SPECTROPHOTOMETRIC STUDY OF X PERSEI

B. B. SANWAL, B. S. RAUTELA, and S. C. JOSHI
Uttar Pradesh State Observatory, Naini Tal, India

(Received 2 October, 1984)

Abstract. The continuum energy distribution of the emission line star X Per (O9.5III–V) has been obtained in the wavelength range 340–710 nm and has been compared with the energy distribution of α Cam in the same wavelength range. The continuum of the star is found to be modified by the circumstellar envelope. A number density of the order of 10^{11} in the envelope has been obtained from the observations of Hα in emission.

1. Introduction

The bright emission line star X Persei (HD 24534; O9.5III–V) has been observed for last many years, both as an emission line object and as a peculiar variable star. This star is situated very close to a weak X-ray source 4U 0352 + 30 and shows emission line variations, variable X-ray emission and strongly variable infrared excess (Viotti *et al.*, 1982). Hutchings *et al.* (1974) found a period of about 581 days for the star from an investigation of spectroscopic data. White *et al.* (1976) have found 22.4 hr and 13.9 min periodicities in the X-ray flux from the star.

During 1972–1973, 1978, and 1980, X Per went through active phases of increased visual brightness, stronger X-ray emission and excesses in both the Balmer continuum and in the infrared (Ferrari-Toniolo *et al.*, 1978; or Viotti *et al.*, 1980). We put this star in our observing programme to investigate its behaviour in the continuum energy distribution, in the wavelength region 340–710 nm.

2. Observations

The photoelectric spectrophotometric observations of X Per covering the wavelength interval 340–710 nm were secured through the 104 cm reflector of the Uttar Pradesh State Observatory, Naini Tal on several nights during 1980–1983. The spectrum scanner consists of a Hilger and Watts monochromator with a Bausch and Lomb 600 lines mm^{-1} grating used in the first order. The system gives a dispersion of 7 nm mm^{-1} at the exit slit. The bandwidth used for these measurements, was kept at 5 nm and a cooled (-20 °C) EMI 9658B photomultiplier and standard d.c. techniques were employed. α Cam was observed as a comparison star with X Per, α Lyr, γ Gem, and ξ^2 Cet have been observed as standard stars.

The calibration of α Lyr by Tug *et al.* (1977) has been used for standardisation purposes. The standard deviations of the individual measurements of comparison star do not exceed $\pm 0^m.03$ in the entire observed wavelength range. The monochromatic magnitudes of X Per and α Cam have been corrected for interstellar reddening. We have

Astrophysics and Space Science **110** (1985) 301–309. 0004–640X/85.15

adopted a value of $E(B - V)$ equal to $0\overset{m}{.}40$ based on Viotti *et al.* (1982) for X Per and $0\overset{m}{.}30$ for α Cam based on Underhill (1982). These values give A_v equal to $1\overset{m}{.}3$ and $0\overset{m}{.}98$ for X Per and α Cam, respectively.

With the above values of A_v and the reddening curve given by Schild (1977) the monochromatic magnitudes of the stars have been corrected for interstellar reddening. The reddening corrected magnitudes of both the stars normalised to 550 nm along with the reddening corrections are given in Table I.

3. Discussion

3.1. Comparison star α Cam

For a comparison of the energy distribution curves of X Per we have observed the star α Cam. On the basis of the spectral classification, the temperatures of both the stars are nearly the same. The star α Cam was observed on several nights, in order to see whether the energy distribution curves show any variations. We found that the energy distribution curves on various nights do not show any prreciable change which is evident from Figure 1. All observed points lie well within the range of observational error. Model atmosphere (Kurucz, 1979) fitting gives an effective temperature around 30 000 K. Viotti *et al.* (1982) have found the effective temperature for X Per around 30 000 K and log g equal to 4. On the basis of these facts we decided that α Cam can be used as a comparison star.

Excess emission from X Per: in order to assess the difference in the energy distribution curves of the two stars, we have plotted the monochromatic magnitude differences

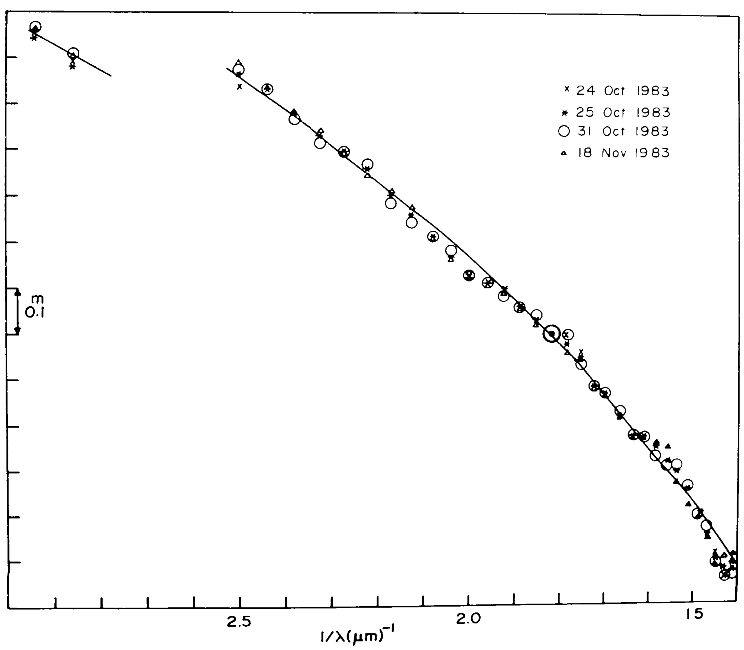

Fig. 1. Energy distribution curve of α Cam. The solid line represents Kurucz (1979) model atmosphere for T_e = 30 000 K and log g = 4.

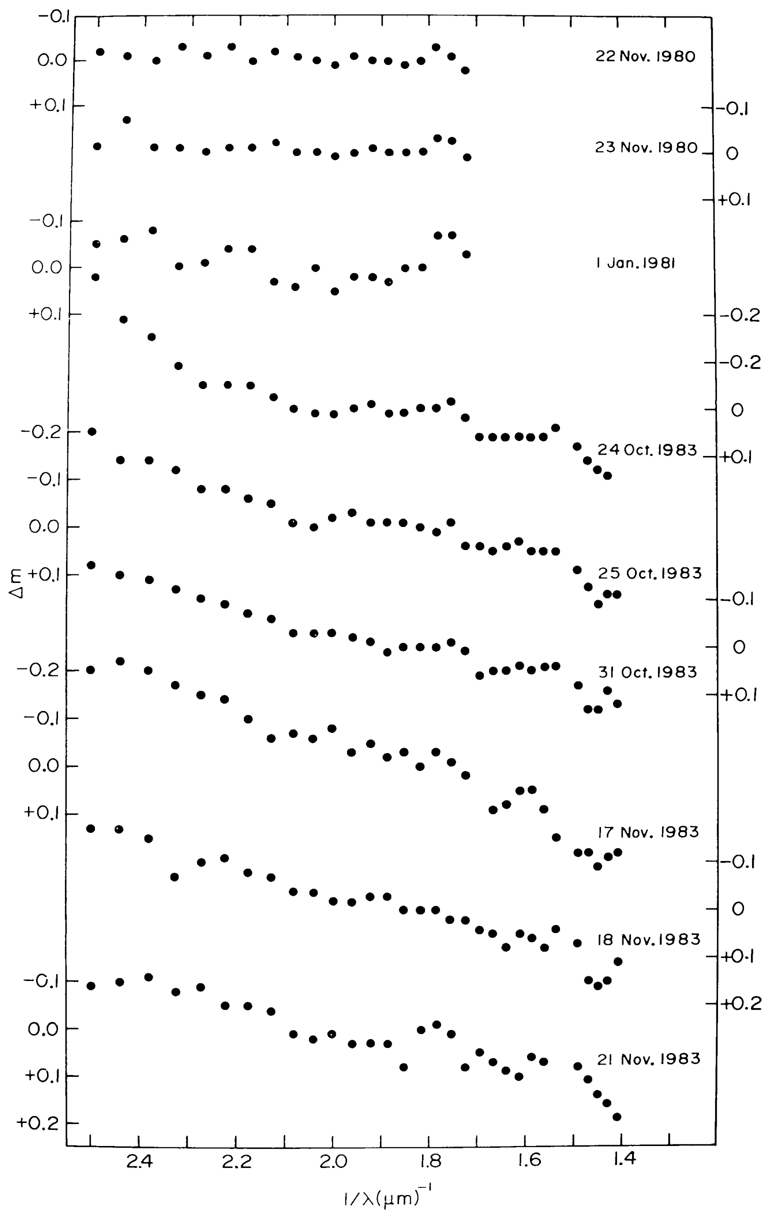

Fig. 2. Monochromatic magnitude differences α Cam − X Per.

between α Cam and X Per against inverse wavelength in Figure 2. It is apparent from this figure that X Per shows variable excess in the Paschen continuum. On three nights, viz., 22 and 23 November, 1980 and 1 January, 1981, the difference of magnitudes is very small. On these nights the Paschen slope of the observed energy distribution curves matches satisfactorily with the Kurucz (1979) model for 30000 K and $\log g$ to 4. A comparison of the observed fluxes for six nights in 1983 with the above model shows that during this period, the star shows excess emission and the excess emission is also varying. We estimated the colour temperature of X Per at 500 nm, to assess the variation

TABLE I

Reddening corrected monochromatic magnitudes of X Per and α Cam normalized to wavelength 550 nm along with reddening corrections (red. corr.)

λ (nm)	X Per									Red. corr. for X Per	α Cam mean	Red. corr. for α Cam
	22 Nov., 1980 (mag)	23 Nov., 1980 (mag)	1 Jan., 1981 (mag)	24 Oct., 1983 (mag)	25 Oct., 1983 (mag)	31 Oct., 1983 (mag)	17 Nov., 1983 (mag)	18 Nov., 1983 (mag)	21 Nov., 1983 (mag)	(mag)	(mag)	(mag)
340	−0.74	−0.74	−0.51	−0.38	−0.57	−0.63	−0.42	−0.71	−0.72	2.17	−0.64	1.63
350	−0.66	−0.71	−0.48	−0.35	−0.40	−0.53	−0.47	−0.66	−0.68	2.12	−0.59	1.59
360	−0.43	−0.43	−0.43	−0.09	−0.24	−0.54	−0.41	−0.62	−0.60	2.07	−0.40	1.56
370	−0.16	−0.60	0.52	0.30	0.14	−0.46	−0.39	−0.43	−0.45	2.02	−0.04	1.52
380	−0.15	−0.19	0.00	0.17	0.01	−0.40	−0.23	−0.36	−0.42	1.98	−0.16	1.49
390	−0.31	−0.41	−0.19	−0.08	−0.20	−0.41	−0.33	−0.39	−0.47	1.94	−0.36	1.46
400	−0.55	−0.55	−0.52	−0.29	−0.37	−0.40	−0.37	−0.40	−0.48	1.90	−0.57	1.43
410	−0.53	−0.47	−0.47	−0.34	−0.39	−0.39	−0.32	−0.37	−0.43	1.86	−0.54	1.40
420	−0.48	−0.48	−0.40	−0.33	−0.34	−0.34	−0.29	−0.34	−0.38	1.80	−0.48	1.36
430	−0.41	−0.43	−0.43	−0.34	−0.31	−0.31	−0.28	−0.36	−0.35	1.76	−0.43	1.33
440	−0.38	−0.39	−0.39	−0.35	−0.32	−0.30	−0.25	−0.29	−0.31	1.72	−0.40	1.30
450	−0.34	−0.35	−0.32	−0.31	−0.29	−0.27	−0.23	−0.25	−0.31	1.69	−0.36	1.27
460	−0.30	−0.29	−0.27	−0.26	−0.24	−0.24	−0.20	−0.22	−0.25	1.65	−0.30	1.25
470	−0.24	−0.24	−0.29	−0.24	−0.21	−0.20	−0.20	−0.19	−0.22	1.63	−0.26	1.23
480	−0.21	−0.21	−0.25	−0.22	−0.20	−0.19	−0.14	−0.17	−0.22	1.60	−0.21	1.20
490	−0.17	−0.17	−0.17	−0.18	−0.17	−0.14	−0.11	−0.13	−0.19	1.57	−0.17	1.18
500	−0.14	−0.14	−0.18	−0.13	−0.11	−0.10	−0.05	−0.11	−0.13	1.53	−0.13	1.15
510	−0.10	−0.11	−0.13	−0.11	−0.08	−0.09	−0.08	−0.09	−0.14	1.49	−0.11	1.12
520	−0.09	−0.08	−0.11	−0.10	−0.08	−0.08	−0.05	−0.06	−0.12	1.44	−0.09	1.09
530	−0.06	−0.06	−0.02	−0.07	−0.05	−0.07	−0.04	−0.03	−0.09	1.39	−0.06	1.05
540	−0.04	0.00	−0.03	−0.04	−0.02	−0.03	0.00	−0.03	−0.11	1.35	−0.03	1.02
550	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.32	−0.0	1.00

Table I (continued)

λ (nm)	X Per									Red. corr. for X Per	α Cam mean	Red. corr. for α Cam
	22 Nov., 1980 (mag)	23 Nov., 1980 (mag)	1 Jan., 1981 (mag)	24 Oct., 1983 (mag)	25 Oct., 1983 (mag)	31 Oct., 1983 (mag)	17 Nov., 1983 (mag)	18 Nov., 1983 (mag)	21 Nov., 1983 (mag)	(mag)	(mag)	(mag)
560	0.05	0.05	0.09	0.02	0.01	0.02	0.05	0.02	0.03	1.29	0.02	0.96
570	0.06	0.08	0.12	0.07	0.06	0.06	0.04	0.03	0.04	1.25	0.05	0.94
580	0.10	0.11	0.15	0.10	0.08	0.11	0.10	0.10	0.04	1.22	0.12	0.92
590	–	–	–	0.07	0.09	0.07	0.07	0.09	0.08	1.19	0.13	0.90
600	–	–	–	0.12	0.13	0.13	0.09	0.13	0.11	1.17	0.18	0.89
610	–	–	–	0.16	0.18	0.17	0.14	0.14	0.13	1.15	0.22	0.87
620	–	–	–	0.16	0.20	0.18	0.18	0.17	0.13	1.13	0.23	0.85
630	–	–	–	0.19	0.21	0.20	0.21	0.19	0.20	1.11	0.26	0.84
640	–	–	–	0.22	0.23	0.24	0.19	0.20	0.21	1.09	0.28	0.83
650	–	–	–	0.26	0.25	0.26	0.16	0.26	0.14	1.08	0.30	0.81
652.5	–	–	–	0.24	0.23	0.21	0.10	0.22	0.08	1.07	–	–
655	–	–	–	0.16	0.16	0.16	0.02	0.15	0.04	1.07	–	–
657.5	–	–	–	0.14	0.10	0.15	0.01	0.09	0.05	1.06	–	–
660	–	–	–	0.17	0.12	0.16	0.06	0.13	0.14	1.06	0.35	0.80
662.5	–	–	–	0.23	0.16	0.19	0.15	0.16	0.27	1.06	–	–
665	–	–	–	0.28	0.20	0.26	0.19	0.22	0.28	1.05	–	–
670	–	–	–	0.32	0.30	0.29	0.22	0.33	0.31	1.04	0.39	0.79
680	–	–	–	0.33	0.32	0.31	0.26	0.30	0.34	1.02	0.44	0.77
690	–	–	–	0.37	0.34	0.36	0.29	0.33	0.35	1.00	0.49	0.75
700	–	–	–	0.38	0.38	0.42	0.32	0.37	0.36	0.99	0.52	0.74
710	–	–	–	0.40	0.37	0.38	0.33	0.40	0.32	0.97	0.51	0.73

in the observed excess emission. To estimate the colour temperature, the relative gradients $G_{\alpha\,\mathrm{Cam,\,X\,Per}}$ and $G_{\alpha\,\mathrm{Cam,}\,\alpha\,\mathrm{Lyr}}$ at 500 nm were found using the relation $G_{A,B} = 0.921 S_{A,B}$ (Kienle, 1941) where $S_{A,B} = d(\Delta m_{A,B})/d(1/\lambda)$ is the slope of the least-squares best fitting strainght line among the points of the corresponding magnitude differences between stars A and B within the limits $1.8 < 1/\lambda < 2.2$. Absolute gradient (ϕ) of α Lyr at wavelength 500 nm (Code, 1960; Lamla, 1965) was used to calculate the absolute gradients of α Cam and X Per for different nights. The colour temperature corresponding to these gradients were read from a $T_c - \phi$ curve for black bodies (Lamla, 1965). The absolute gradients thus found and colour temperatures are listed in Table II.

Colour temperatures at 500 nm reveal that colour temperature of X Per in 1980–1981 is about 2000 K lower than that of α Cam but in 1983 the difference is about 4000 to 7000 K.

It is expected that the envelope surrounding the star has modified the energy distribution curves and the density of the envelope is also changing which is reflected in the change found in the colour temperatures in 1980–1981 and 1983.

TABLE II

The derived parameters of X Per on various nights

Date	Absolute gradient (ϕ) at 500 nm	Colour temperature (K)	Total energy Hα (ergs cm^{-2} s^{-1})	Number density in the shell (cm^{-3})
22 Nov., 1980	0.83	21 300	–	–
23 Nov., 1980	0.83	21 300	–	–
1 Jan., 1981	0.84	20.800	–	–
24 Oct., 1983	0.88	19 300	2.63×10^{-10}	6.1×10^{11}
25 Oct., 1983	0.92	18 200	3.54×10^{-10}	6.8×10^{11}
31 Oct., 1983	0.98	16 800	2.42×10^{-10}	5.4×10^{11}
17 Nov., 1983	1.02	16 000	2.72×10^{-10}	5.6×10^{11}
18 Nov., 1983	0.98	16 800	3.12×10^{-10}	6.1×10^{11}
21 Nov., 1983	1.02	16 000	4.18×10^{-10}	6.9×10^{11}

3.2. Variation of Visual Magnitude

In Figure 3 we have plotted the reddening corrected monochromatic magnitudes of the star at wavelength 550 nm (which is approximately equal to the reddening corrected visual magnitude of the star) versus time. This figure shows that the star shows very irregular variations. The visual magnitudes of X Per on 1 January, 1981 and 18 November, 1983 are almost equal but the colour temperatures on these night are 20 800 and 16 800 K, respectively. Also, there is a difference of $0^{m}_{\cdot}18$ in the visual magnitudes of X Per on 31 October, 1983 and 18 November, 1983 yet the colour temperature is the same on these dates. Normally, an increase in the material in the circumstellar envelope reflects itself as an increase in the visual magnitude and a decrease in the colour temperature in Be stars. Therefore, it is hard to explain this behaviour in case of X Per in terms of a change in the amount of the circumstellar matter in the envelope alone. The intrinsic variations of the star may be contributing to this behaviour.

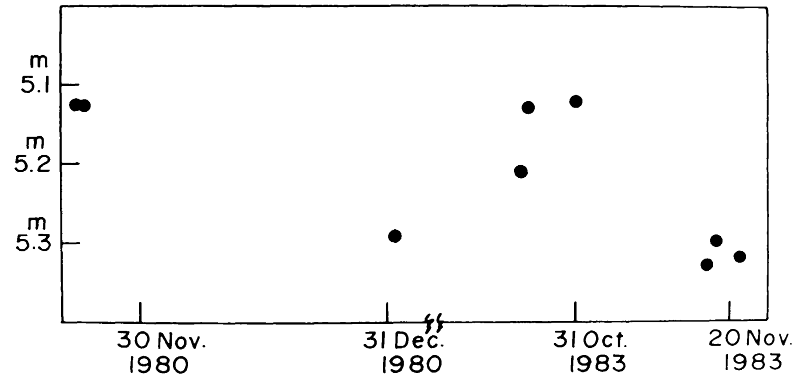

Fig. 3. Variation of visual magnitude of X Per with time.

3.3. Hα VARIABILITY

Our observations show that the Hα emission lines show variations in equivalent widths and in the shape of the profile from night to night (Figure 4). This type of event is common for X Per. Kaitchuck *et al.* (1980) and Murdin *et al.* (1976) have also reported variations in Hα. The equivalent width of Hα reported in the literature ranges from 3

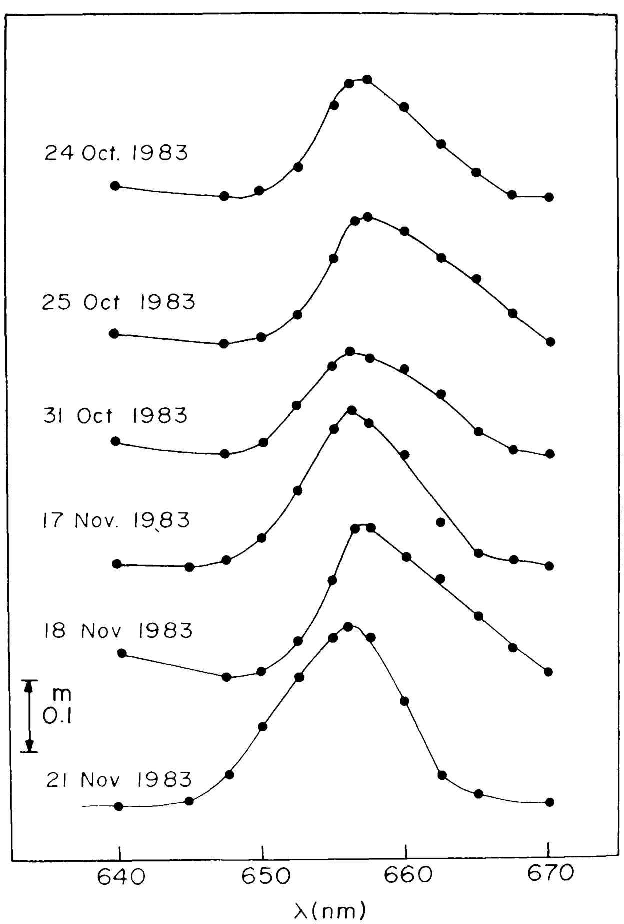

Fig. 4. Hα emission observed on various nights.

to 8 Å. A comparison of the average energy in the Hα line measured during 1971–1972 by Boloshina *et al.* (1982) and that measured by us shows that during 1971–1972 the strength of Hα emission was larger by a factor of 1.4 as compared to our 1983 observations and during 1979 (Viotti *et al.*, 1980) the same is smaller by a factor of 3.1.

A rough estimate of the particle number density in the envelope of the star has been made using the amount of energy measured by us in the Hα line. To this end we have applied the formula

$$E_{ik} = 4\pi A_{ki} h \nu_{ik} Z_k \int_{r_0}^{r_1} n_e n_+ r^2 \, \mathrm{d}r ,$$

(Ambartsumyan, 1958) which, however, is not strictly applicable to the envelopes of Be stars since the envelope of Be stars have parts which are transparent and which are optically thick to the line radiations of the subordinate series of hydrogen.

By use of the values

$$Z_k = \frac{n_k}{n_e n_+}$$

(Ambartsumyan, 1958),

$$A_{ki} = 4.410 \times 10^7 \, s^{-1} , \qquad n_e = n_e^0 \left(\frac{r_0}{r}\right)^2 , \qquad n_+ = n_+^0 \left(\frac{r_0}{r}\right)^2 ,$$

and an extension of the limit of the emitting volume from $r_0 = 4.1 \, R_\odot$ (Bernace *et al.*, 1983) to $r_1 = 18.7 \, R_\odot$ (Mufson *et al.*, 1980) an average number density, $\simeq 10^{11}$ cm^{-3} is obtained for the envelope. An estimate of the electron density in the reversing layers of the star obtained from the quantum number of the last visible Balmer line – namely line H_{23} – reported by Brucato and Kristian (1972), gives a value of 10^{13} for the electron density.

References

Ambartsumyan, V. A.: 1958, *Theoretical Astrophysics*, Pergamon Press, pp. 495 and 424.

Bernacca, P. L., Bianchi, L., Dorren, J. D., and Perryman, M. A. C.: 1983, *Astron. Astrophys.* **122**, 17.

Boloshina, E. V., Glushneva, E. N., Doreshenko, B. T., Kolotilov, E. A., Mossakovskaya, L. B., Obechinnikov, S. L., and Fetisova, T. S.: 1982, in E. N. Glushneva (ed.), *Spectrophotometry of Bright Stars*, Nauka, Moscow, p. 47.

Brucato, R. J. and Kristian, J.: 1972, *Astrophys. J.* **173**, L105.

Code, A. D.: 1960, in J. L. Greenstein (ed.), *Stellar Atmospheres*, University of Chicago Press, Chicago, p. 50.

Ferrari-Toniolo, M., Persi, P., and Viotti, R.: 1978, *Monthly Notices Roy. Astron. Soc.* **185**, 841.

Hutchings, J. B., Cowley, A. P., Crampton, D., and Redman, R. O.: 1974, *Astrophys. J.* **191**, L101.

Kaitchuck, R. H., Honeycutt, R. K., and Mufson, S. L.: 1980, *IAU Symp.* **88**, 233.

Kienle, H.: 1941, *Z. Astrophys.* **20**, 239.

Kurucz, R. L.: 1979, *Astrophys. J. Suppl. Ser.* **40**, 1.

Lamla, E.: 1965, in H. H. Voigt (ed.), *Landolt-Bornstein VI*, Springer-Verlag, Berlin, p. 382.

Mufson, S. L., Kaitchuck, R. H., Hutter, D. J., Indiana, U., and Wood, K. S.: 1980, *Bull. Am. Astron. Soc.* **12**, 500.

Murdin, P., Penston, M. V., and Penny, A. J.: 1976, *Monthly Notices Roy. Astron. Soc.* **176**, 233.
Schild, R. E.: 1977, *Astron. J.* **82**, 337.
Tug, H., White, N. M., and Lockwood, G. W.: 1977, *Astron. Astrophys.* **61**, 679.
Underhill, A.: 1982, in A. Underhill and V. Doazan (eds.), *B Stars with and without Emission Lines,* NASA SP-456, Washington, D.C., p. 85.
Viotti, R., Ferrari-Toniolo, M., Giangrande, A., Persi, P., Bianchi, L., Grasdalen, G., Kalv, P., and Stalio, R.: 1980, *Second European IUE Conference*, ESA SP-157, p. 165.
Viotti, R., Ferrari-Toniolo, M., Giangrande, A., Persi, P., and Boratta, G. B.: 1982, in M. Jaschek and H. Groth (eds.), 'Be Stars', *IAU Symp.* **98**, 423.
White, N. E., Mason, K. O., Sanford, P. W., and Murdin, P.: 1976, *Monthly Notices Roy. Astron. Soc.* **176**, 201.