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Time-resolved high-resolution spectroscopy of an Hα outburst of μ Centauri (B2IV-Ve)*

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Summary. Following a phase of very weak emission but extreme variations of the V/R ratio of the equivalent widths of its two components in early February, 1987, μ Cen developed a new highly symmetric doubly-peaked emission at Hα. The total equivalent width decreased by 1.5 Å within only two days. During the time of maximal growth of the feature an additional emission component with a full width of 800–900 km s^{-1} partly filled in the underlying stellar absorption. If caused by Thomson electron scattering, the short duration of this phenomenon further strengthens the classification of the event as an outburst. The event at Hα was accompanied by conspicuous line profile variability of the C II λλ6578, 6583 Å doublet which after the outburst also included dramatic V/R variations of emission components. The latter seem to have been detected for the first time in Be stars. After 17 and another 19 days, respectively, this first Hα outburst was followed by two comparable, slightly fainter ones. In Hα, maxima of the emission strength are usually preceded by a period of strong V/R variations and also appear to be accompanied by a phase of decreasing visual brightness of the star.

From the synopsis with the similar 1985 event reported by Peters (1986) for the same star, a first attempt is made to abstract the general pattern of such outbursts. Potential problems of elliptical ring and decelerated, balloon filling models are outlined. Processes governing the mass loss from Be stars and the evolution of their envelopes are briefly discussed. Apparently, Be stars do not undergo outbursts each time when their pulsation amplitude is large. For example, in 1986 April, very weak but extremely strongly V/R variable Hα emission was observed in μ Cen while for at least 10 days there was no indication of enhanced mass loss. The with respect to 1986 April much stronger wings and the considerably shallower core of the Hα absorption are probably closely connected with (precede?) the emission event.

Key words: Be stars – circumstellar matter – mass loss – outbursts – nonradial oscillations

1. Introduction

The variability of emission lines is one of the defining characteristics of the Be phenomenon (though not of every individual Be star because some have been remarkably stable over decades). There are many well documented cases (see, e.g., the atlas of Hubert–Delplace et al., 1979) where Be stars have temporarily lost their emission lines. UV resonance line profiles extending beyond the stellar escape velocity and especially also their variability unambiguously identify the Be phenomenon as one of variable mass loss. It is interesting that also in the UV all signatures of mass loss can at times be so weak or even undetectable that judged merely by the strength of circumstellar lines a Be star may become indistinguishable from other non-supergiant B stars in which significant mass loss has not been observed beyond ~B2 (Snow, 1987; Grady et al., 1987 and references therein).

One of the most remarkable recent discoveries seems to be that a 'classical' emission line B star after having temporarily lost its traditionally defining attributes, may still reveal its true nature by the variability of its stellar absorption lines. Penrod (1986, see also Baade, 1987a) finds that Be stars are characterized by line profile variations with both low and high spatial frequencies while Bn stars (broad-lined B stars in which Hα was never observed in emission) display only the latter. This variability is usually identified with low- and high-order nonradial oscillations, respectively (for a review see Baade, 1987a, b). Like the circumstellar phenomena, the pulsation amplitude, too, is variable, and Penrod (1986, 1987) and Smith (1987, private communication) report an anticorrelation of the two in the sense that the low-order mode pulsation amplitude decreases after a major enhancement of the mass loss rate as deduced from the Hα emission line strength. That mass loss events of Be stars are actually driven by instabilities of the low-order nonradial pulsation pattern is therefore at least a strong possibility (Penrod, 1986). This would require a mechanism that relatively suddenly channels part of the pulsation energy into the ejection of matter. At present, details of such a mechanism are not known with any certainty (cf. Baade, 1987a) but it is clear that in any given star for the same pulsation amplitude there are phases with and without enhanced mass loss. Therefore, the effect of the pulsation amplitude, if any, at any instant either depends on the previous pulsation history or on some other global atmospheric parameters. There are suggestions (for references and a discussion see Baade, 1987a) that these two possibilities may not really be

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* Based on observations collected at the European Southern Observatory, La Silla, Chile

alternatives but that changes of global atmospheric properties such as density or temperature profile are long-term effects of the pulsation.

In that interpretation, the event-like nature of the mass loss process from Be stars plays an important role. So far, most of the evidence for the existence of mass loss events has come from polarimetry (Guinan and Hayes, 1984 and references therein) which has detected increases of the polarization within just a few days whereas the subsequent decrease usually lasted several times longer. The amplitudes of these polarization events span at least one order of magnitude so that one may have to envisage a broad spectrum of mass loss events which is heavily weighted (in frequency) to small amplitudes. Much additional insight into their nature could be gained if one succeeded in mapping the morphology of the development of a new emission phase also from line profile variations at high spectral resolution. Because of the possible role of preceding secular changes of the atmosphere, observations immediately prior to a mass loss event appear particularly important at this stage.

To our knowledge, the series of Hα profiles obtained of μ Cen (=HR5193=HD120324; B2IV-Ve) in 1985 March by Peters (1986) by far came closest to this goal. Unfortunately, unfavourable weather conditions prevented a continuous observational coverage. But the rise time clearly was shorter by a large factor than the subsequent lifetime of the new emission line. μ Cen is a relatively active B2e star which is known to have several times suffered a more or less complete loss of its emission line spectrum. Peters (1984, 1986; see also Dachs et al., 1986a) gives a detailed account of its recent observational history. Since 1977, only faint flickering emission has been occasionally observed. Noteworthy Hα emission was last seen in 1984 June, had almost vanished by 1985 January, and was no longer detected in 1985 February, shortly before the event recorded by Peters (1986). Since then the emission has remained very weak but at the same time maintained a high level of variability (Peters, 1986; Hanuschik, 1986; Baade, 1987a). We report here the detailed development of one event in 1987 February which seems to belong to the high-amplitude tail of the distribution of such events during a period of generally very weak line emission. Observations of two subsequent events place a rather high lower limit on the maximum frequency at which such outbursts can occur.

2. Data acquisition and reduction

2.1. *High-resolution Hα spectroscopy*

High-quality spectra were obtained with the European Southern Observatory (ESO) Coudé Echelle Spectrometer (CES) fed by the 1.4 m Coudé Auxiliary Telescope (CAT) at La Silla. With the long camera of the CES and a Reticon array of 1870 diodes as the detector, the length of the observed spectra was about 55 Å at the two central wavelengths chosen (Hα and He I λ 6678). The instrumental full widths at half maximum (FWHM) of 2.5 (Hα) and 2.65 (He I 6678) diodes measured in the thorium h.c. lamp comparison spectrum correspond to a spectral resolution of 76 mÅ at either wavelength. After the usual reduction procedures, the typical S/N attained in the 15 minute exposures made was 300 and 500, respectively, per diode. (The value given for Hα does not include the effect of the numerous telluric water vapor lines.)

CES spectra are known to suffer from some vignetting of as yet unexplained nature. The attenuation amounts to about 5% at the blue edge of the spectrum and decreases roughly linearly over the first ~400 diodes. However, the amplitude of the depression is different for stellar exposures than for flat field exposures taken with a quartz lamp positioned close to the spectrograph's entrance slit. The agreement is better but still not perfect between stellar observations and flat field exposures taken with a lamp in the dome, presumably because a small misalignment between CAT and CES introduces some additional dependence on telescope position. Accordingly, the normalization of the spectra to the continuum may locally be in error by 1–2% if an interpolation across broad lines like Hα is needed which in Be stars almost fills the frame. The error averaged over the full line width is however much smaller. These numbers have been determined both from Hα observations of early-type supergiants where this line is much narrower, and from other, virtually line free, spectral regions. For observations such as the ones reported in this paper that have been obtained at nearly identical telescope positions, the internal consistency is far better.

2.2. *Medium-resolution Hα spectrophotometry*

The series of high-resolution CAT/CES spectroscopy was preceded, accompanied and followed by lower-resolution Hα spectrophotometry obtained with a rapid scanning grating spectrometer attached to the 61 cm Cassegrain reflector of the University of Bochum at La Silla. The instrument has been described by Haupt et al. (1976); its actual operating mode and performance for the study of Balmer emission lines are summarized, e.g., by Dachs et al. (1981). Step width and nominal resolution of the scans was 1 Å for the 1987 January measurements and 2 Å in February and March; effective wavelength resolution equals about 2.5 Å for all data. The scanner wavelength scale is only relative and has during the reduction been adjustated such that central absorption minima of Hα profiles correspond to the rest wavelength of the line. Forward and backward scans were separately recorded and then averaged. The S/N of measured Hα intensities usually averages about 100 to 200 per wavelength step (2 or 1 Å) with a few exceptions when it was lower (Jan. 30: about 40; Jan. 29 and 31, March 05 and 09: about 80).

Evaluation and reduction of the spectra were performed by using the Image Handling And Processing (IHAP) system developed at ESO.

2.3. *VBLUW photometry*

Photometry was done with the 91-cm telescope at La Silla in the Walraven *VBLUW* system. A detailed description of the properties of this system can be found in Lub and Pel (1977) and references therein. Between 1987 February 6 and March 10 a total of 16 observations were made which in the Walraven system each consist of simultaneous measurements in all five channels. The diaphragm had a diameter of 16″; because of the brightness of μ Cen the optical attenuator had to be used which is a drum with several slots that rotates in the beam and therefore is truly neutral in its effect on the measured colors. The integration time for the first 6 measurements was 4 × 16 s each while for the last 10 observations only 2 integrations of 16 seconds have been averaged. To calibrate the data, *VBLUW* standard stars have been observed in the usual way. However, because of requirements of the ongoing primary observing programme, no nearby comparison star has been measured. The data were reduced using the reduction package available at the Sterrewacht Leiden.

3. Results

3.1. Description of the 1987 observations

3.1.1. CES high-resolution spectroscopy

Figure 1 depicts a series of Hα profiles obtained at nightly intervals between 1987 February 02 and 09 and a few single later profiles. The main finding is a substantial increase of the emission strength within just two days from February 03.4 to February 05.4. Over the rather arbitrarily chosen range from 6545 to 6585 Å the equivalent width (E.W.) of the entire Hα complex dropped from 2.9 to 1.4 Å (see also Sect. 3.1.2, Table 1, and Fig. 5). An uncertainty of 0.5% in the interpolation of the continuum over this very broad line would mean that these numbers could be in error by as much as 0.15 Å. The minimum of the equivalent width was recorded on February 05.4 while the emission peaks attained their maximum height on February 08.3.

Three observations (Fig. 3) of He I λ 6678 reveal considerable variability of the stellar component which had already been seen during earlier epochs and identified with nonradial pulsations (Baade, 1984, 1987a, b). Very striking are also the changes of the two emission components. As had been noted (Baade, 1987a) for previous observations of μ Cen, also in 1987 February the line

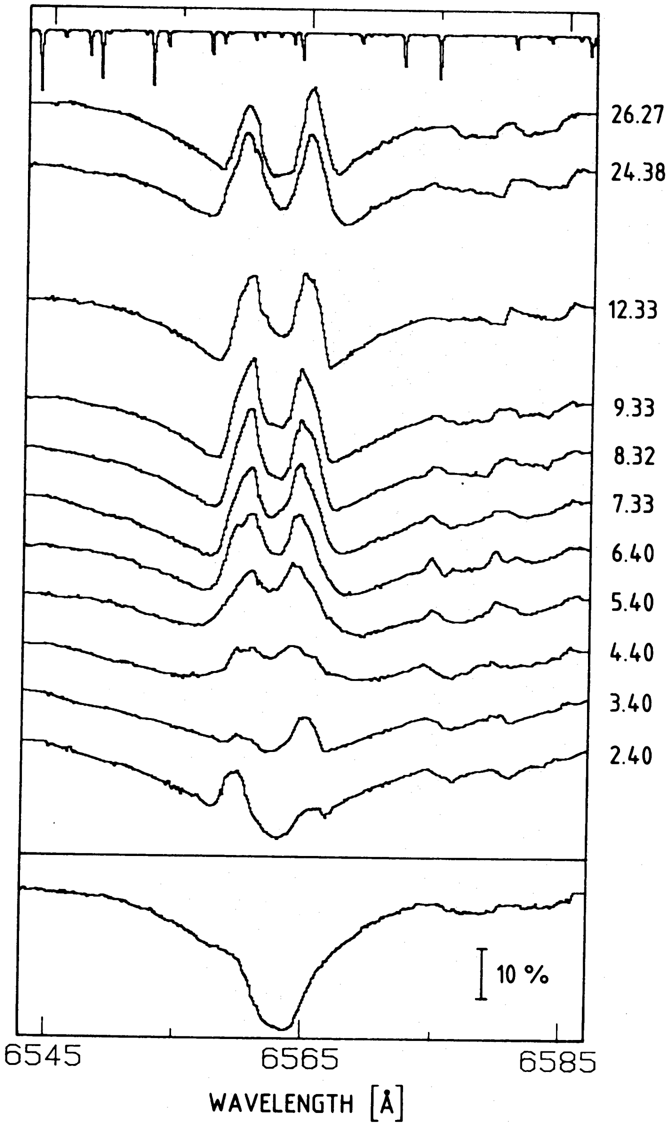

Fig. 1. Upper panel: The sudden development of Hα emission in μ Cen in 1987 February. Observing dates (UT of 1987 February) are shown to the right; only for the spectra taken between February 02.4 and 09.3 is the vertical spacing proportional to the time elapsed. Lower panel: For comparison the Hα profile of μ Cen on 1986 April 01, is shown. Note the much deeper core and weaker wings of the absorption component. The total equivalent widths on 1986 April 01, and 1987 February 02, happen to be the same (2.9 Å). All spectra are normalized to the apparent continuum. The scale in units of the adjacent continuum is provided by the vertical bar in the lower right corner. Strong telluric lines have been removed by linear interpolation across their full width. The mean telluric spectrum corrected for in this way is shown at the top of the upper panel

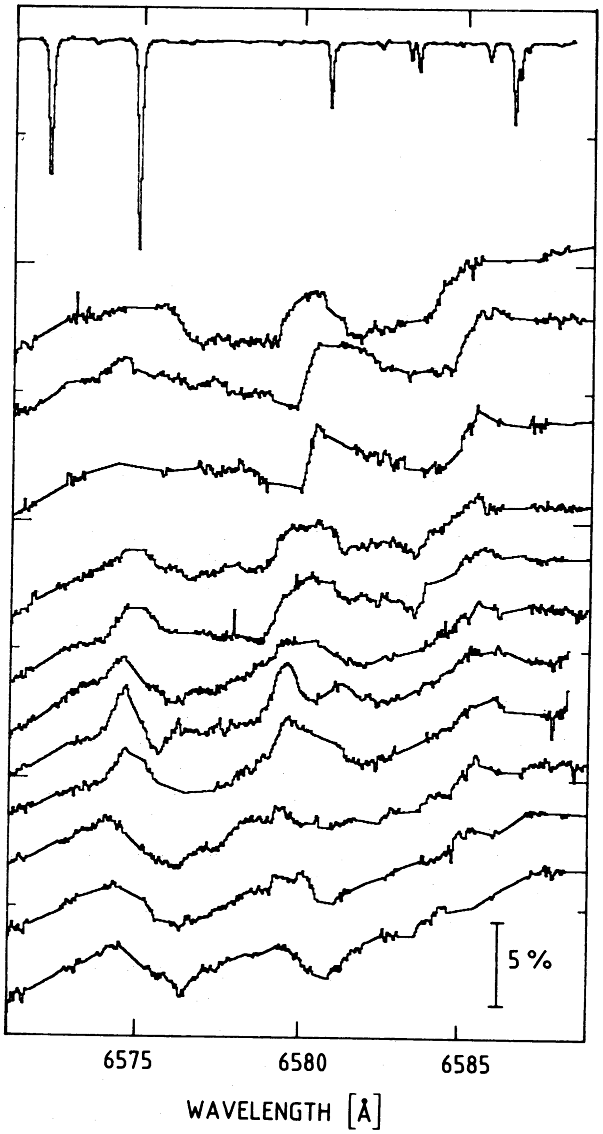

Fig. 2. This is an enlargement of a part of Fig. 1 (upper panel only) in order to better show the variability of the C II λλ 6578, 6583 lines. The (relative) flux scale is displayed in the lower right corner. The absorption line profile variability is considerable; note the occurrence of emission components after February 4, the first day of the Hα outburst

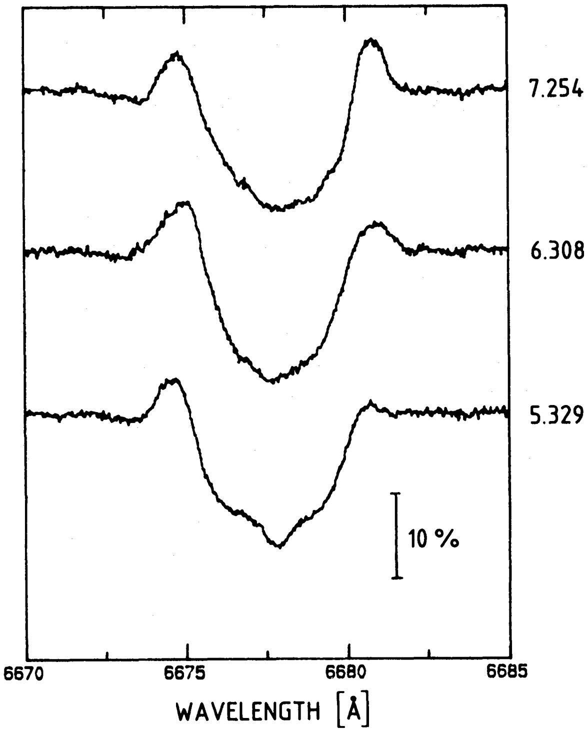

Fig. 3. Some isolated snapshots of He I λ 6678 in μ Cen. The relative vertical displacement of the spectra is kept constant at 20% of the continuum flux and does not relate to the time elapsed between consecutive observations. Observing dates (UT of 1987 February) are given to the right; the vertical bar in the lower right corner indicates the flux scale relative to the adjacent continuum

profile variability of the C II doublet at λλ 6578, 6583 appeared to be much more pronounced (see Fig. 2) than the one seen in He I λ 6678. But evidently, the small number of observations and the phase difference between observations of the two sets of lines preclude a firm conclusion. A result not hitherto reported for Be stars is the unambiguous detection of emission in the C II doublet.

In addition to the above global description of the observations, the following details are worth noting:

1. There appear to be large-amplitude variations of the V/R ratio of the two emission components in all four lines observed. They were the largest on February 02–03, preceding the spectacular rise of Hα emission intensity during the following days. However, while in the C II and He I lines this activity continues also after the Hα outburst of February 04–05, the Hα emission profile initially remains fairly symmetric with $V/R \sim 1$. Only three days after the outburst, on February 08, the height of the red component can be seen to have decreased by about 4% of the continuum flux. There was no detectable change the following day, and on February 12 the profile is again symmetric because the blue component, too, has weakened.

2. On February 04, to a much lesser extent also the day before and after, the broad stellar absorption line is extremely shallow. Different normalization methods (cf. Sect. 2) did not succeed in removing the difference between this observation and spectra taken 2 days earlier or later. We do not have photometric data for this epoch but the similarity of the absolute spectroscopic signal recorded during all nights nearly rule out the possibility that the shallowness of the line is due to some broadband (> 50 Å) continuum veiling. Subtraction of the mean profiles before and after this phase implies an extremely broad line emission with a full width of 800–900 km s^{-1}. At the center, it amounted to 5% of the continuum flux or more but, of course, is not easy to separate from the upcoming doubly-peaked emission. The estimated E.W. of this broad component was about 0.5 Å. This component was no longer detectable on February 07; at most traces of it were present on February 06 when the conventional doubly-peaked emission was already fully developed.

3. In Fig. 1 we also show an Hα profile, obtained on April 01, 1986 (Baade et al., in preparation) which among those available to us is the least contaminated by emission. It is substantially deeper but also has much less pronounced and extended wings than the profile of February 02, 1987, and both profiles happen to have the same E.W. (2.9 Å). A dozen additional Hα observations in 1986 April all show the same deep core although rapid V/R variations with substantial amplitude were seen from April 2 on. Similar Hα profiles were obtained by Hanuschik (1986) in early 1985 before and after the emission event described by Peters (1986).

4. Before the outburst, the isolation of the two Hα emission components from one another is rather pronounced; after the outburst, the two peaks are clearly defined; but during the outburst (February 04) there is almost no central depression at all. The peak separation was about 280 km s^{-1} on February 02.4., dropped to 150–160 km s^{-1} during the main outburst (February 04–05), and later on (February 06–12) slightly increased to 170–200 km s^{-1}. The former range is probably associated with the rapid V/R variability while the latter represents a continuous increase as the central depression gains in relative strength. In contrast to the peak separation, the full width at 'zero' intensity (FWZI) of 370 km s^{-1} remained nearly unchanged at all times (not considering the transient very broad component mentioned above).

5. The emission in He I λ 6678 as seen in Fig. 3 is clearly weaker on February 05 than on February 07, i.e. after the outburst. Only from longer series of observations could one have deduced whether this increase was real or merely apparent due to the sampling of the rapid variability. In the former case, the emission strength of this line would have continued to rise *after* the Hα emission had reached its maximum.

6. On February 02–04, there was no evident emission in the C II lines, whereas it was clearly seen in each of the six observing nights between February 05 and 12. It is therefore possible that the C II emission developed (or got enhanced) only during the outburst. We note that the peak separation of about 3–5 Å measured in the simultaneous Hα profiles and the difference in wavelength of the two C II lines (4.8 Å) are rather similar so that the violet emission component of C II λ 6578 and the red one of C II λ 6583 are probably blended. This explains the apparent triple structure with peaks near λλ 6574, 6580 and 6586.

7. Although the sampling of our data with time is very incomplete, there is no indication of a rapid drastic decrease in the amplitude of the stellar absorption line profile variability.

3.1.2. Medium-resolution spectroscopy

The spectrophotometric data obtained at the 61 cm telescope between 1987 January 29.3 and March 15.3 are plotted in Figs 4a–4c. In order to better show the details of the Hα profiles, the original wavelength coverage of the measurements of $\lambda\lambda$ 6500–6630 has been cut down to $\lambda\lambda$ 6525–6600. Equivalent widths measured on these profiles are listed in Table 1, following the usual convention that emission components above the continuum contribute to the total E.W. with negative sign.

The development of Hα around the 1987 February 04–05 burst as seen at medium resolution can be described as follows:

During the last nights of January, only very weak doubly-peaked emission is visible in the wings of the photospheric Hα absorption line (Fig. 4a), with a peak separation of about 300 km s^{-1} ($\approx 2\,v \sin i$, cf. Slettebak, 1982). The phase of rapidly increasing Hα emission during the first February nights was only recorded at the CAT (Fig. 1), while for the following period of maximum emission between February 05 and 07, profiles measured with the Bochum scanner can be compared with those obtained nearly simultaneously at higher resolution with the CES. This comparison clearly shows that the double-peak structure of the profiles shown in Fig. 1 with a peak separation of only about 3 Å is only marginally resolved by the scanner (Fig. 4a); likewise, the peak height appears to be reduced in the profiles measured with the scanner.

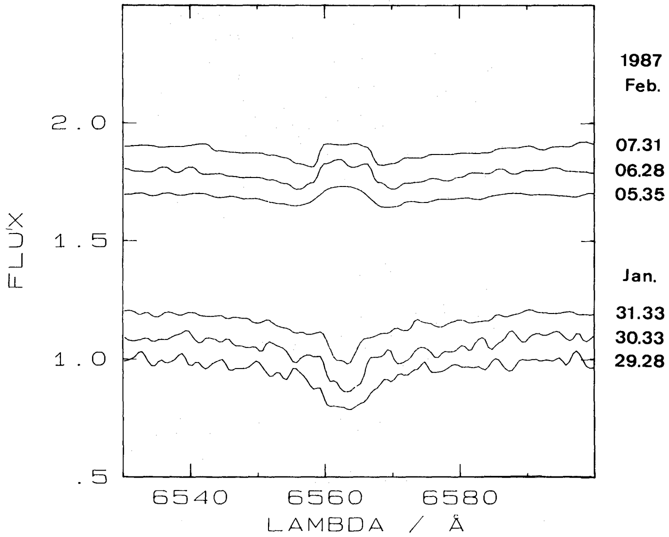

Fig. 4a. Medium resulution Hα line profiles of μ Cen between 1987 January 29 (bottom) and February 07 (top). Fluxes are normalized to the mean ambient continuum intensity. Different line profiles are displaced with respect to the lowermost shown by one-tenth of continuum flux per day

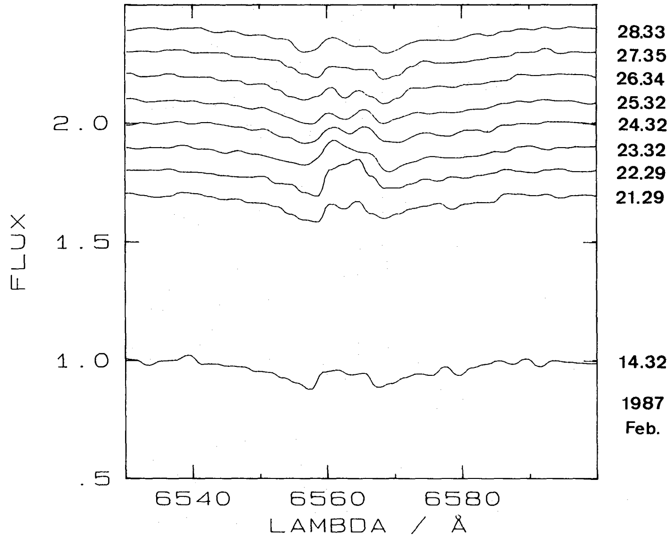

Fig. 4b. Same as Fig. 4a except for period being 1987 February 14 (bottom) to February 28 (top)

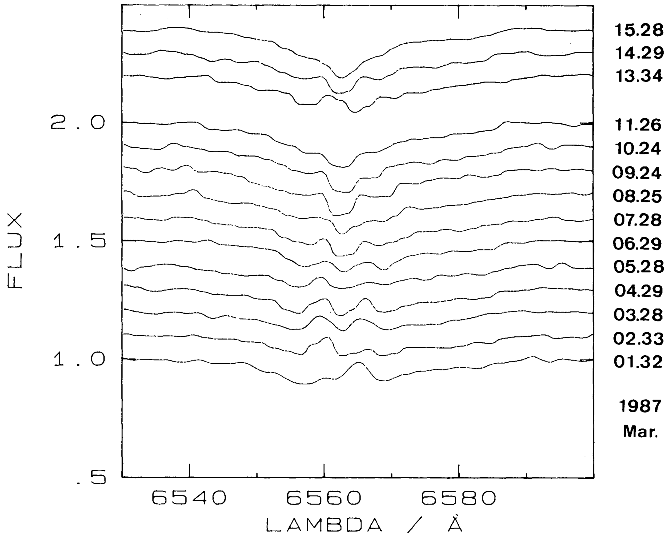

Fig. 4c. Same as Fig. 4a except for period being 1987 March 01 (bottom) to March 15 (top)

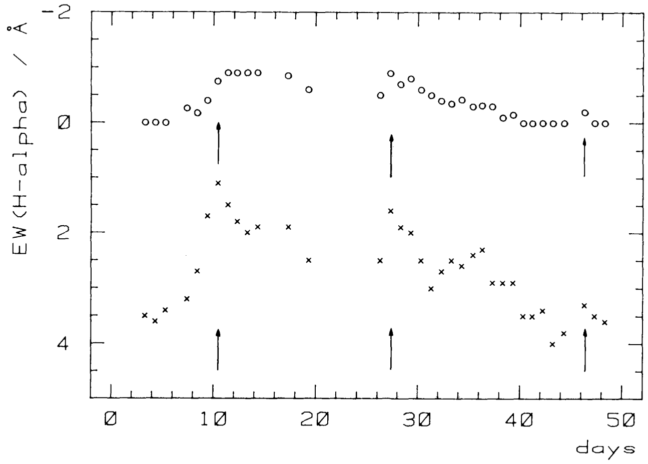

Fig. 5. Equivalent widths (in Å) of the total Hα absorption (crosses) and emyssion circles) in μ Cen *vs.* the time elapsed (in days) since 1987 January 26.0 (UT). Peaks corresponding to three Hα emission events on February 05 and 22, and March 13 are marked by arrows.

After the maximum of the Hα emission recorded February 05–09, central doubly-peaked Hα emission was again much fainter on February 14.3 and 21.3, but had suddenly recovered its former maximum strength by February 22.3 and 23.3 (Fig. 4b). Thereafter, the intensity of the two Hα peaks slowly decreased until March 11.3 while their separation gradually increased. Weak *V*/*R* variations were superimposed to this phase of declining emission intensity. In the sampling of this activity by our

Table 1. Equivalent widths (in Å) of Hα total absorption (abs.) and of Hα emission (em.) for μ Cen

Date (UT 1987)	E.W. (abs.)	E.W. (em.)
Jan. 29.3	+3.5	
30.3	+3.6	
31.3	+3.4	
Feb. 02.4	+3.2	−0.3
03.4	+2.7	−0.2
04.4	+1.7	−0.4
05.4	+1.1	−0.75
06.4	+1.5	−0.9
07.3	+1.8	−0.9
08.3	+2.0	−0.9
09.3	+1.9	−0.9
12.3	+1.9	−0.85
14.3	+2.5	−0.6
21.3	+2.5	−0.5
22.3	+1.6	−0.9
23.3	+1.9	−0.7
24.3	+2.0	−0.8
25.3	+2.5	−0.6
26.3	+3.0	−0.5
27.3	+2.7	−0.4
28.3	+2.5	−0.35
Mar. 01.3	+2.6	−0.4
02.4	+2.4	−0.3
03.3	+2.3	−0.3
04.3	+2.9	−0.3
05.3	+2.9	−0.1
06.3	+2.9	−0.15
07.3	+3.5	
08.2	+3.5	
09.2	+3.4	
10.2	+4.0	
11.3	+3.8	
13.3	+3.3	−0.2
14.3	+3.5	
15.3	+3.6	

observations, the V/R variations between February 28 and March 02 suddenly attained a very large amplitude, possibly preceding another weak burst of Hα emission on March 04 (Fig. 4c).

Finally, a third (if not fourth, see above) weak enhancement of the Hα emission during the survey period had occurred by March 13.3 (Fig. 4c).

3.1.3. *VBLUW* photometry

The results of the 16 *VBLUW* observations of μ Cen are compiled in Table 2. The first column gives the civil date (UT) while column 2 provides the Julian dates. The following ten columns contain the *VBLUW* parameters and their estimated errors (note that in the *VBLUW* system it is customary to use a log-intensity scale instead of magnitudes). The error estimates are based on the errors of each night's solution (i.e., instrumental sensitivity, atmospheric extinction) as determined from the measurements of

Table 2. *VBLUW* photometry of μ Cen

Date (UT 1987)	Julian date 2,446,000+	V	$\sigma(V)$	$V-B$	$\sigma(B-V)$	$B-U$	$\sigma(B-U)$	$U-W$	$\sigma(U-W)$	$B-L$	$\sigma(B-L)$	V_J	$\sigma(V_J)$	$(B-V)_J$	$\sigma((B-V)_J)$
Feb. 07	833.8730	1.3733	0.0026	−0.0745	0.0020	0.0196	0.0015	−0.0192	0.0016	−0.0042	0.0021	3.4579	0.0065	−0.2074	0.0052
09	835.8766	1.3686	0.0023	−0.0783	0.0018	0.0300	0.0016	−0.0206	0.0015	+0.0012	0.0027	3.4700	0.0058	−0.2178	0.0046
10	836.8816	1.3690	0.0035	−0.0756	0.0024	0.0282	0.0042	−0.0203	0.0025	−0.0028	0.0047	3.4687	0.0088	−0.2104	0.0062
11	837.8800	1.3652	0.0058	−0.0719	0.0019	0.0238	0.0021	−0.0177	0.0020	−0.0067	0.0023	3.4779	0.0145	−0.2003	0.0049
14	840.8828	1.3655	0.0023	−0.0787	0.0034	0.0293	0.0021	−0.0218	0.0024	−0.0002	0.0024	3.4777	0.0058	−0.2189	0.0088
15	841.8874	1.3789	0.0041	−0.0858	0.0022	0.0309	0.0016	−0.0246	0.0022	+0.0021	0.0022	3.4448	0.0103	−0.2384	0.0057
21	847.8718	1.3804	0.0026	−0.0736	0.0030	0.0257	0.0018	−0.0208	0.0018	−0.0028	0.0022	3.4401	0.0065	−0.2050	0.0077
23	849.8974	1.3783	0.0023	−0.0720	0.0018	0.0214	0.0021	−0.0180	0.0027	−0.0050	0.0027	3.4564	0.0058	−0.2006	0.0046
24	850.8862	1.3597	0.0056	−0.0723	0.0042	0.0237	0.0073	−0.0170	0.0074	−0.0048	0.0075	3.4917	0.0140	−0.2014	0.0108
25	851.8720	1.3663	0.0027	−0.0774	0.0022	0.0263	0.0021	−0.0210	0.0021	−0.0023	0.0026	3.4756	0.0068	−0.2153	0.0057
26	852.8829	1.3635	0.0022	−0.0758	0.0021	0.0283	0.0021	−0.0208	0.0027	−0.0015	0.0022	3.4825	0.0055	−0.2110	0.0054
28	854.9015	1.3707	0.0027	−0.0743	0.0030	0.0215	0.0018	−0.0183	0.0020	−0.0031	0.0019	3.4644	0.0068	−0.2069	0.0077
Mar. 02	856.8907	1.3761	0.0040	−0.0721	0.0026	0.0193	0.0018	−0.0169	0.0022	−0.0046	0.0023	3.4507	0.0100	−0.2009	0.0067
04	858.8801	1.3679	0.0031	−0.0748	0.0026	0.0285	0.0022	−0.0219	0.0024	−0.0022	0.0022	3.4714	0.0078	−0.2082	0.0067
05	859.8998	1.3657	0.0018	−0.0752	0.0023	0.0286	0.0020	−0.0218	0.0021	−0.0014	0.0020	3.4769	0.0045	−0.2093	0.0059
11	865.9003	1.3704	0.0040	−0.0763	0.0015	0.0266	0.0019	−0.0203	0.0014	−0.0045	0.0018	3.4653	0.0100	−0.2123	0.0039

the standard stars. The last 4 columns supply the more conventional Johnson parameters V_J and $(B-V)_J$ which were calculated from the *VBLUW* parameters using the following conversion formulae:

$$V_J = 6^m 885 - 2.5(V + 0.033(B-V)) \quad (1)$$

$$(B-V)_J = 2.571(V-B) - 1.020(V-B)^2 + 0.500(V-B)^3 - 0^m 010 \quad (2)$$

Further conversions of *VBLUW* parameters into parameters of other photometric systems are not possible.

Figures 6 and 7 illustrate the contents of Table 2. The V magnitude and the four colours of the Walraven system are plotted against the Julian data in Fig. 6. The same is done in Fig. 7 for the Johnson magnitude V_J and colour $(B-V)_J$. In either figure, bars indicate the estimated errors; they are somewhat larger than for conventional differential photometry. But there is no indication that the scatter increases towards short wavelengths which should be the worst affected by an inaccurate compensation of atmospheric extinction, etc. The color curves – except for the single measurement on JD 2,446,841.9 (February 15) – are clearly consistent with the hypothesis of constant colors. But it may be significant that the V magnitude (a) was decreasing after the first spectroscopic burst near JD 2,446,831 (February 04–05, which was not covered by our photometry), (b) reached a maximum slightly prior to the second burst around JD 2,446,849 (February 22–23), and (c) went through another little hump 2 days before the possible very weak burst around JD 2,446,859 (March 04) was seen in the scanner data (Sect. 3.1.2, Fig. 4c).

3.2. *Synopsis with Peters' 1985 event*

The observations presented by Peters (1986) and ours described above have sufficiently much in common to make it tempting to extract a general pattern of Be star outbursts. While below we do emphasize the similarity of the events, any real generalization of course not only requires a larger number of events (especially bigger ones) but should also be based on a sample of stars which cover a representative range in $v \sin i$. With this in mind, a (modest) Hα outburst assumed to begin at a time of nearly no line

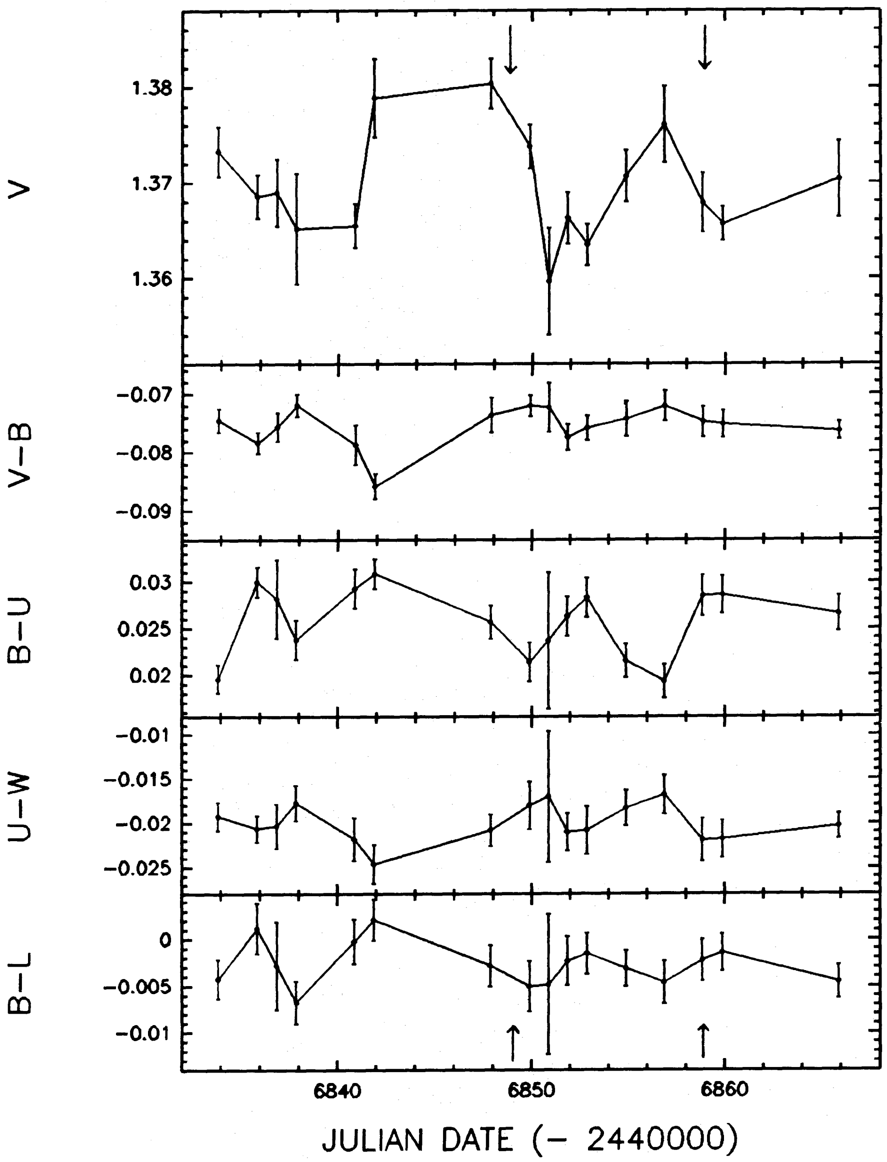

Fig. 6. The parameters of the Walraven photometric system as measured in μ Cen plotted versus Julian date. Vertical bars denote the estimated errors associated with each measurement. Note the different scales of the ordinates. Arrows in the V panel indicate the two small Hα emission maxima falling into the period of photometric observations. J. D. 2,446,832 corresponds to 1987 February 05.5

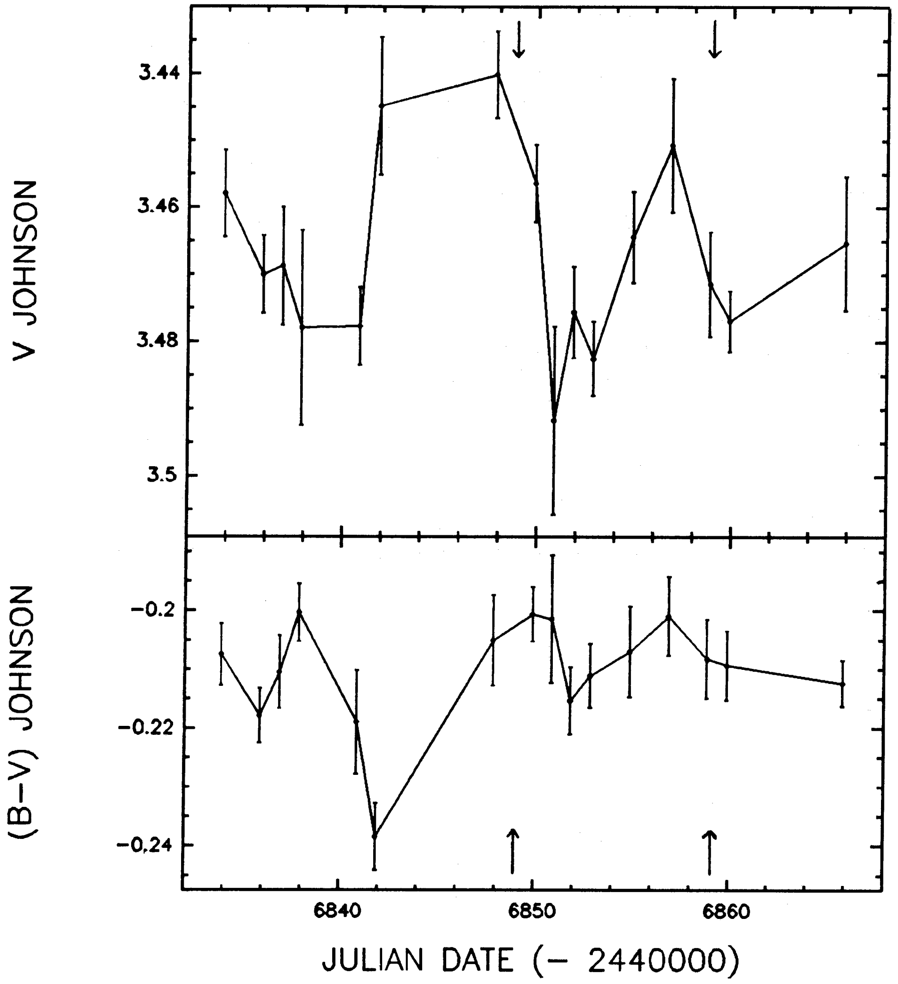

Fig. 7. Johnson V and $(B-V)$ light and colour curves of μ Cen. The data shown here have been derived from those of Fig. 6 by means of the conversion formulae (1) and (2) of the text. Arrows in the V panel indicate the two small Hα emission maxima falling into the period of the photometric observations

emission may for a star like μ Cen be synthesized from the following:

1. The first phase is one of relatively weak V/R variable emission. This type of emission may develop within two days (Peters, 1986) if not within several hours (cf. Baade, 1987a; Baade et al., in preparation). We shall call it phase 1 emission. (At the beginning of our CES observations, μ Cen was already in this phase).

2. During both the 1985 and the 1987 events, the V/R amplitude was very high. It is therefore possible that with a large V/R amplitude the chance of the subsequent occurrence of a stronger and less variable Hα emission is enhanced (compare also Sect. 3.1.2 and Fig. 4c for the possible event around March 04). On the other hand, it appears almost certain that not all phases of mere V/R variable emission are followed by a phase of more conventional doubly-peaked emission (phase 2 emission hereafter).

3. In 1985, that second phase began at most 3 days after the V/R variable phase while in 1987 the delay was at least 2 days. The build-up of the phase 2 emission took less than three days in 1985 and two in 1987. During the latter (stronger) event, a very broad emission component appeared during that transition phase. A slight enhancement of the extreme red wing of the Hα emission during a small event originally detected by simultaneous polarimetry (Hayes, 1985; private communication) has also been seen in ω Ori (Baade 1986). Therefore, if such a broad component is typical of phases of enhanced mass loss, one could even without knowing the simultaneous observations with the Bochum scanner tell from the CES Hα profiles of February 24 and 26 alone that they were taken at least 1–2 days *after* the outburst (which in fact had occurred around February 22; see Sect. 3.1.2) because there were no extended emission line wings on February 26 and only traces of them on February 24.

4. As can be seen from both the 1985 and the 1987 data, in Hα the residual V/R variability of phase 2 does not even come close to the one of phase 1 whereas in both He I λ 6678 and C II $\lambda\lambda$ 6578, 6583 the V/R amplitude was large.

5. The phase 2 Hα emission of 1985 began visibly to fade after about one week. After the same amount of time the somewhat stronger emission of 1987 was relatively much less reduced.

6. Slettebak (1982) measured the $v \sin i$ of μ Cen as $155\,\mathrm{km\,s^{-1}}$ so that under the conventional assumption that all Be stars are fast rotators, the inclination angle i probably does not exceed 30 degrees. Peters' (1984, 1986) analysis of extensive IUE and Copernicus observations detected no significant differences in UV resonance lines between periods of strong and weak Balmer emission. One is therefore led to assume that most of μ Cen's mass loss takes place at low stellar latitudes (cf. Sect. 4).

We think it likely that the same sequence of events can also take place when there already is a more or less stationary circumstellar envelope. But the spectroscopic detection of such an event, at least at Hα, may be more difficult since in the disk model of Poeckert and Marlborough (1978) changes of the density in the inner part ($r \leq 6R_*$) of the envelope have relatively minor effects on the Hα emission while, however, the ones on Hβ are remarkable. Similarly, Dachs et al. (1986b) present empirical evidence that, to first order, the equivalent width of the Hα emission depends primarily on the square of the effective disk radius which a small mass loss event would probably not alter very much.

4. Discussion

There is only one quantitative model of steady-state Be star envelopes (Poeckert and Marlborough, 1978), which furthermore is not available to us, and attempts to explain Be star outbursts have so far only been qualitative (cf. Baade, 1987a). The final understanding of our observations therefore will have to await further progress in modeling Be star envelopes. But our data clearly constrain the range of admissible models of Be systems and their variability.

4.1. *Mass loss rate and geometry*

The pronounced symmetry of the early phase 2 emission in both 1985 and 1987 implies an at least axisymmetric envelope. Although non-circular shapes, such as elliptical rings, are not excluded, they appear less probable because they are consistent with symmetric profiles of lines formed in the envelope only for particular orientations with respect to the observer. The same type of reasoning had already been used (Baade, 1985) to argue that the cyclic long-term V/R variations of some shell stars are not due to the precession of elliptical disks.

From the Hα emission line E.W. of 2 Å, Peters (1986) estimates that a total mass of 10^{-11}–10^{-12} $M_\odot$ was contained in the envelope after the 1985 event. Therefore the increase in E.W. by 1.5 Å in 1987 would correspond to a very similar amount of mass that was ejected after phase 1. Because the FWZI of the Hα emission was constant so that the growth in emission strength took place exclusively at lower velocities, this mass was probably deposited at a larger distance from the central star than was the one of phase 1.

Typical mass loss rates of Be stars as determined from UV resonance lines range between 10^{-11} and $3\,10^{-9}$ $M_\odot\,\mathrm{yr}^{-1}$ (Snow, 1981). Adoption of the upper estimate for the mass lost to the envelope during the 1987 event, 10^{-12} $M_\odot$, in combination with a maximal duration of the outburst of 2 days yields an instantaneous mass *transfer* rate to the envelope during this event of $5\,10^{-10}$ $M_\odot\,\mathrm{yr}^{-1}$. Let us for a moment ignore the potentially very substantial difference between star-to-envelope mass *transfer* rates and genuine mass *loss* rates and just compare them anyway. (Another point of concern is that comparing a mass loss event with a presumably more steady wind may not be particularly resonable.) No evidence of a wind has ever been observed in the UV spectrum of μ Cen (Snow, 1981; Peters, 1984, 1986), placing its *apparent* (cf. below) UV mass loss rate at the lower limit of the range given above. Grady et al. (1987) only list μ Cen among those Be stars that have "shown strong, undisplaced or extremely low-velocity absorption similar to the shortward-shifted discrete component". Most importantly, a wind was not even seen (Peters, 1986) during the 1985 event when the mass transfer rate was probably similar to the one in 1987 and a detection should have been possible. Accordingly, one-dimensional models that describe the extended atmospheres of Be stars basically as a radial stack of various zones (Doazan and Thomas, 1982; Doazan, 1987) may have problems ensuring mass conservation. Because of the pole-on aspect of μ Cen inferred from its low $v \sin i$, Peters (1986) had therefore concluded that the bulk of the mass transfer to the Hα emitting envelope takes place at low stellar latitudes. Analysis of the available archival IUE spectra of Be stars (Grady et al., 1987) appears to add also some statistical support for the prevalence of such a situation.

Interesting is in this regard also the development of the central reversal seen in the phase 2 Hα emission. On February 04, the day of the main outburst, the profile is nearly flat-topped, and the central reversal reached its full strength only two days later. Since it appears unavoidable to assume that the mean distance of the Hα emitting gas from the central star was at least not larger than after the outburst any effects due to obscuration by the central star should have been the strongest during the early phase. Since this was obviously not the case, again a flattened geometry is implied for the mass loss process. In order not to exclude self-absorption in the envelope, to our knowledge the only alternative discussed in the Be star literature, a geometrically very thin disk is not possible, either, because self-absorption in the envelope of course requires some minimum optical path length.

In a rotating disk model, the peak separation in units of the stellar $v \sin i$ of double-lobe emission profiles is probably (Hirata and Kogure, 1984) a measure of the radius of the disk at the outer edge. The near-identity in μ Cen of the peak separation and $2\,v \sin i$ prior to the first outburst (cf. Sects. 3.1.1 and 3.1.2) therefore implies an initially very small extent of the line-emitting region. After this as well as the second outburst the peak separation decreased, i.e., the disk radius was growing, in agreement with the expectation based on the strengthening of the line emission.

The most plausible explanation of the super-broad Hα emission component during the transition from phase 1 to phase 2 is Thomson scattering of the Hα line emission (and continuum radiation) by rapidly moving electrons (Poeckert and Marlborough, 1979); during this phase a sharp rise of the continuum polarization should have been observable (cf. Guinan and Hayes, 1984; Baade, 1986). Together with the development of the phase 2 emission this shows that there was a mass outflow component which rather suddenly set in and after two days also stopped rapidly. This behaviour is best described as an outburst. By contrast, Doazan and Thomas (1982, see also Doazan, 1987) use the analogy to a balloon that is gradually being inflated. In their model, the deceleration from super-escape velocities to below $100\,\mathrm{km\,s^{-1}}$ by previously lost material is vital. The constant symmetry and radial velocity of the phase 2 emission constrain the outflow velocity in μ Cen's 1987 Hα emitting envelope to at most $10\,\mathrm{km\,s^{-1}}$ and require that any deceleration would have been nearly instantaneous. It is not easy to imagine that interaction between a stellar wind and some circumstellar matter that is invisible both in our and in Peters' data might have accomplished such deceleration.

Under the assumption of disk-like envelopes (based on the pronounced correlation between intrinsic polarization and infrared excess), the infrared excess of Be stars measured by IRAS has been used (Waters, 1986; Waters et al., 1987; Lamers, 1987) to infer mass loss rates which exceed those quoted above for UV observations by up to two orders of magnitude. Waters et al. (1987) and Lamers (1987) therefore take up earlier suggestions (Poeckert, 1982; Baade, 1985) of a two-component mass loss from

Be stars which consists of a constant relatively weak and essentially spherical (with the possible exception of the polar regions) radiation-driven component and a usually stronger but variable component at low stellar latitudes. Lamers and Waters (1987) call the reason for the latter "the Be mechanism". Undoubtedly, the outbursts of μ Cen are episodes of enhanced efficiency of this mechanism. Lamers (1987) discusses how the relative importance of this mechanism in very luminous OB stars is diminished by the substantially increased radiation pressure. However, observations of rapid variability of Hα emission profiles and equivalent widths may reveal traces of the "Be mechanism" or a related process even in OB supergiants (Baade, 1987c).

4.2. Fingerprints of the possible mass loss mechanism(s)

After the outburst, the emission that was seen in C II $\lambda\lambda$ 6578, 6583 and He I λ 6678 already during phase 1, did not disappear; neither did the rapid V/R variability terminate. The sudden decrease in amplitude of the V/R variability in Hα after February 04 is therefore not understood, especially because rapid V/R variations are often also seen in Be stars with fully developed envelopes. A change of the line-transfer conditions in an expanding envelope is not the most likely cause since the matter from which the V/R variable emission originates is moving at the highest velocities seen in the Hα emission while the bulk of the ejecta displays smaller velocity shifts.

A more plausible explanation is a shift of the ionization balance owing to changes of the radiation field in the outer atmosphere. Variations of the stellar radiation field have for long been suspected (e.g., Peters 1984) to accompany changes of the circumstellar envelope seen in the visible; the possible small brightenings associated with the spectroscopic events covered by our photometry add to this circumstantial evidence. It has recently been strengthened by the detection (Barylak and Doazan 1986, Peters and Polidan 1987) of considerable UV flux variations in four Be stars including μ Cen. The fundamental difference in the strength of the wings of Hα between 1986 April and 1987 February (Fig. 1) may belong to the same category. But without observations of other lines, the distinction between photospheric pressure variations and scattering by circumstellar electrons is very uncertain. In any case, within a picture of global changes in the extended atmosphere also the possible increase of the emission in He I λ 6678 *after* the Hα outburst may become more plausibly explainable.

Although the true nature of the rapid V/R variability in Be stars is not finally explained (cf. Baade, 1987a) the identity of V/R and pulsation periods clearly identifies the stellar low-order nonradial pulsation as its cause (Smith and Penrod, 1984; Penrod, 1986; Baade, 1987a). The continued variability of stellar absorption lines and circumstellar V/R ratios (He I λ 6678, C II $\lambda\lambda$ 6578, 6583) after μ Cen's first 1987 outburst therefore shows that the surface pulsation amplitude was not strongly affected by whatever the causal connection between pulsation and mass loss events may be. At first sight, this seems at variance with Penrod's (1986, 1987) and Smith's (1987, private communication) observations of other stars over longer periods of time where some days to weeks after an outburst he found the low-order mode amplitude considerably reduced.

On the other hand, the second and third outburst (with a possible fourth one between these two) of μ Cen occurred within only 17 and 19 days after the respective previous one, and yet another outburst followed three weeks later at the end of March (Ghosh et al. 1987; Baade et al., in preparation). This supports the conclusion (Baade 1986) derived from polarimetric observations (Hayes, 1985, unpublished) of ω Ori that the mass loss from Be stars may at least occasionally consist of numerous small events rather than one big one or just a constant wind of unspecified nature. If mass loss events do derive (part of) their energy from the stellar pulsation, the observed (occasional) high frequency of such events lets it appear conceivable that both the amount by which the pulsation amplitude decreases after an event and the time needed by the atmosphere to return to its pre-outburst state depend on the preceding history in general and the size of the outburst in particular. A search for a correlation between the amplitude of an event and the time elapsed since the previous event would therefore be an observational test of the hypothesis that the conditions for an outburst are slowly built up by the pulsation.

There has been some discussion (Henrichs, 1987; Snow, 1987; Grady et al., 1987) whether the narrow components of UV resonance lines of so-called superions are superimposed to a broad component or whether the entire feature is just a quasi-continuum of many narrow components. Certainly the observed variability is predominantly due to the narrow components. Yet, the origin and nature of these narrow components is far from being understood (cf. Henrichs, 1987 and references therein). Assuming that below the detection threshold of our ground-based observations the frequency of mass loss events still keeps rising towards lower amplitudes and that (at suitable inclination angles) UV resonance lines are better tracers of variations in the mass flux, it appears not inconceivable to identify the two phenomena with one another. But one would not necessarily expect to detect an *eventwise* correlation because, even if it existed, several circumstances could easily obliterate it: (i) different sensitivities of Hα (and continuum polarization) on the one hand and UV resonance lies on the other to mass flows at different stellar latitudes, (ii) intrinsic instabilities of the mass flow (wind). (iii) If radiation pressure somewhere plays a role in accelerating the outflow, an obviously non-radiatively driven mass ejection could actually lead to a temporary breakdown of the wind because the radiation pressure of relatively low luminosity objects such as Be stars is too weak to sustain a high-density wind.

If the Hα envelopes of Be stars are a very special case of cool, very dense winds (Baade, 1987a) a deficiency in effective radiation pressure could also induce a (partial) collapse of the Hα envelope. This would reveal itself by V/R ratios greater than unity which in fact are observed but have not so far found a convincing explanation (Baade, 1985). Doazan et al. (1985, 1987; see also Doazan, 1987) recently made the important discovery that in γ Cas and θ CrB $V/R<1$ when the E.W. of the C IV $\lambda\lambda$ 1548, 1550 doublet is large and vice versa. Assuming that the strength of the C IV lines is a reliable measure of the mass loss rate, one may try to combine this correlation with point (iii) above: When the wind has become very dense (strong C IV) part of the matter in the Hα envelope falls back to the star ($V/R>1$). Motions in the Hα envelope are again mainly outward directed ($V/R<1$) when the wind density has decreased (weaker C IV). Because of the assumed blocking of the radiation pressure, a correlation with the E.W. of the Hα emission is not expected (as is the case with θ CrB, Doazan 1987). Since most of the variability in the E.W. of the C IV lines is due to discrete components (cf. Doazan et al., 1987), discrete components would in the above picture occur at times when the envelope is unstable. The discrete components could therefore be due to instabilities of the wind, e.g. induced by the interaction with inward moving blobs of gas.

Peters (1984) was the first to ask whether, specifically in the case of μ Cen, Be phases last the longer the stronger the Hα emission is. Since then, three more Be phases, namely the 1984–1985 period and the 1985 and 1987 events, have obeyed that rule. Assuming that the mass transfer generally terminates after a short while as it was the case for the 1987 event, this may mean that the *absolute* rate at which the envelope is dispersed varies by a noticeably smaller factor than does the amount of matter contained in envelopes of different epochs. If, as discussed above, radiation pressure plays a role in the dissolution of Be star envelopes, one might expect just this.

As has been briefly discussed in the Introduction, a large pulsation amplitude may at times have no effect at all on the instantaneous mass loss rate, and one therefore needs to search for a correlation between the occurrence of mass loss events and other atmospheric parameters. The very strong V/R variations in Hα shortly prior to the 1985 and possibly at least two of the 1987 events might lead to the suspicion that an outburst will happen each time when the V/R amplitude exceeds a certain threshold. Since the V/R-to-pulsation amplitude ratio is variable, the V/R amplitude could, in fact, be a useful indicator if an increased V/R amplitude means that because of long-term variations of the atmosphere the short-term effects of the pulsation have increased. Comparison with 1986 April observations of μ Cen (Baade et al., in preparation) when the V/R variability of the very weak Hα emission was extreme but no stationary emission developed for at least 10 days, suggests once more that most probably there are additional factors to be considered. The far-UV flux distributed (cf. Peters and Polidan, 1987) or the relative strength of the core and the wings of the Hα absorption currently appear the most promising symptoms but others also need to be tested.

4.3. Expectations from and strategies for future observations

We have emphasized above that a reliable interpretation can only come from observations of more events by means of a larger variety of observing techniques at different wavelengths (and from improved theoretical analyses). In view of the many decades that have passed since the discovery of the variability of the line emission in Be stars until the first detailed mapping of only one outburst in just one line, this may appear utopic. However, utilizing the most sensitive observing techniques, whenever possible including polarimetry, and not settling for a S/N of 200 where 800 can be reached, one can improve the odds by orders of magnitude by exclusive concentration on stars that (like ω Ori or λ Eri) are known to be active and/or (like μ Cen) have temporarily lost or almost lost a formerly strong emission. We speculate that the detection of at least one small event per fortnight will be possible if about a half dozen such stars can be monitored simultaneously.

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