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A spectroscopic search for variability of Be stars in the SMC*

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Abstract. Two low-$v \sin i$ early-type Be stars in the area of the young cluster NGC 330 in the Small Magellanic Cloud (SMC) were monitored with the VLT and the UVES echelle spectrograph during 8 consecutive nights. Exposure times between 45 and 60 min yielded a signal-to-noise ratio of about 80. The temporal variance in the line profiles does not significantly differ from the one of the continuum in both sets of about two dozen spectra. Four more stars were observed only once or twice; their line profiles, too, were not asymmetric. This is in marked contrast to the Galaxy, where short-term line profile variability would normally have been detected with high probability in at least one out of any two randomly selected Be stars of early spectral sub-class and low $v \sin i$. Some possible repercussions on the understanding of the Be phenomenon are briefly discussed.

Key words. stars: emission-line, Be – stars: variable: general – galaxies: individual: SMC

1. Introduction

In Galactic early-type Be stars, photometric (Balona 1990; Balona 1995) and spectroscopic (e.g., Rivinius et al. 2002; Penrod 1986) variability with periods between 0.5 and 2 days is extremely widespread. For more than a century, intensive observations at all wavelengths have not furnished a compelling hint at the origin of the Be phenomenon, namely the formation and maintenance of a rapidly rotating circumstellar disk (Rivinius et al. 2001). Therefore, when the ubiquity of the rapid variability was recognized, a link to the Be phenomenon was hypothesized almost immediately (e.g., Abbott et al. 1986). In fact, Rivinius et al. (1998a) eventually found a correlation between phases of constructive interference between photospheric periods and the times of star-to-disk mass transfer events in μ Cen (B2IVe, $v \sin i = 143\,\mathrm{km\,s^{-1}}$). However, the physics of these outbursts is entirely unknown.

There are numerous emission-line B stars also in the LMC and the SMC (e.g., Keller et al. 1999). Low-resolution spectroscopy has shown that these stars rotate rapidly and have broad Balmer emission lines (Hummel et al. 1999; Hummel et al. 2001; Mazzali et al. 1996). Therefore, it makes sense to assume that these stars and Galactic Be stars form one common class and also owe their disks to the same process(es).

In addition, there is a strong hint from the photometry of Be stars in the SMC cluster NGC 330 (Balona 1992) that low-metallicity Be stars share also the periodic variability with their Galactic counterparts. Pulsating β Cephei stars have not been found in LMC or SMC (e.g., Balona 1993), which is explained by too low a metallicity to sustain the opacity-dependent κ mechanism as the driver of the pulsations. Accordingly, Balona (1992) concluded that the variability of the Be stars not only in NGC 330 but also in the Galaxy is not due to pulsation, the proposed alternative explanation being rotational modulation.

On the other hand, detailed studies of Galactic Be stars (e.g., Maintz et al. 2002; Rivinius et al. 2002; Štefl et al. 2002) have shown that the periodic part of their low-order line profile variability (*lpv*) *is* excellently accounted for by nonradial pulsation (*nrp*). The advent of the *Very Large Telescope* (VLT) now affords the same modeling techniques to be applied to observations of similar quality of Be stars in the SMC.

2. Target selection, observations, and data reduction

Photometry and spectroscopy agree that in Galactic Be stars periodic variability is most common among the early spectral sub-classes. Moreover, observations as well as *nrp* modeling show (Rivinius et al. 2002) that the *lpv* is most easily detected in stars viewed at inclination angles, i, of up to roughly 30 degrees. For

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Table 1. Observed stars in NGC 330.

No.[1]	V^2 mag	$B-V^2$ mag	ΔV^2 mag	$v \sin i$ [3] km s^{-1}	$n_{\rm obs}$
B5	15.47	−0.06	0.04	200	1
B12	15.37	−0.08	const.	40	23
B14	15.54	−0.10	0.05	250	2
B17	15.30	−0.13		140	25
B32	14.95	−0.15	0.04	30	2
B36	15.60	−0.06	0.03	180	1

[1] Robertson (1974), [2] Balona (1992), [3] this work.

Galactic Be stars, this translates to a $v \sin i$ of less than 150 km s^{-1}.

Accordingly, candidate targets were identified on the basis of their published visual magnitudes and $B-V$ colors as well as of the width of their Hα emissions. NGC 330 was an obvious choice as the host cluster so that photometric data could be taken from Balona (1992); spectral parameters were available from Hummel et al. (2001).

Reconnaissance spectra were obtained of 5 Be stars in, or near, NGC 330 (Table 1). NGC 330-B32 does not have a record of line emission but was added to the sample on account of its photometric variability (Balona 1992). None of the 6 stars showed asymmetric line profiles, the give-away finger print of the *lpv* in Galactic Be stars (e.g., Baade 1987; Rivinius et al. 2002). The brightest star, NGC 330-B32, still did not reveal line emission (Fig. 1) even at the resolving power of UVES. The two next brighter ones, NGC 330-B12 and NGC 330-B17, have a promisingly low $v \sin i$; their Balmer emission profiles resemble the ones of Galactic Be stars with large-amplitude *lpv* most closely (Fig. 1). Because the observing time available permitted to study only 2 stars in sufficient detail, all subsequent observations were made of these two stars.

With an rms error of only 0.005 mag, NGC 330-B12 was the most constant star in Balona's (1992) observations. However, this does not disqualify it as a target. The $v \sin i$ of only 40 km s^{-1} identifies NGC 330-B12 as an extreme pole-on star, where cancellation effects reduce the photometric signature of non-standing wave modes ($m \neq 0$) below detectability. Nothing is stated by Balona about NGC 330-B17, which is #384 in his list. (Of the other stars listed by Balona as being variable Be stars all but one are more than a magnitude fainter than the ones in Table 1.)

For comparison with Galactic Be stars, two objects were added to the database of this study, namely 28 CMa (B2 IV-Ve, $v \sin i = 80$ km s^{-1}) and HR 5223 (B2 IIIep, $v \sin i = 70$ km s^{-1}). Their variability is representative of low-$v \sin i$ early-type Be stars in the Galaxy (Rivinius et al. 2002). For 28 CMa 32 spectra obtained in January 1999 with the FEROS spectrograph (Kaufer et al. 2000) were available, for HR 5223 only 8 spectra from July 1999. At a spectral resolving

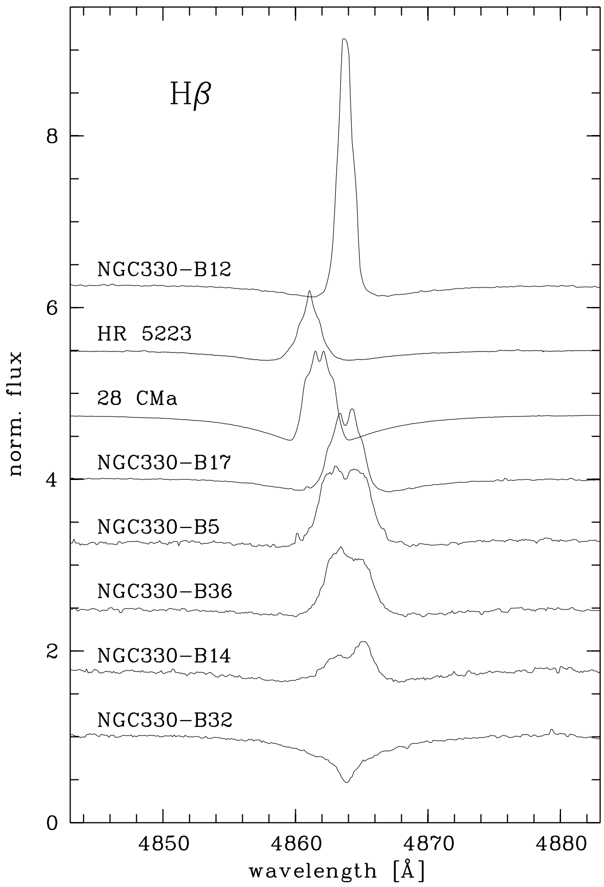

Fig. 1. The average Hβ line profiles of the Be stars in the SMC and of two Galactic Be stars.

power of 48 000, the S/N amounted to 200 and 90, respectively, per 0.03-Å pixel.

The observations took place in 8 half nights between Aug. 2, 2001 and Aug. 9, 2001 and used the UVES echelle spectrograph (Dekker et al. 2000). The blue and the red arm covered the wavelength ranges 373-500 nm and 555-to 946 nm, respectively. With typical slit widths between 1.0 and 1.2 arcsec ($R = 45\,000$ and $R = 38\,000$, respectively) exposure times amounted to 45–60 min. Two to four spectra were observed per night and monitored star. Bias, flat field, and wavelength calibration exposures were obtained every morning following the stellar observations. All data were processed with the standard UVES pipeline (cf. Ballester et al. 2000). The results were rebinned to a lower resolving power of about 25 000. Thereafter, the typical signal-to-noise ratio (S/N) per resolution bin around 480 nm was between 50 and 100, typically about 80.

3. Analysis and results

Figure 1 shows the Hβ profiles of the 6 SMC and 2 Galactic stars. The similarity between the Be stars from the two different host galaxies is in agreement with the conclusion obtained from lower resolution spectroscopy by Hummel et al. (2001) that the physical mechanisms governing the dynamics and morphology of the disks seem

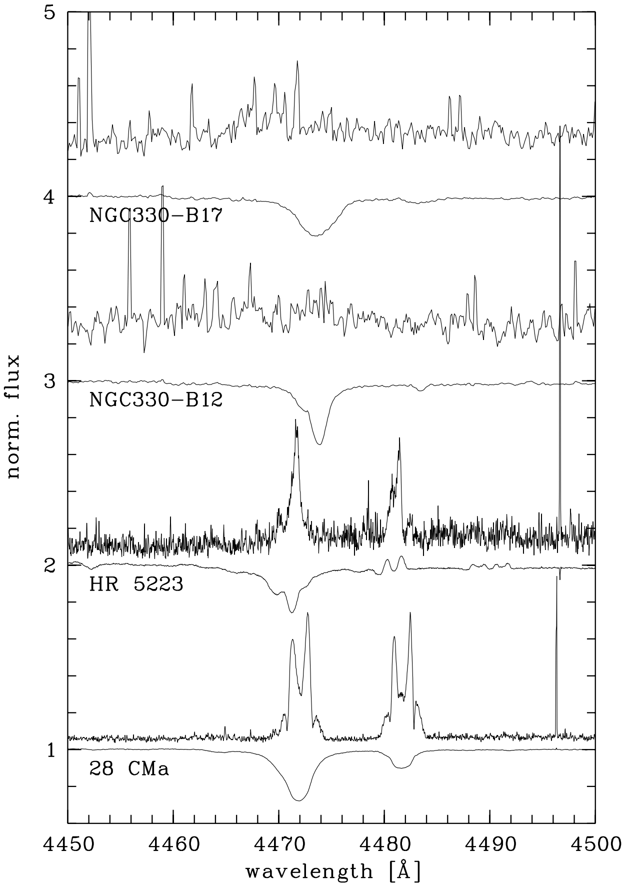

Fig. 2. The mean spectra of NGC 330-B12 and NGC 330-B17 in the region around He I 4471 and Mg II 4481. Also shown is the rms variability per spectral bin ($= \sqrt{TVS}$) of the respective time series. The distance between two tickmarks on the ordinate corresponds to an rms of 1% of the continuum; the continua of the corresponding mean spectra mark the zero-points of the rms scales. For comparison, equivalent information is included for the Galactic Be stars 28 CMa and HR 5223, which have similar spectral type and $v \sin i$. Note the the strong filling-in by emission of the Mg II line in HR 5223, which nevertheless does not prevent the detection of the variability. The weakness of the same line in the two SMC stars is due to the lower abundance; there is no obvious indication of significant contamination by line emission. A possible marginal asymmetry of this line could be due to a blend with Al III.

to be basically independent of the metallicity. The specific appearance of the emission profiles indicates (cf. Poeckert & Marlborough 1978) low to intermediate inclination angles, as intended. The mean spectra of the SMC stars confirm the fulfillment also of the second selection criterion, i.e. an early-B sub-class.

The sets of spectra of NGC 330-B12 and NGC 330-B17 were subjected to the same time series analysis techniques, that have been successfully applied to Galactic Be stars (Rivinius et al. 1998b). For instance, in the 32 spectra of 28 CMa, they readily recover the period of 1.37 d (Baade 1982). By contrast, for both NGC 330-B12 and NGC 330-B17 not even a trace of a periodicity emerged in any spectral feature.

In order to check whether there was any variability at all, temporal variance spectra (TVS; Kaufer et al. 1996) were constructed. In each spectral bin, a TVS contains the variance in that bin of all available spectra. A TVS can, thus, be conveniently used to compare the noise in spectral lines with the one in the continuum and to search for patterns within line single profiles as well as a function of conditions of line formation.

In NGC 330-B12 and NGC 330-B17, there is no significant difference between the variance in line profiles and continuum (Fig. 2 shows the wavelength region around He I 4471 and Mg II 4481). That is, at a S/N of 80 and a spectral resolving power of 25 000 these two SMC Be stars do not exhibit *lpv*. By the examples of 28 CMa and HR 5223 Fig. 2 illustrates also what would have been expected if Be stars in the SMC behave in the same way as do Galactic Be stars. The VLT/UVES observations would have detected such variability in NGC 330-B12 and NGC 330-B17 with high significance.

The much lower metallicity of the SMC Be stars (cf. Fig. 2) puts them only at a relatively mild disadvantage as the detectability of *lpv* is concerned: their helium lines are essentially not any different from those of Galactic Be stars. Moreover, if in a Galactic Be star *lpv* is detected in one helium line, it is detected also in all other ones, provided the data quality is the same.

4. Discussion and conclusions

Several reasons for this non-detection of *lpv* in the SMC stars are conceivable:

- At 45–60 min, the UVES exposure times were longer than typically chosen for bright Galactic objects. But this not likely to explain the observed differences. There is no indication that in NGC 330 the periods are any shorter than in the Galaxy. Degradation of the temporal resolution of series of observations of Galactic Be stars to 45–60 min does not critically reduce the detectability of the main, low-order *lpv*.
  In the Galaxy, the hottest Be stars show a tendency towards *nrp* modes with higher degree, ℓ, and shorter periods. This makes them more difficult to detect by spectroscopy as well as photometry. However, the stars selected for this study reside, if anything, more in the cooler part of the range $-0.20 \leq B - V \leq -0.05$, within which Balona (1992) detected periodic variables.
- In Galactic Be stars, there can be long-term variations, during which the *lpv* and/or photometric amplitude drops below conventional detection thresholds (e.g., Sareyan et al. 1998). But this does not appear to be too common a phenomenon.
- The single-site observations, which moreover extended only over half nights, may have led to a very unfortunate phase sampling. However, this should only render any derived periods rather uncertain whereas the evidence of variability and/or asymmetry would not nearly be so drastically affected.

- The stars observed with the VLT are more luminous than the ones, which Balona (1992) found to vary periodically. However, their photospheric as well as their emission line profiles distinguish them clearly from supergiants, and in the Galaxy no hint seems to have emerged at a possible dependency of the variability of non-supergiant Be stars on luminosity.
- The variability of early-type Be stars in SMC and Galaxy is genuinely different.

The latter would be a possibly far-reaching conclusion founded on a seemingly very small statistical basis. However, if in the Galaxy two Be stars were randomly selected from a sample compiled according to the same criteria (early spectral type and low $v \sin i$) and observed in an analogous fashion, our observing experience as well as our reading of the literature predicts with high confidence that *lpv* will be firmly detected in at least one of them. Considering also the lack of asymmetries in the line profiles of the four SMC stars observed only once or twice, one can not easily dismiss the possibility of a real difference, and if only in the incidence and/or amplitude of the *lpv* as a function of stellar parameters. Additional observations of 1–3 Be stars in the SMC but also in the LMC, which has a metallicity intermediate between Galaxy and SMC, would probably settle this point unambiguously.

Several conjectures can be attached to this possibility:

- The periodic short-term variability of Be stars would not be related to the Be phenomenon. The correlation between outbursts and the beating of several *nrp* modes in μ Cen – as well as the more pronounced occurrence of low-order *g*-modes in Be rather than in rapidly rotating non-Be stars (Baade 1987) – would be kind of coincidental. The fact that late-type Be stars do not share this variability would no longer be an obstacle to one global explanation of the Be phenomenon, because this explanation would not involve *lpv*.
- If, owing to their much lower metallicity, Be stars in the SMC did not pulsate, this would not surprise. However, theory does not firmly predict this (Pamyatnykh 1999 and private comm., 1998).
- A possible absence of *lpv* in Be stars in the SMC would have no implications whatsoever for the interpretation of the *lpv* in Galactic Be stars.
- A mismatch between photometric and spectroscopic variability of SMC Be stars would not pose a major additional problem: even in the Galaxy only few Be stars have been monitored spectroscopically and photometrically in parallel, with rather different degrees of correlation of the results. While there are stars, in which photometric variability has not, or only hardly, been detected although the *lpv* is quite significant, the opposite does not seem to have been observed so far. Non-contemporaneous photometry and spectroscopy often suggest even different periods. Accordingly, the unexpected result would not be the lack of agreement between photometry and spectroscopy but the absence of spectroscopic variability.

Whether the observations reported in this study will be a stumbling block or a stepping stone towards the understanding of the Be phenomenon can be clarified by additional observations, the scope and strategy of which are easily defined (cf. above). It would be prudent to defer any major conclusions until after their analysis.

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