DETECTION OF ADDITIONAL ABSORPTION IN THE POST-OUTBURST SPECTRA OF μ CENTAURI

K. K. GHOSH, K. KUPPUSWAMY, S. PUKALENTHI, AND G. SELVAKUMAR
Indian Institute of Astrophysics, Vainu Bappu Observatory, Kavalur, Alangayam NA, TN 635701, India
Received 16 October 1990; revised 9 April 1991

ABSTRACT

A large number of photographic (92) and CCD (27) spectra of the pole-on Be star, μ Cen, were obtained between February 1987 and May 1990. From the results of the above-mentioned spectra we detected a weak outburst in March 1987 which was probably the fourth after the major outburst of this star in early February 1987. Recently we have detected two major outbursts of this star between June 1989 and May 1990. From the comparison of the active (outburst and post-outburst period) and quiescent phase spectra, it has been found that the absorption depths and the equivalent widths of the ionized lines (Si II, S II, N II, Fe II, and Fe III) were stronger during the active phase than the quiescent phase. Possibility for the existence of matter at polar latitudes or the increase of the photospheric temperature due to the nonradial pulsations have been suggested to explain the observed results. Also the decrease in equivalent widths of Hα absorption line was detected, on the timescales of months, before the major outburst of April 1990. This may be used as an indicator for the development of an outburst and it has been suggested that the conditions for an outburst are slowly built up and probably the nonradial pulsation plays the role for the development of the outburst condition.

1. INTRODUCTION

μ Centauri (HR 5193, HD 120324, MWC 229; B2 *IV-Ve*, $V \sin i = 155$ km s^{-1}), a nonradial pulsator, is currently one of the active Be stars which has undergone, several times, complete loss of its emission line spectrum. This star has displayed quite frequent outbursts in its spectra (Peters 1984, 1986; see also Dachs *et al.* 1986). Detail accounts of the occurrence of outburst until 1987 has been given by Baade *et al.* (1988). Also, the possible role of nonradial pulsations on the episodic mass loss of Be stars (instabilities of the lower-order nonradial pulsation pattern drive the mass loss events), especially for μ Cen, were discussed by them. However, most of the outburst observations were concentrated on few optical emission lines, Hα, C II (6578 and 6583 Å) and He I (6678 Å). Apart from these lines, there may be many other optical lines in absorption which may provide important information about the star. Peters (1984) suggested for the pole-on Be star, μ Cen, that the detection of any additional absorption in the outburst or post-outburst spectra of this star may indicate the presence of matter at polar latitudes. Therefore, spectroscopic studies of both photospheric and envelope lines of μ Cen during the outburst phase may provide important results. In this paper we present the results of spectroscopic observations of this star during quiescent and active phases which were obtained between February 1987 and May 1990.

2. OBSERVATIONS

Spectra of μ Cen were regularly obtained between February 1987 and May 1990. The Bhavanagar spectrograph, a 125 mm camera and 1800 grooves mm^{-1} grating was used at the cassegrain focus of 77 cm reflector of Vainu Bappu Observatory, India. All the spectrograms were obtained on Kodak 09802 emulsion with a reciprocal dispersion of 18 Å mm^{-1} and they were digitized using PDS-1010 M microdensitometer. Reductions of all the spectrograms were done using RESPECT software package (Prabhu *et al.* 1987) following the same procedure which has been described in detail in a previous paper (Ghosh *et al.* 1989)

CCD observations of Balmer (Hβ and Hα), Si II (6347 and 6371 Å) and He I (5876 Å) profiles were carried out on several nights between February 1989 and May 1990, with the Echelle and UAG (Universal Astronomical Grating) spectrographs at the coude and cassegrain focii of 102 cm reflector of VBO, India. A Photometrics CCD (Ram Sagar & Pati 1989) with a 254 mm camera (reciprocal dispersion $\sim$7.4 Å mm^{-1}) and an Astromed CCD (Ananth *et al.* 1989) with a 508 mm camera (reciprocal dispersion $\sim$3.8 Å mm^{-1}) were used as detectors at the focal planes. The typical S/N around continuum level at Hα attained in the 30 min exposures made was in the range 100–150 except the spectra of June 1989 (S/N$\sim$60). The data reductions were carried out using the revised version of the RESPECT software package. The steps followed for the reduction scheme were: Correction of the raw data for readout and dark noise; flat-field correction; wavelength calibration (error was around $\pm$0.05 Å for coude spectra and $\pm$0.10 Å for cassegrain spectra), normalize to continuum intensity; conversion of geocentric velocity scale. Reduction details of CCD spectra have been described in a previous paper (Ghosh 1990).

3. RESULTS AND DISCUSSION

In total 92 photographic spectra of μ Cen were obtained in the blue and Hα regions on several nights between February 1987 and August 1989. Also 18 coude echelle and nine cassegrain CCD spectra were obtained on 12 nights between February 1989 and May 1990. From the analysis of 1987 spectra, we detected a weak outburst of μ Cen (Ghosh *et al.* 1987) at the end of March 1987 which was probably the fourth outburst after the major outburst of early February 1987 (Baade *et al.* 1988). In this paper we will mainly concentrate on the recent changes in the spectra of this star between January 1989 and May 1990. During this period we have detected two major outbursts of this star. Results of those outbursts are given below.

 0004-6256/91/031191-06$00.90

3.1 First Outburst (June 1989)

Four CCD spectra in the Hα region of μ Cen obtained between February and June 1989 are shown in Fig. 1 and four photographic spectra obtained between 29 June and 9 July 1989 are shown in Fig. 2. In order to compare the spectral variability in other lines, apart from Hα, of this star during quiescient and active phases three spectra in the wavelength region 6425–6600 Å are plotted in Fig. 3. Apparently all the spectra of Fig. 3 may look noisy but they are well-exposed spectra which were smoothed (same cutoff frequency were applied to all the spectra) to remove the noise. Also, vertical lines of Fig. 3 show that different spectral lines of the three spectra correspond one to one.

3.2 Second Outburst (April 1990)

After the major outburst of June 1989, μ Cen displayed Hα emission, at least, until the end of August 1989. Due to its location relative to the Sun we could not observe the star until January 1990. However, probably, very weak Hα emission was present in the spectra of February 1990, but it was surely absent in the spectra of March 1990 (Fig. 4). The spetra of this star obtained by Peters (1990) on 2 April 1990 and our spectra obtained on 9 and 10 April 1990 display strong emissions in Hα, and He I lines which suggest that recent mass loss episode of this star has taken place between 17 March and 2 April 1990. Coude CCD spectra of μ Cen obtained between 9 and 10 April 1990 are shown in Figs. 5–7. Figure 5 displays the Hα profiles which clearly show two emission components on a broad photospheric absorption with $V \simeq R = 1.24\, I/I_c$. However, the H$\beta$ profiles (Fig. 6) of 9 April also display two emission components embedded on a very broad photospheric absorption with $V/R \simeq 1$ and that of 10 April shows $V > R$. From Fig. 7 it can be clearly seen that He I (5876 Å) profile shows two weak emission components with a central broad absorption. No V/R variations ($V/R \simeq 1$) of this profile were found between 9 and 10 April 1990.

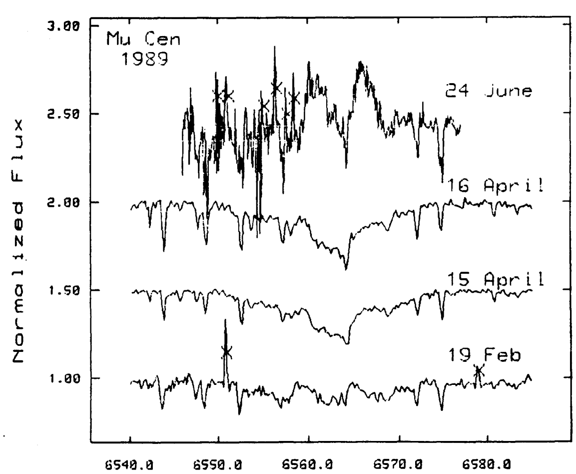

FIG. 1. CCD spectra of μ Cen in the Hα region. Date of observations are shown in the right. × marks indicate the cosmic ray hits.

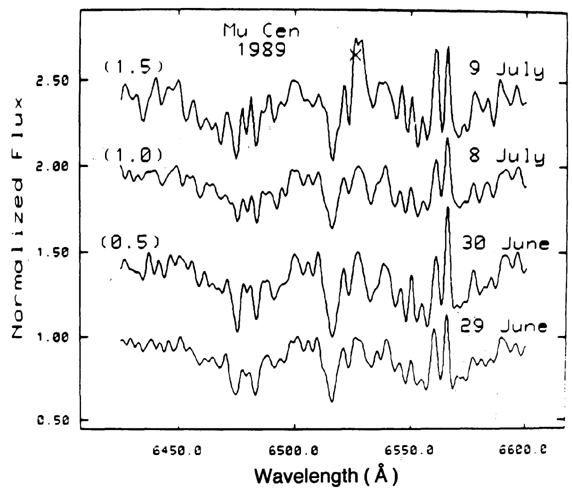

FIG. 2. Photographic plate spectra of μ Cen in the 6425–6600 Å wavelength region. Dramatic changes of the emission components of Hα between 29 and 30 June and 8 and 9 July 1989 may be noted. × mark indicates the plate defect.

CCD spectra of μ Cen were also obtained in the Si II region (6347 and 6371 Å) during the quiescent (15 April 1989) and active (19 February 1989 and 9–10 April 1990) phases. Those spectra are shown in Fig. 8. From this figure it is clearly evident that the absorption depths and the equivalent widths of Si II and S II/Fe II lines were much stronger during the active phases than the quiescent phases of the star.

A few CCD cassegrain spectra of this star have been displayed in Fig. 4. This figure shows that V/R variations of Hα have taken place between 18 April and 18 May 1990. From

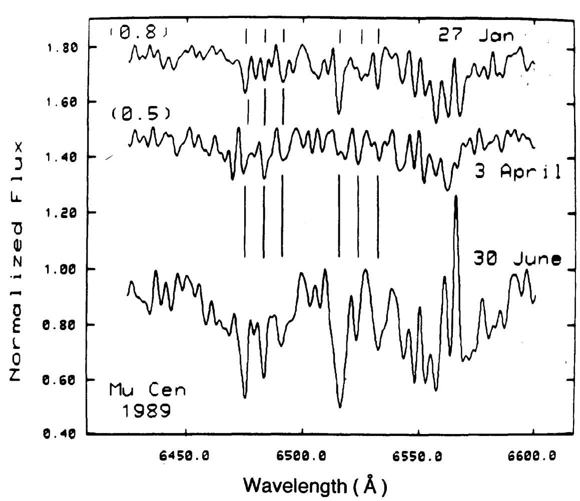

FIG. 3. Same as Fig. 2, but for different dates. Three spectra of this figure represent different phases of μ Cen. Top: shows the spectrum of μ Cen just a few days before the outburst (4 February 1989), when weak emissions were present in Hα. Middle: displays quiescent phase spectrum (when Hα was in pure absorption). Bottom: shows the spectrum of this star after the major outburst. Vertical lines show that there are one-to-one correspondences among the different lines of the three spectra.

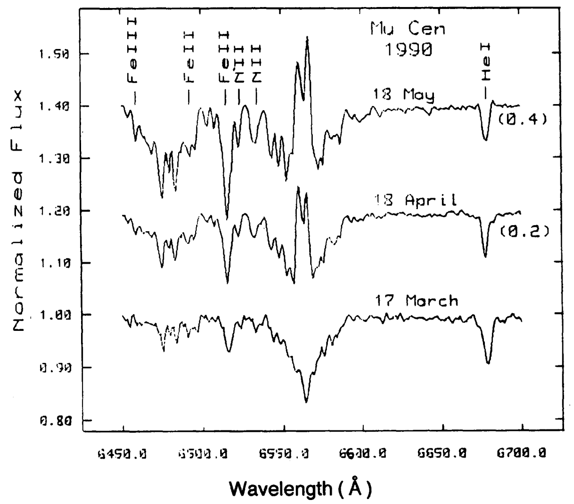

FIG. 4. CCD spectra of μ Cen in the Hα region before the outburst and after the outburst. Note the dramatic changes, not only the Hα but also the absorption lines of Fe II, Fe III, and N II. Also note that the He I (6678 Å) line was almost unchanged during different phases (see text). Probably, very weak emissions were present at the wings of the He I line of 18 May 1990.

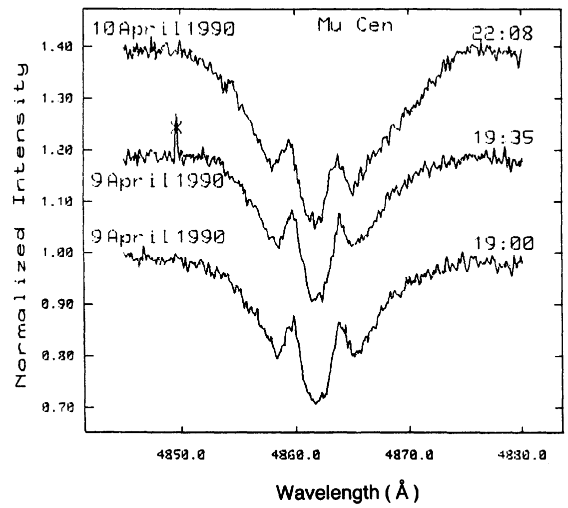

FIG. 6. Same as Fig. 5, but for Hβ profiles.

previous observations of this star which were taken by Baade *et al.* (1988), it was found that this star displayed short-term V/R oscillations during the 2–3 months activity. However on the basis of our limited and scattered observations it is not possible to draw any conclusions about the V/R variability. Most striking and important changes of the absorption depths and equivalent widths of N II, Fe II, and Fe III lines can be clearly seen in Fig. 4. This confirms our previous observations obtained from photographic spectra during the first outburst of this star (January–June 1989; Fig. 3). Another important feature to notice from this figure (Fig. 4) is that the absorption depths and equivalent widths of the He I (6678 Å) line were almost unchanged during the quiescent and active phases of μ Cen or may be, they were slightly weaker during the active phase than the quiescent phase. Probably, very weak emissions were present at the wings of this He I (6678 Å) line which can be seen from the spectrum of 18 May 1990 (Fig. 4). These independent observations again support the previous observations obtained from the spectra of this star in the wavelength region 6340–6380 Å which suggested that the absorption depths and equivalent widths of the ionized lines were stronger during the active phase than the quiescent phase.

Results of the above observations are summarized as follows: From the comparison of the Hα profiles which were in pure absorption, of μ Cen obtained between February and March 1990, it can be clearly seen that the equivalent width of Hα was weaker in March (3.53 $\pm$ 0.09 Å) than in Febru-

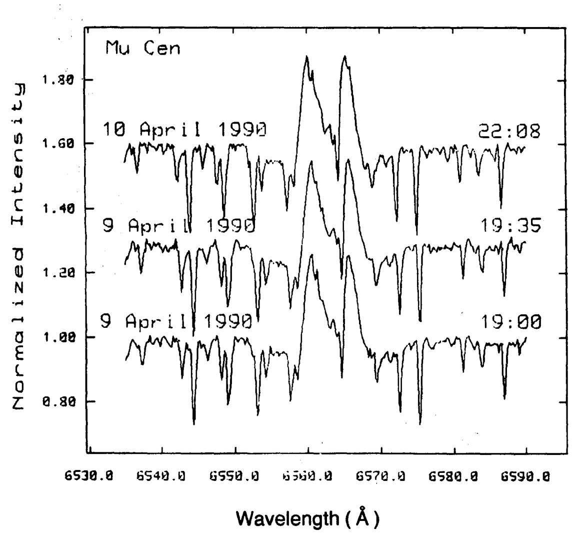

FIG. 5. Hα profiles of μ Cen after the second major outburst of April 1990.

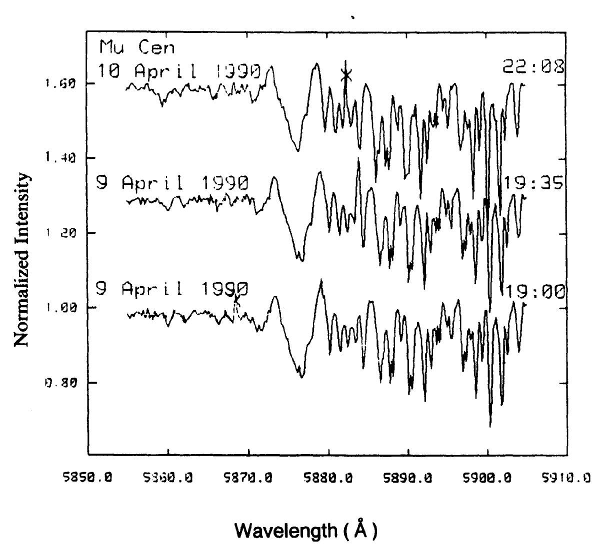

FIG. 7. Same as Fig. 5, but for He I profiles.

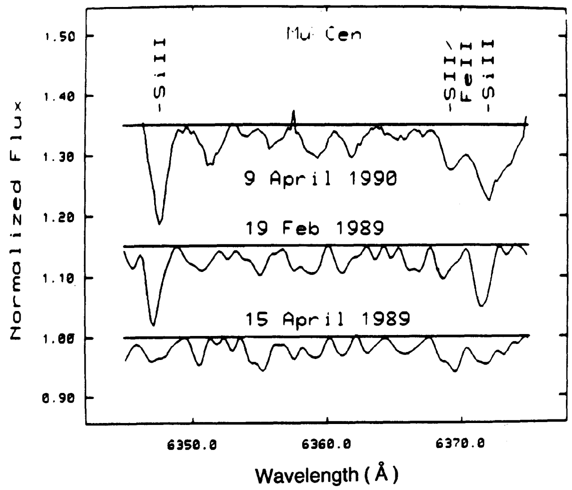

FIG. 8. CCD spectra of μ Cen in the Si II (6347 and 6371 Å) region during different phases. Spectrum of 15 April 1989 represent the quiescent phase spectrum of the star and that of 19 February 1989 and 9 April 1990 represent the spectra of the same star after weak and major outbursts respectively. Dramatic changes of the ionized lines after the outburst may be noted.

ary (3.98 $\pm$ 0.09 Å). Baade *et al.* (1988) also found that the equivalent width of Hα of μ Cen dropped from 2.9 to 1.4 Å within two days, just before the outburst of 1987. We have also observed almost the same phenomena on a longer timescale before the second outburst of this star which took place between the middle of March and the first week of April 1990. Therefore it may be suggested that the decrease in equivalent width of Hα may be used as an indicator of outburst.

From Figs. 1 and 3 it can be clearly seen that weak emission with $V<R$ was present at the end of January 1989 which was still present until February 03 with $V>R$ (Peters 1989a). But the Hα profile of 4 February displayed relatively stronger emission with $R>V$ (Peters 1989a) and our observed Hα profiles of February 19 show double emission with $V \simeq R \simeq I_c$ (Fig. 1). Close inspections of Hα profiles [ours and Peters (1989b)] of April 1989 show that the absorption core was deeper compared with February and probably very weak emission components were present on the wings. The deeper absorption core of the Hα suggests that the emission had weakened. However, the Hα profile of 13 June displayed strong emission with $V/R = 1.2I_c$ (Peters 1989c) and that obtained between 22 and 24 June have shown still stronger emission with $V \simeq R \simeq 1.3I_c$ (Bhattacharyya *et al.* 1989). According to Peters (1989c), this was the strongest emission event of this star since 1980. Spectra of μ Cen obtained between 25 June and 8 August have displayed two large amplitude V/R variations (29–30 June and 8–9 July) which can be clearly seen from Fig. 2. Same type of V/R variations were also observed in this star between 9 April and 18 May 1990, after the second major outburst. From the comparison of the spectra shown in Figs. 3 and 4, it is clearly evident that the depths of the absorption lines, in the spectral region 6450–6540 Å, varied with the emission strengths of Hα of μ Cen.

Equivalent widths of absorption and emission lines of μ Cen observed between January 1989 and May 1990 are presented in Table 1. Errors in measuring the equivalent widths of different absorption and emission lines of μ Cen are not shown along with the measured values. They are presented as a footnote to the table and calculations of error estimations were done following the same procedure described in Ghosh (1990a). In Fig. 9 we have plotted the equivalent

TABLE 1. Measured equivalent widths of absorption and emission lines of μ Cen.

Wavelength (Å)	Identification (Multiplet)	27 Jan 1989	Equivalent Width* (Å) 19Feb 1989	April 1989	June 1990	17Mar 1990	April 1990	May 1990
6347.09	SiII (2)		0.16	0.12			0.35	
6369.40	SII(19)/FeII(40)		0.09	0.05			0.13	
6371.40	SiII(2)		0.18	0.08			0.33	
6458.68 6491.28	FeIII P(3)– $ FeII _!	1.22	1.24	0.87	3.34	1.12	2.81	3.04
6516.05 6522.30	FeII(40)– NII(45) _!	0.65	0.77	0.55	1.51	0.50	0.95	1.07
6533.00	NII(45)	0.26	0.31	0.17	0.52	0.20	0.37	0.49
6562.82	H (1)	-0.74	-0.46	3.64	-1.81	3.53	-1.38	-1.63
6678.15	HeI(46)	0.91	0.89	0.97	0.83	0.94	0.69	0.71

$ Equivalent width of the whole absorption complex around these lines is listed.

* Error in equivalent width [W(λ)] measurements are as follows:

0.01 Å for 0.1 > W(λ) < 0.3 Å; 0.02 Å for 0.4 > W(λ) < 0.5 Å; 0.04 Å for 0.5 > W(λ) < 1.0 Å; 0.05 Å for 1.0 > W(λ) < 1.5 Å; 0.09 Å for 1.5 > W(λ) < 3.5 Å.

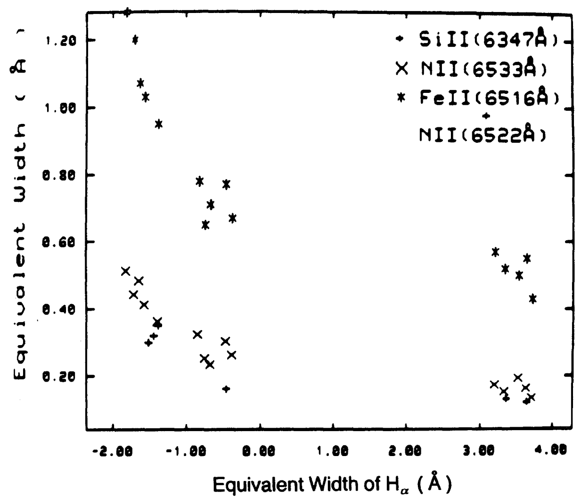

FIG. 9. Plot of the equivalent widths of the ionized lines (Fe II, N II, and Si II) vs the equivalent widths of Hα of μ Cen. Negative equivalent widths of Hα indicate the equivalent widths of the emission components of the Hα line.

widths of the ionized lines (Fe II, Si II, and N II) versus the equivalent widths of Hα line. From this figure and Table 1 and also from Figs. 3, 4, and 8, it can be clearly seen that when Hα was in absorption (quiescent phase), the equivalent widths of the ionized absorption lines were minimum and during the active phase (presence of Hα emission) they were relatively stronger. This in fact was observed earlier by Peters (1984) from more limited observations containing lines from the more highly ionized species. From the comparison of the UV spectra observed during active and quiescent phases of μ Cen, Peters (1984) found that Si III, Si IV, and Al III lines were slightly stronger and broader during the active phase than the quiescent phase. On the basis of her results, Peters (1984) suggested that the photospheric temperature of the star increases during such active periods.

Be stars have displayed radical changes in He I (6678 Å) line (apart from Balmer and C II lines) (Peters 1984, 1986, 1987, 1988; Baade *et al.* 1988; Smith, Peters & Grady 1991) during the active phase. Spectra of μ Cen obtained by Peters (1990) between 2 and 16 April 1990, have shown two emission components ($1.04I_c$) with a central absorption of He I (6678 Å) which revealed no change during a 2 week period. He I (5876 Å) profiles obtained by us on 9 and 10 April 1990 also show two emission components with a broad central absorption ($V \simeq R \simeq 1.04I_c$). We also could not detect any changes in this line between 9 and 10 April 1990 (Fig. 7). But the cassegrain spectra of this star obtained on 18 April 1990 do not show any emission (probably very weak emission was present at the red wing) and that obtained on 18 May 1990 shows a weak P Cygni profile (Fig. 4). These results suggest that weak activities were present in the circumstellar envelope (the medium from where the emission lines originate) of the star even after 2 months of the outburst.

In this paper we shall not discuss the cause(s) of the outburst of μ Cen, because several authors have already discussed the possible outburst mechanism(s) of this star (Baade *et al.* 1988, and references therein). Here our main interest is to discuss the dramatic changes in the spectra of μ Cen during quiescent and active phases. Large amplitude V/R variations of this star during 29–30 June and 8–9 July 1989 (Fig. 2) and between 9 April and 18 May 1990 were observed and those variations were well above the 3-σ limit [for detail error analysis of V/R see Ghosh (1989)]. These rapid large amplitude V/R variations suggest that most probably we have observed weak outbursts of this star after the major outbursts. These results support the previous observations of this star obtained by Baade *et al.* (1988) and Ghosh *et al.* (1987). Also it supports the previous conclusions made by different authors (Baade *et al.* 1988, and references therein) that the mass loss from Be stars may occasionally consist of many events rather than one big one or a just steady wind of unspecified nature. In this connection it is important to mention one of our interesting results. Baade *et al.* (1988) suggested that a search to find out the correlation between the amplitude of an event and the time elapsed since the previous event may provide an observational test for the hypothesis that the conditions for an outburst are slowly built up by the pulsation. We found that the equivalent width of the absorption line of Hα [$W(\alpha)$] of μ Cen has slowly decreased between February and March 1990 and this was the period just before the outburst. This slow decrease of $W(\alpha)$ may be due to the changes of global atmospheric parameters such as density and temperature profile of the star which in turn may be long-term effects of the pulsation. Therefore, our results support the hypothesis of Baade *et al.* (1988) that the conditions of an outburst are slowly built up for which pulsation may play an important role.

From the above results it can be summarized that during the active phases (outburst and post-outburst period) of the star, the absorption depths and the equivalent widths of the ionized lines increased with respect to the quiescent phase. At present it is very difficult to make any positive comment about the cause(s) of the above-mentioned observed changes in the post-outburst spectra of μ Cen. Only the following few suggestions can be mentioned.

(i) Peters (1984) suggested that any additional absorption seen in a number of photospheric lines from abundant ions during an active phase of μ Cen will indicate the presence of matter at polar latitudes since this star appears to be a pole-on Be star with an inferred inclination angle of 25° to our line of sight. Therefore, on the basis of this suggestion and from our observed results it may be suggested that matter was present at polar latitudes only during the active phase of this star.

(ii) Another interpretation for the observed increase in the absorption depths and equivalent widths of the ionized lines of μ Cen during its active phase may be the effects of the changes in the photosphere. From the published results it can be clearly seen that the star's visual brightness correlates well with its Balmer emission-line strength (Dachs 1982, and references therein). From our results we have also found the beautiful correlation between the absorption depths and the equivalent widths of the ionized lines and the Hα equivalent widths (Fig. 9). Therefore, combining these two results we find that the absorption depths and the equivalent widths of the ionized lines are correlated with the visual brightness of the star, i.e., the absorption depths and the equivalent widths of the ionized lines increase with the increase of the visual brightness of the star and vice versa.

A spectrum is composed of continuum (free-free and bound-free transitions) and line (bound-bound transitions) fluxes. Therefore, the depths of the absorption lines can increase under two conditions. (i) If there is no change in the continuum flux but line flux increases and (ii) if both the fluxes increase but the increase in the line flux is much more than the continuum flux. Observational results discard the first possibility because the visual brightness increases during the active phase at least by 10% compared to quiescence. Also, Ghosh *et al.* (1990) have found in η Cen that during its active phase both continuum and line fluxes increased which supports the second possibility.

During the active phase period, continuum flux may arise partly from the newly formed envelope and partly from the photosphere but it can be shown from energetics point of view that it is not possible by the envelope to produce the line fluxes of ionized elements like S II, Fe III, and N II. The increase in the photospheric temperature (during the active phase of the star) can produce the additional absorptions as well as the increase in the equivalent widths of the ionized lines. Now the question is how the photospheric temperature can increase? Probably, long-term effects of the nonradial pulsations may change the global atmospheric properties such as temperature or density of the star. However, unless one does the detail theoretical spectral analysis (NLTE) of μ Cen, the above-suggested physical process remains a pure assumption and one should not take it literally.

Our sincere thanks to the referee for comments and suggestions that helped to improve the paper.

REFERENCES

Ananth, A. V., Srinivasan, R., Srinivasulu, G., Chandramouli, S. S., and Chinnapan, V. 1989, VBT Newslett., No. 1, 7
Baade, D., Dachs, J., Van de Weygaert, R., and Steeman, F. 1988, A&A, 198, 211
Bhattacharyya, J. C., and Ghosh, K. K. 1989, IAU Circ. No. 4806
Dachs, J., 1982, in Be Stars, IAU Symposium No. 98, edited by M. Jaschek and H. G. Groth (Reidel, Dordrecht), p. 19
Dachs, J., *et al.* 1986, A&AJ, 63, 87
Ghosh, K. K., Velu, C., Kuppuswamy, K., Jayakumar, K., and Rosario, M. J. 1987, IAU Infor. Bull. Var. Stars., No. 3056
Ghosh, K. K. 1989, MNRAS, 240, 637
Ghosh, K. K. Apparao, K. M. V., and Tarafdar, S. P. 1989, ApJ, 344, 437
Ghosh, K. K. 1990, ApJ, 360, 239
Ghosh, K. K. 1990a, ApJS, 72, 103
Ghosh, K. K., Pukalenthi, S., Jayakumar, K., Kuppuswamy, K., Sanjeevkumar, T., and Muniandi, A. 1990, A&AS, 82, 557
Peters, G. J. 1984, PASP, 96, 960
Peters, G. J. 1986, ApJL, 301, L61
Peters, G. J. 1987, Be Star Newslett., ESO, No. 16, 15
Peters, G. J. 1988, ApJL, 331, L33
Peters, G. J. 1989a, Be Star Newslett., ESO, No. 20, 11
Peters, G. J. 1989b, Be Star Newslett., ESO, No. 21, 10
Peters, G. J. 1989c, IAU Circ. No. 4816
Peters, G. J. 1990, Be Star Newslett., ESO, No. 22, 19
Prabhu, T. P., Anupama, G. C., and Giridhar, S. 1987, BASIn, 15, 98
Ram, Sagare, and Pati, A. K. 1989, BASIn, 17, 6
Smith, M. A., Peters, G. J., and Grady, C. A. 1991, ApJ, 367, 302