve such a well-tuned equilibrium, the velocity law at large could be deduced. Other studies had arrived at the same result before, but the evidence was always rather indirect. This confirmation was important because the problem with a Keplerian disk is that its specific angular momentum is larger than at the stellar equator even if the star were rotationally unstable. Models for the disk formation need to account for this.

The Disk Life Cycles

Be stars are too old for their disks to be fossils of the formation of the central stars. The stellar radiation pressure and intrinsic dynamical instabilities have cleared the circumstellar space a long time ago. So the disks must be 'decretion' disks, i.e. consist of matter lost from the central star. (In binaries, the disk matter may also originate from a Roche lobe overflowing companion. β Lyrae is the most prominent example. However, the existence of single Be stars and of Be stars in high-mass X-ray binaries with neutron star secondaries mandate other explanations.)

It was already known before that Be stars undergo outbursts. The HEROS spectra could further illustrate how common such phases of enhanced mass ejection are. More interesting is, however, that these events seem to basically follow one generalised temporal profile, which may be scaled up or down in strength and duration. This pattern includes that a significant part of the matter is ejected with super-critical velocities and eventually does manage to merge with the disk (Fig. 2).

Figure 3: Two emission systems can be distinguished in these Balmer emission profiles of FV CMa. They indicate the simultaneous existence of two structural entities, which must be spatially separated from each other: The pair with the higher velocity separation rotates faster and is therefore closer to the star. Maybe the disk bears some resemblance with Saturn's rings although the geometrical thickness of the disk is a considerable fraction of the stellar diameter. However, the inner ring expands and eventually reaches the outer disk.



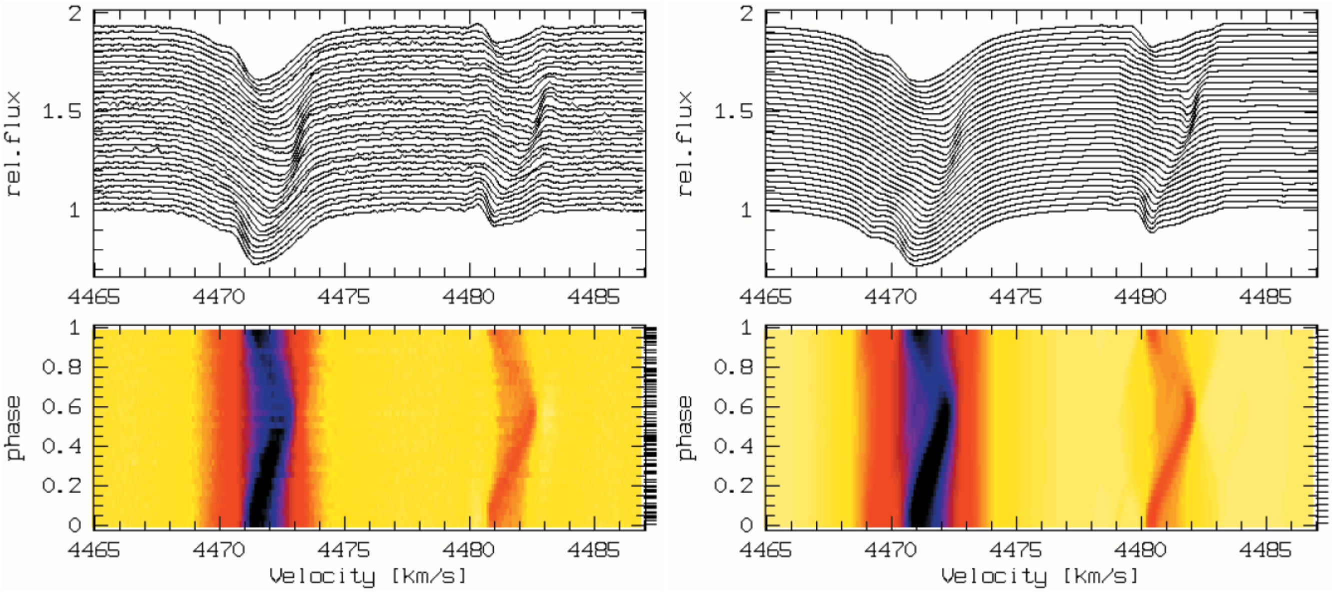


Figure 4: Observed (left) and modelled (right) line profile variability of He I 4471 and Mg II 4481 in ω CMa. The stellar and atmospheric model parameters are identical for both lines. And yet, the line-specific appearance of the observed lpv *is reproduced properly, like the forbidden component contribution on the blue side of He I 4471 and the relatively sharp absorption core of Mg II 4481. The helium line forms preferentially at higher stellar latitudes, where the temperature is higher. The dependency of also the pulsational velocity field on latitude, then, results in different variability. This sets tight constraints on the possible models.*

Since the velocity fields of most non-radial pulsation modes deviate from spherical symmetry by their own characteristic pattern, which furthermore is added to the large rotational velocity, the observed line profiles are crude 1-D maps of the stellar surface. The partial degeneracy of these maps is lifted by the different response of spectral transitions to the atmospheric conditions prevailing between the hot poles and the equatorial regions with their rota-

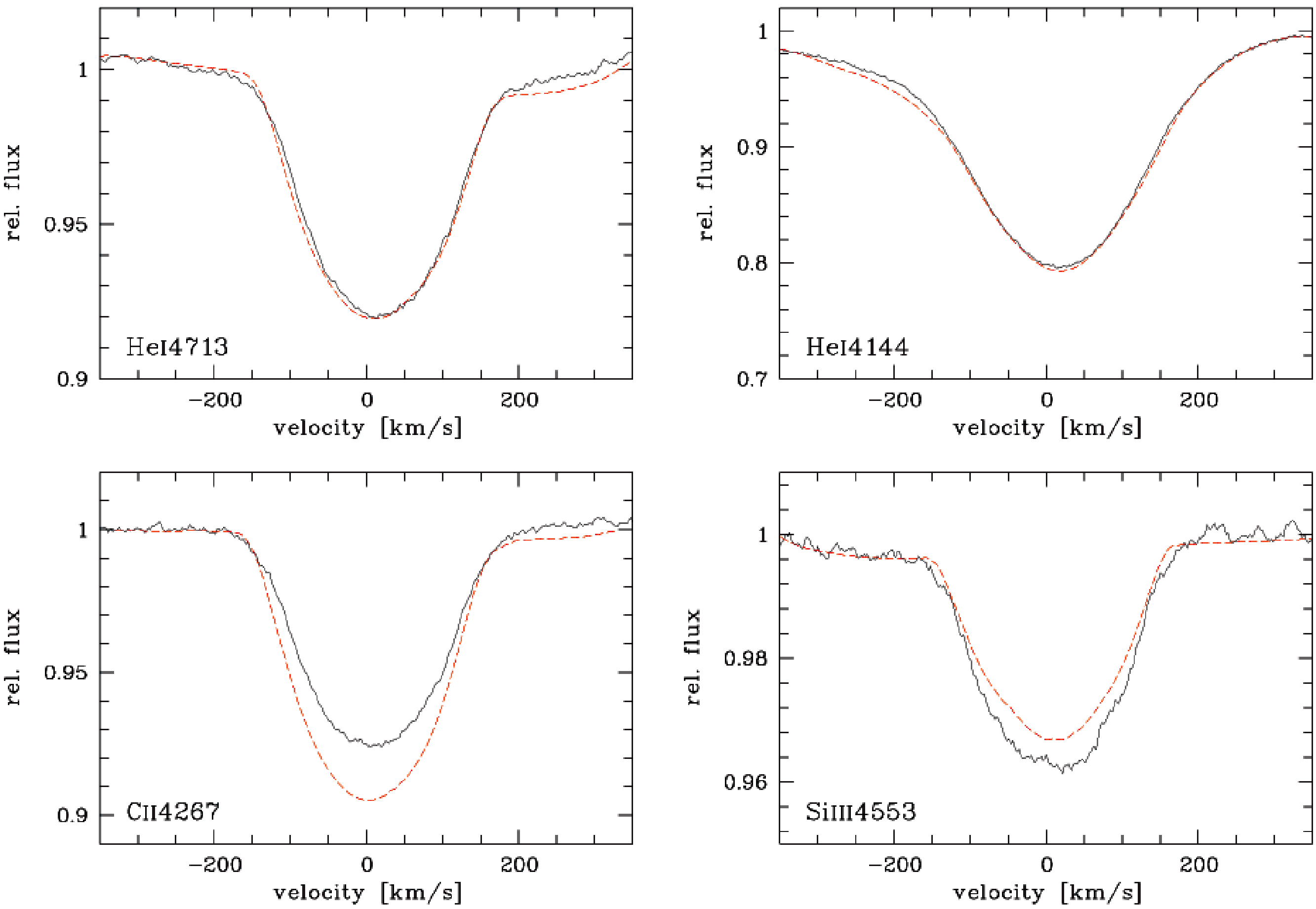


Figure 5: Selected time-averaged observed and modelled line profiles of μ Cen. Apart from crude initial guesses of the primary stellar parameters, the only input to the modelling procedure were the residuals *from the mean profile of He I 4713. And yet, also the mean profile is nearly perfectly matched by the model. The fit is nearly as good also for the other He I lines (unless contaminated by emission). Si III 4553, too, is still reasonably well reproduced while the applied LTE model is known to produce too strong C II 4267 absorption. These results encourage the idea that quantitative, absolute parameters can be derived from stellar pulsation modelling ('astero-oscillometry').*

tionally reduced effective temperature and gravity. HEROS was the first instrument to produce dense series of electronic high-resolution spectra covering the full optical wavelength range. Accordingly, this mapping potential could be fully exploited, especially since contamination by the disk is more readily recognisable when numerous lines can be compared. In this way, the pulsational nature of the line profile variability could be unambiguously established.

A separate *Messenger* article will describe the modelling techniques in more detail. However, it is worthwhile mentioning already here that by modelling the line profile *variability,* i.e. merely the residuals from the mean profiles, global stellar parameters can be derived. These, in turn, permit a model spectrum to be calculated, that matches the observed *spectrum* stunningly well (Fig. 5). Since nonradial pulsations of various kinds are very wide-spread among early-type stars, this might lay the foundation to an entirely new stellar analysis technique, which could be called astero-oscillometry.

Pulsation and Outbursts

The HEROS observations of Be stars initially focused on the 3rd-magnitude star μ Centauri, which seemed to undergo the (then still much more enigmatic) outbursts particularly often. In fact, this choice was highly fortunate as the later analysis of the Hipparcos all-sky database has not furnished any more active Be star than μ Cen. The real thrill, however, of this star unfolded with the discovery that its outbursts, which had been assumed to be stochastic, not only repeated periodically but with two periods, namely 29 and 52 days, which correspond to beat periods between the nonradial pulsation modes with the largest amplitudes.

Would this be the century-long sought key to the understanding of the Be phenomenon? At most partly: Late-type Be stars are not known to be periodically variable or to undergo outbursts and so need to be explained differently. Most of the repetition times of Hipparcos outbursts of Be stars are of the order of 100–200 days, sometimes more. To establish such timescales as periods requires observations with a time baseline of at least twice that length, whereas the ESO 50-cm was de-commissioned already in 1997. So, we were fortunate to be able to arrange for the relocation of HEROS from La Silla to other places and eventually, in 2000, to the 2-m telescope at the Ondřejov Observatory of the Czech Republic. However, in Ondřejov the weather is not much better than in Garching; and there are only very few bright, active equatorial Be stars, for which previous series of observations could be continued.

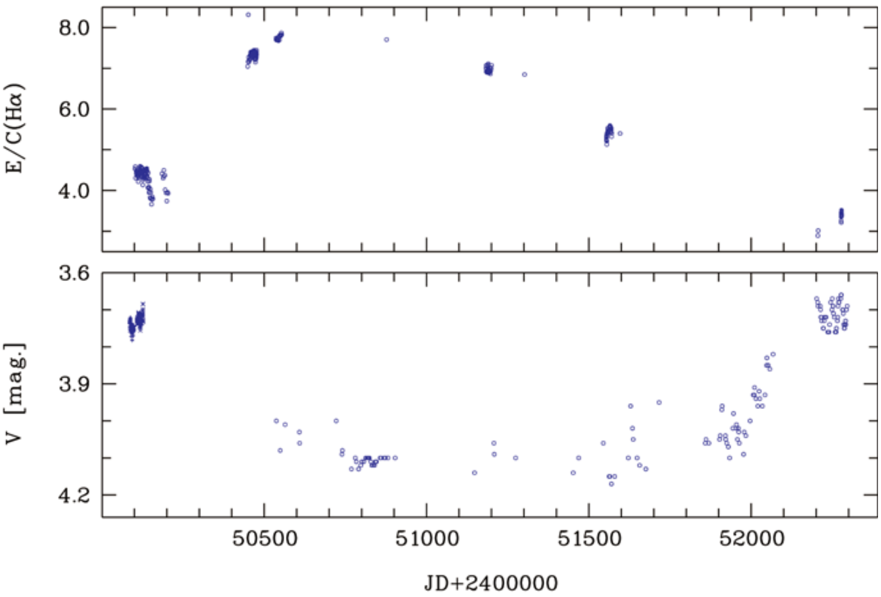


Figure 6: The ratio of the peak height of the Hα emission to the adjacent continuum (top) and the visual magnitude (bottom) of 28 CMa in series of observations covering 7 consecutive annual observing seasons.

Combining Past and Present

Comprehensive though the information contents of HEROS spectra is, it always represents only a small fraction of the complete facts. Accompanying other observations are therefore particularly valuable. Sometimes they can be secured even retroactively.

A simple joke claims: 'The world's largest telescope is when all people look into the same direction'. In fact the collective light-gathering power of all eyes of mankind exceeds even the one of the VLT and will be topped only by some ELT. By implication, the smallest telescope is the eyes of a single person. However, what has been largely forgotten since the days of a F.W.A. Argelander is that a well-trained pair of human eyes is a surprisingly good measuring instrument. So, we have recently teamed up with Argentine amateur astronomer Sebastian Otero (Liga Iberoamericana de Astronomia, Buenos Aires), who has taught himself the almost extinct art of visual photometry and, in a good night, reaches an accuracy of a few hundreds of a magnitude.

He has recently alerted us to a new outburst of the bright Be star 28 CMa. We had observed the previous major outburst with HEROS in 1996. But, then, there was no way to obtain accompanying photometry. Building up on our conclusion that outbursts of Be stars are very similar, we are now stitching the two only partly overlapping series of data together by occasionally 'borrowing' a new FEROS spectrum as a safeguard against the much longer timescale of 28 CMa than of the Be stars observed by us before.

The disk of 28 CMa is seen almost face-on. Stars with edge-on disks are known to fade during an outburst. The brightening of 28 CMa would therefore suggest, as has been argued by others before, that after an outburst the disk is in some area optically thick even in the continuum. This would divert light into directions above and below the disk. However, to explain an amplitude of 40% in this way is a real challenge.

Confusing SMC

Both pulsations and mass loss depend sensitively on metallicity. It would be extremely useful to check whether there are any systematic differences between Be stars in the Galaxy and the SMC. In some fields and clusters of the latter, one-half and more of all B-type stars show emission lines. Moreover, at least Be stars in NGC 330 are known to exhibit photometric short-term variability of the same kind as in the solar neighbourhood. By sacrificing a little bit in S/N and temporal resolution, the impressive throughput of VLT+UVES should permit the observation of stars that are 10,000 times fainter than the ones we had monitored with HEROS and the ESO 50-cm telescope, and thereby to reach NGC 330 spectroscopically.

We submitted a corresponding observing proposal, which apparently presented the picture emerging from the first sections of this article so affirmatively that the OPC concluded that we would not find any difference between Galaxy and SMC. This would not be interesting enough to confirm observationally with as scarce a resource as the VLT. Fortunately, the move of FORS2 from Kueyen to Melipal opened a special observing window with UVES

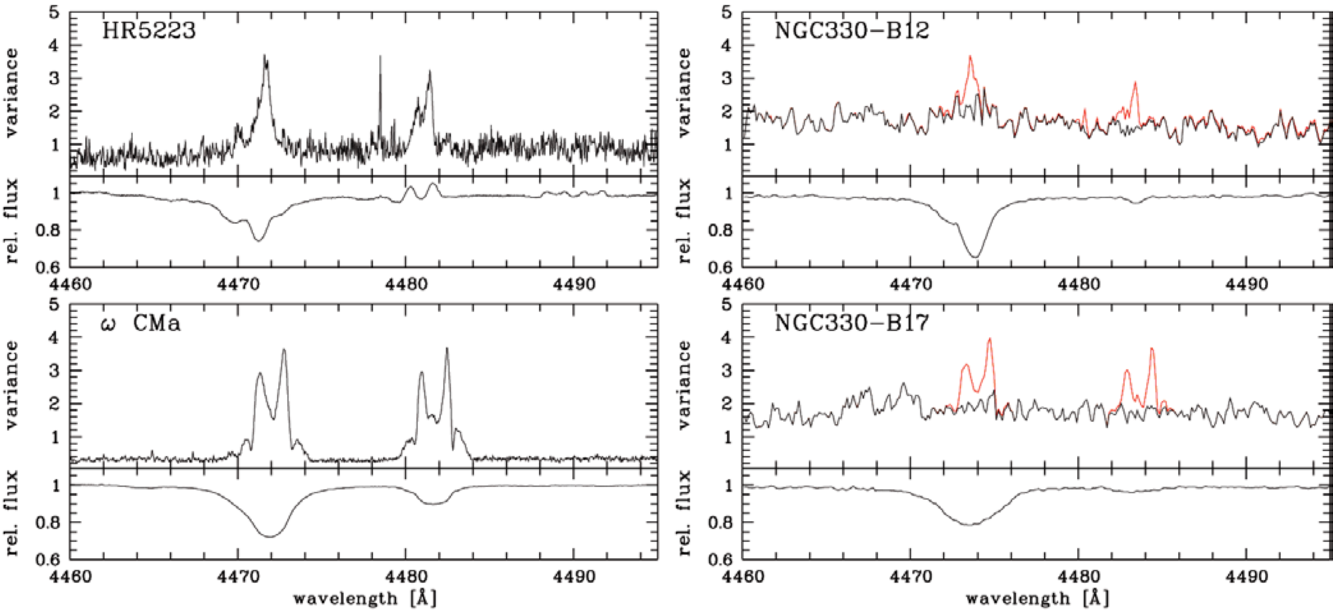


Figure 7: Mean line profiles and their temporal RMS variance of Galactic (left; observed from La Silla) and SMC (right; observed with the VLT and UVES) early-type, pole-on Be stars compared. The red overplot demonstrates the expected RMS variance if the SMC stars underwent the same variability as their Galactic counterparts. The differences in the strength of the Mg II 4481 line are due to the metallicity of the SMC, which is about 80% lower than in the Galaxy.

on Kueyen in August 2001, and the Director General's Discretionary Time Committee recommended some reconnaissance observations.

The results are shown in Figure 7: Not only is there a difference between Galactic and the two SMC Be stars we observed but the latter are not variable at all at a level that would have been easily detected in Galactic observations of the same quality! There is, of course, the possibility of this result being due to small number statistics. However, since we believe that this possibility is probably very small, we submitted a letter to some major astronomical journal. Only to be told by the first referee that our data were not interesting. This problem has meanwhile been fixed. But the puzzle of the Be phenomenon persists with some old questions answered and some new complexities added, and the expansion and analysis of the HEROS database continue.

Acknowledgements: We are indebted to too numerous people at the Landessternwarte Heidelberg and the European Southern Observatory (La Silla and Garching) to give credit to all of them individually. We have not forgotten the manifold technical, scientific, and administrative support.

Spectroscopy of Quasar Host Galaxies at the VLT: Stellar Populations and Dynamics Down to the Central Kiloparsec

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1. Scientific Context

Discovered more than 40 years ago, and in spite of tremendous theoretical and observational efforts, quasars and their host galaxies remain puzzling objects. It seems now established that at least all large galaxies harbour massive black holes (e.g., Magorrian et al. 1998), and that quasar-like activity may be a common but transient phenomenon in galaxy evolution. However, very little of the physical processes at work *during* such episodes of nuclear activity is actually understood. The following questions list some of the important issues still to be solved: What are the time-scales involved in the fuelling (or refuelling) of massive black holes? Does the material they burn come from mergers? Do all galaxies contain a black hole or only the most massive ones? What is the exact relation between galaxies and quasars? Is the feedback from a luminous Active Galactic Nuclei (AGN) onto its host galaxy important? Is it in the form of huge quantities of ionising radiation or does it manifest itself directly as mechanical outflows such as jets?

Quasar host galaxies have been studied almost exclusively by imaging. Examples of such work are numerous and use a broad variety of telescopes, instruments and post-processing techniques. The Hubble Space Telescope (HST) data of Bahcall et al. (1997) have shown that quasars occur in all types of galaxies. Stockton et al. (1998) used