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RAPID CONTINUUM LEVEL VARIABILITY IN Be STARS EARLIER THAN B2

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ABSTRACT

A large number of Hα profiles were scanned for 12 Be stars and four standard stars on six nights between 1988 January 29 and February 7 with the time resolution ~ 45 s and a good signal-to-noise ratio (83–127 at continuum around Hα). Very careful data analysis (including instrumental and extinction effects) was performed to search for rapid spectral variability in those stars. A method has been described to find out the standard deviation value ($\sigma[F_c]$) of continuum counts (F_c) measurements. Errors due to photon statistics and scintillation in F_c measurements were estimated and compared with the observed errors. From this comparison it was found that the observed errors were larger than the estimated errors. Using the theoretical expression of Lacy for standard deviation of equivalent width, we have calculated the estimated values of $\sigma_T\{W(\alpha)\}$ for equivalent widths of H$\alpha[W(\alpha)]$. Results of the present study show that the Be stars earlier than B2 displayed rapid continuum level (F_c) variability in their spectra which were beyond $\pm 3\sigma(\bar{F}_c)$, and it has been shown that these variations were not due to the random noise. Be stars later than B2 did not display any such rapid variations of F_c. We could not detect any rapid variations of $W(\alpha)$ in our program stars during the interval of our observations. It has been suggested that the observed variations of F_c may be due to the interactions between nonradial pulsations and background-radiation driven wind associated with the Be stars earlier than B2. These interactions may inject variable plasma into the circumstellar envelope which may lead to rapid and irregular variations of F_c.

Subject headings: line profiles — stars: Be

I. INTRODUCTION

Spectroscopic and photometric variability of Be stars over years, months, and days are well established (Doazan 1982; Slettebak 1988 for a bibliography), but changes in hours and minutes have been a subject of vivid debates for years. Many observations have been reported, which claim the reality of the rapid variations of the line profiles and the equivalent widths of lower Balmer lines (Bijaoui and Doazan 1979; Hutchings *et al.* 1971; Luud 1978; Mamatkazina 1978; Slettebak and Snow 1978; Ghosh *et al.* 1988) and on the other hand, the majority of studies gives a negative answer on the question of reality of the rapid variations (Baliunas and Guinan 1976; Haefner, Metz, and Schoembs 1975; Lacy 1977; Slettebak and Reynolds 1978). Therefore, the present situation is more doubtful for the rapid spectral variability of Be stars. In this connection it is important to mention that the studies of rapid variations of continuum emission of these stars seem to be particularly interesting. But to the best of our knowledge, only very few stars were observed to search for such variability (Chalabaev and Maillard 1983; Fontaine, Lacombe, and Wesemael 1983). Therefore, confirmation of rapid variations is important if the physical processes in Be stars are to be understood.

In order to search for such variability we observed 12 Be stars (brighter than 5th magnitude) in the Hα region (in total we obtained 1731 Hα profiles) on several nights. Study of the rapid continuum level variability was also performed for those stars.

It is important to mention here that high time-resolution observations with moderate signal-to-noise (S/N) ratio accompanied by a careful analysis of possible instrumental effects and atmospheric variations which can produce spurious results, are necessary to search for rapid spectral variability.

II. OBSERVATIONS

Photoelectric scans for the Hα emission line of our program stars which are listed in Table 1, were obtained on six nights between 1988 January 29 and February 7 using the rapid scanning grating spectrometer attached to the 102 cm Cassegrain reflector of Vainu Bappu Observatory, Kavalur, India. Technical details of the grating spectrometer were described by Bappu (1977). Actual operating mode and performance of this instrument which was used for the study of rapid emission-line variability, have been described in detail in a previous publication (Ghosh 1988).

Hα profiles were always scanned in the first order of the spectrometer grating (1800 lines mm^{-1} blazed at 5000 Å). Nominal bandwidth of the spectrometer is 3 Å. Forward scans were obtained over the wavelength range of 180 Å centered at 6563 Å.

On each night, many spectrophotometric standard stars (at different hour-angles) and sky background plus dark counts were also scanned in the Hα region using the same instrument. This provided us with the values of the atmospheric extinction coefficients, and no appreciable variations of the coefficients were found during the interval of our observations.

Nightly extinction values and the wavelength dependence of the instrumental sensitivity were obtained from the results

TABLE 1

PROGRAM AND STANDARD STARS

HR	HD	Name	V_{mag}	MK
496.......	10516	Φ Per	4.07	B2 Ve
1087.......	22192	ψ Per	4.23	B5 Ve
1273.......	25940	48 Per	4.04	B3 Ve
1463[a]......	29248	ν Eri	3.93	B2 III
1789.......	35439	25 Ori	4.95	B1 Ve
1910.......	37202	ζ Tau	3.00	B4 IIIe
1934.......	37490	ω Ori	4.51	B2 IIIe
2356.......	45725	β Mon	4.57	B4 Ve
2538.......	50013	κ CMa	3.47	B2 IVe
2745.......	56014	27 CMa	4.66	B3 IIIe
3034.......	63462	o Pup	4.48	B1 IVe
3454[a]......	74280	η Hya	4.30	B3 V
4534[a]......	102647	β Leo	2.14	A3 V
4787.......	109387	κ Dra	3.87	B6 IIIe
5132[a]......	118716	ε Cen	2.30	B1 III
5941.......	142983	48 Lib	4.88	B5 IIIe

[a] Standard stars.

of the standard stars, and they were applied to the observed values of the program stars to obtain instrumental and extinction free counts.

III. DATA ANALYSIS AND ERROR ESTIMATION

Each observed Hα profile was normalized by a linear continuum fitted to selected continuum points at (6485 ± 6) Å [λ_1], (6500 ± 6) Å [λ_2], and (6610 ± 6) Å [λ_3]. Coefficients of the linear fit were used to compute the continuum counts at 6563 Å (F_c) of each Hα profile. Average of all the F_c values of a star obtained in a night provides the nightly mean value of $F_c[\bar{F}_c]$ of that star.

Standard deviation values of continuum counts of each profile were measured at λ_1, λ_2, and λ_3 and the mean of these three values provides the standard deviation of $F_c(\sigma[F_c])$ of each Hα profile. Mean of all the $\sigma(F_c)$ values of a star in a night is equal to the nightly mean value of $\sigma(F_c)[\sigma[\bar{F}_c])$ of that particular star.

For rapid variability studies, one has to be extremely careful to estimate the different sources of errors (e.g., photon statistics, scintillation, etc.) introduced into the observations (Lacy 1977). In order to estimate the error which is due to photon statistics in F_c measurements, we have used the expression of Williams *et al.* (1974) (expression [6] of their paper) which is as follows:

$$\sigma_{\text{phot}}(F_c) = (F_c/n)^{1/2}, \tag{1}$$

where F_c is the average counts in the n continuum channels (in our case $n = 5$). Similarly the error which is due to scintillation in F_c measurement is estimated as follows:

$$\sigma_{\text{scin}}(F_c) = \sigma_s F_c, \tag{2}$$

where σ_s is the relative error due to the scintillation. Young (1974) has shown that the low-frequency component of the scintillation noise has the form

$$\sigma_s = S_0 D^{-2/3} M^p \exp(-h/h_0)[1/(4\tau)]^{1/2}, \tag{3}$$

where D is the diameter of the reflector, M is the air mass, h is the observer's height above the sea level, $h_0 = 8000\ m$ is the atmospheric scale height, τ is the integration time per channel, $S = 0.09$ for D in centimeters and $p = 3/2$ to 2 depending on wind direction (for our study we shall use $p = 2$). Therefore, the total estimated error (due to photon statistics and scintillation) in F_c measurement is

$$\sigma_{\text{T}}(F_c) = \left\{ \sigma_{\text{phot}}^2 + \sigma_{\text{scin}}^2 \right\}^{1/2}. \tag{4}$$

We have computed the values of $\sigma(F_e)$ using equations (1)–(4) and they are presented in Table 2. From this table it can be seen that the estimated errors for all the stars are less than the observed errors of F_c. This is because of the other sources of errors, e.g., diffraction in the focal plane of the telescope, stray light, seeing, dispersion (chromatic differential refraction), flexure (in either the telescope tube, the mirror supports, or the scanner or its mounting), polarization, and thermal effects, etc. which we have not incorporated in the calculations of the estimated errors, because they are relatively smaller than the other sources of errors (photon statistics and scintillation). However, all the small errors added together may account for the difference between the observed and the estimated errors of F_c. Therefore, for the present study we shall use $\sigma(F_c)$ as the standard deviation value of F_c.

Expected values of the standard devation of equivalent widths of Hα, $\sigma_{\text{T}}\{W(\alpha)\}$, may be calculated using the theoretical expression for σ_{T} of Chalabaev and Maillard (1983) (expression A10 of their paper). But, in their calculation they have considered only the photon statistics error. Therefore, we shall follow the method of Lacy (1977) who has considered both photon statistics and scintillation errors. Using equation (3) of Lacy's paper we have computed the $\sigma_{\text{T}}\{W(\alpha)\}$ values for the observed Hα profiles, and the nightly mean value of $\sigma_{\text{T}}\{W(\alpha)\}, \sigma_{\text{T}}\{\overline{W(\alpha)}\}$, of the individual stars was computed from the average of all $\sigma_{\text{T}}\{W(\alpha)\}$ values of a star obtained in a night.

From the results of the observed variations of F_c (see Figs. 1*a*–1*d*) of the four standard stars (in total 378 Hα profiles were scanned), it was found that those variations with respect to the nightly mean values of F_c, were within $\pm 2\sigma(\bar{F}_c)$. Similarly, it was also found that $W(\alpha)$ variations of those stars (figures are not shown here) were within $\pm 2\sigma_{\text{T}}\{\overline{W(\alpha)}\}$. Therefore, on the safety side the observational error in measuring F_c and $W(\alpha)$ variations for our program stars are fixed as $\pm 3\sigma(\bar{F}_c)$ and $\pm 3\sigma_{\text{T}}\{\overline{W(\alpha)}\}$, respectively.

Data analysis of all the observed Hα profiles is performed on VAX-11/780 Computer of Vainu Bappu Observatory using the spectrophotometric package developed by A. V. Raveendran and the RESPECT software package (Prabhu, Anupama, and Giridhar 1987).

TABLE 2

Parameters of Hα Profiles of the Observed Stars

Star	Epoch (1988)	N	Mid (UT)	X	$\bar{F}_c$	$\sigma_T(F_c)$	$\sigma(\bar{F}_c)$	$\overline{W(\alpha)}$ (Å)	S/N	$\sigma_T\{\overline{W(\alpha)}\}$ (Å)
φ Per	Jan 30	54	14:17	1.51	20985	111	201	−24.36	104	±0.66
HR 496	Jan 31	139	14:22	1.55	21432	117	197	−24.72	109	±0.67
....	Feb 03	28	14:17	1.57	21173	117	204	−24.54	104	±0.68
....	Feb 07	39	14:44	1.50	21269	117	207	−24.61	103	±0.65
ψ Per	Feb 02	72	14:43	1.28	17956	98	193	−25.67	93	±0.74
HR 1087	Feb 03	43	15:01	1.31	18372	103	197	−26.22	93	±0.76
....	Feb 07	47	14:33	1.29	18241	100	194	−25.89	94	±0.74
48 Per	Feb 03	33	15:40	1.32	21643	120	208	−14.67	104	±0.52
HR 1273	Feb 07	67	15:34	1.35	21412	129	204	−14.41	105	±0.54
ν Eri	Jan 31	09	15:23	1.03	23915	107	213	+5.83	112	±0.14
HR 1463	Feb 02	39	13:41	1.04	23624	109	216	+6.11	109	±0.14
....	Feb 03	34	13:43	1.03	23817	106	218	+6.07	109	±0.14
....	Feb 07	21	13:37	1.05	23324	110	214	+5.96	109	±0.13
25 Ori	Feb 07	59	16:36	1.11	9581	56	114	−8.24	84	±0.45
HR 1789										
ζ Tau	Jan 30	98	15:51	1.01	48384	172	424	−6.07	114	±0.29
HR 1910	Feb 07	38	17:33	1.10	48871	197	445	−5.94	110	±0.31
ω Ori	Feb 02	68	16:06	1.02	16389	75	184	−7.29	89	±0.39
HR 1934	Feb 03	21	17:51	1.24	16405	92	176	−7.21	93	±0.42
....	Feb 07	23	17:56	1.32	16331	100	188	−7.11	87	±0.44
β Mon	Feb 02	65	18:18	1.14	12442	68	145	−16.64	86	±0.59
HR 2356	Feb 07	26	18:24	1.22	12374	70	149	−16.51	83	±0.64
κ CMa	Jan 29	70	17:29	1.07	27841	118	255	−13.84	109	±0.42
HR 2538	Feb 07	67	19:06	1.35	28673	158	258	−13.90	111	±0.47
27 CMa	Jan 29	112	20:27	1.60	11748	82	138	−3.84	85	±0.39
HR 2745	Feb 03	34	19:16	1.40	11241	68	131	−3.75	86	±0.35
o Pup	Jan 30	117	19:33	1.12	17479	86	194	−7.83	90	±0.39
HR 3034	Feb 03	45	19:59	1.23	17824	98	200	−7.69	89	±0.40
....	Feb 07	33	20:02	1.29	17539	103	197	−7.77	89	±0.42
η Hya	Jan 31	12	17:24	1.08	16928	85	190	+3.61	89	±0.11
HR 3454	Feb 02	20	20:19	1.12	16875	88	192	+3.55	88	±0.12
....	Feb 03	37	19:15	1.03	17216	83	185	+3.56	92	±0.12
β Leo	Jan 29	46	21:55	1.00	58816	194	463	+8.04	127	±0.17
HR 4534	Jan 30	52	21:05	1.02	57947	198	467	+7.88	124	±0.17
κ Dra	Jan 31	19	22:33	1.84	20042	142	196	−15.86	102	±0.58
HR 4787	Feb 02	37	21:29	1.88	20419	148	189	−15.71	108	±0.59
....	Feb 03	26	22:59	1.86	20537	147	191	−15.69	107	±0.59
....	Feb 07	77	21:40	1.85	20298	145	203	−15.74	100	±0.59
ε Cen	Jan 29	38	22:45	1.36	56142	296	470	+3.81	119	±0.14
HR 5132	Jan 30	59	22:17	1.40	55911	310	466	+3.78	120	±0.15
....	Feb 07	11	22:19	1.35	55724	290	472	+3.70	118	±0.13
48 Lib	Jan 30	74	23:38	1.23	9959	60	114	−14.55	87	±0.60
HR 5941	Feb 03	52	23:42	1.16	10137	58	116	−14.74	87	±0.59
....	Feb 07	48	23:43	1.11	10024	56	114	−14.83	88	±0.59

IV. RESULTS AND THEIR DISCUSSION

Series of Hα profiles (Table 2) of 12 Be stars and four standard stars (Table 1) were obtained on six nights between 1988 January 29 and February 7. Because of the poor resolution (3 Å) of our scanner instrument, it was not possible to study the profile variations. Therefore, neither all the observed Hα profiles nor the subsequent differences between the profiles are presented here. Only one Hα profile of each star is shown here in Figures 2*a*–2*c*. Total number of observed Hα profiles (N), midexposure time, in UT, and mean airmass (X) of profile scans are listed in Table 2 along with the nightly mean values of F_c, $\sigma_T(F_c)$, $\sigma(\bar{F}_c)$, $W(\alpha)$, $\sigma_T\{W(\alpha)\}$, and the signal-to-noise (S/N) ratio.

From the plots of $W(\alpha)$ variations, with respect to $\overline{W(\alpha)}$ in units of $\sigma_T\{\overline{W(\alpha)}\}$, (figures are not presented here) of all the program stars, it was found that they were within the observational error limit [$\pm 3\sigma_T\{\overline{W(\alpha)}\}$]. This suggests that the rapid variations of $W(\alpha)$ were absent in all the 12 Be stars during the interval of our observations. Also, it can be seen from Table 2 that the night-to-night variations of $W(\alpha)$ were absent in our program stars between 1988 January 29 and February 7.

Continuum level variations of the observed Be stars which are listed in Table 1, with respect to their nightly mean values ($\bar{F}_c$), in units of $\sigma(\bar{F}_c)$, are plotted in Figures 3*a*–3*l*. Perusal of these figures suggests that the rapid variations of F_c, which

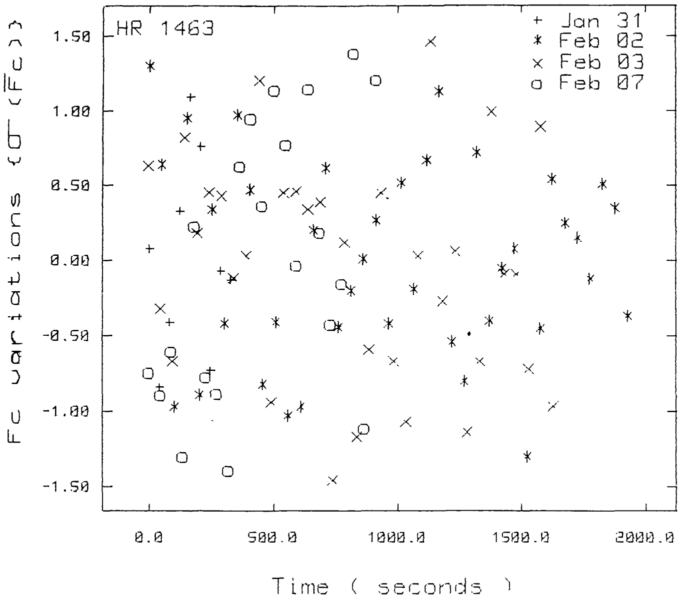

FIG. 1*a*

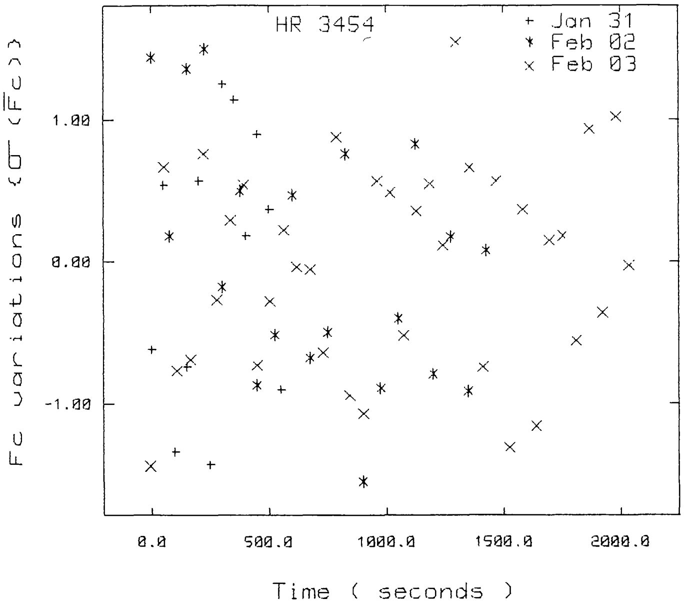

FIG. 1*b*

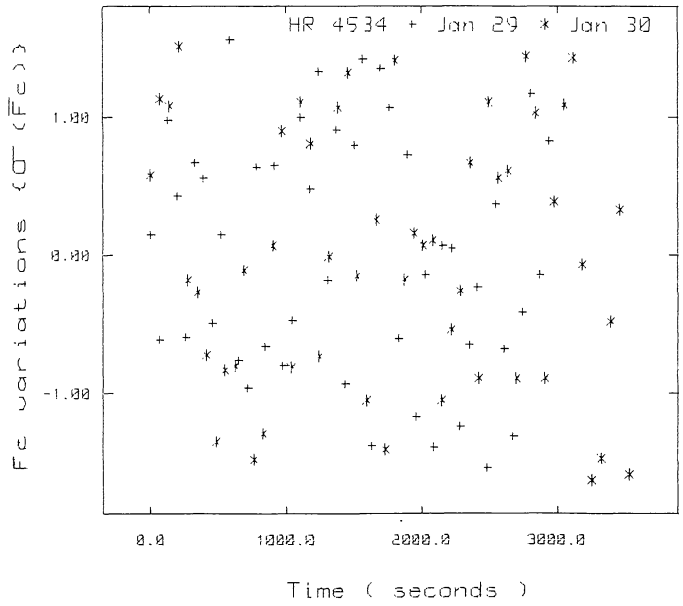

FIG. 1*c*

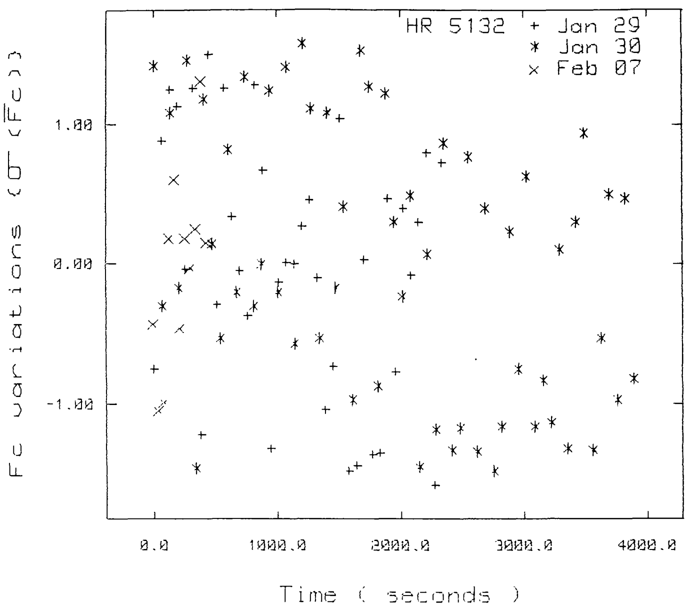

FIG. 1*d*

FIGS. 1*a*–1*d*.—Continuum level (F_c) variations of the standard stars with respect to their nightly mean values, in units of $\sigma(\bar{F}_c)$, vs. the elapsed time in seconds from the time of first observation on each night. Different symbols are used for individual nights.

are beyond the observational error limit ($\pm 3\sigma[\bar{F}_c]$), were present only in five Be stars (HR 496 [Fig. 3*a*], HR 1789 [Fig. 3*d*], HR 1934 [Fig. 3*f*], HR 2538 [Fig. 3*h*], and HR 3034 [Fig. 3*j*]), and the rest of the seven Be stars did not display any such variations. Rapid variations of F_c displayed by the five Be stars may be intrinsic to the stars or it may be observational in origin (for example, it may be due to the random noise). Therefore, before we conclude about the variations, it is necessary to investigate the probability of such events (which are above $\pm 3\sigma[\bar{F}_c]$) which are due to the random noise in a long series of observations. Assuming the Gaussian distribution of the random noise, we computed the probability of F_c variations, in units of $\sigma(\bar{F}_c)$, for the five Be stars and they are shown in Figure 4. It is clearly evident from this figure that the probability of F_c variations (due to the random noise) beyond $\pm 3\sigma(\bar{F}_c)$ is extremely low. Therefore, the ob-

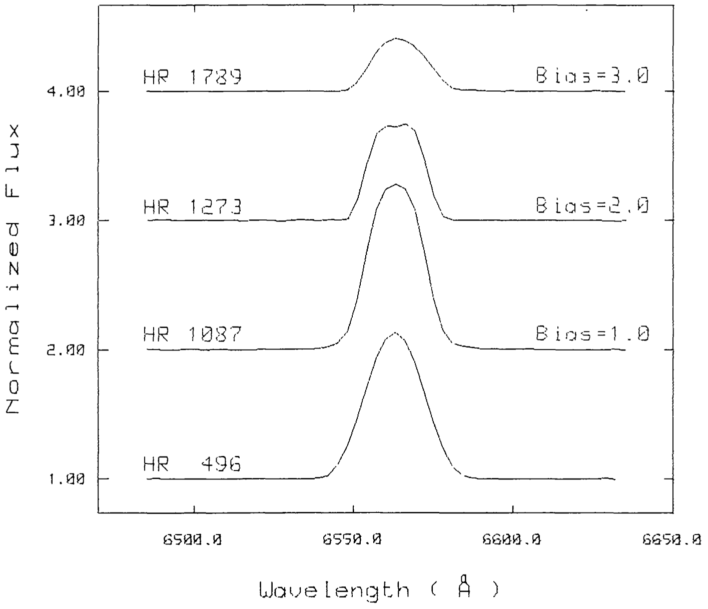

FIG. 2*a*

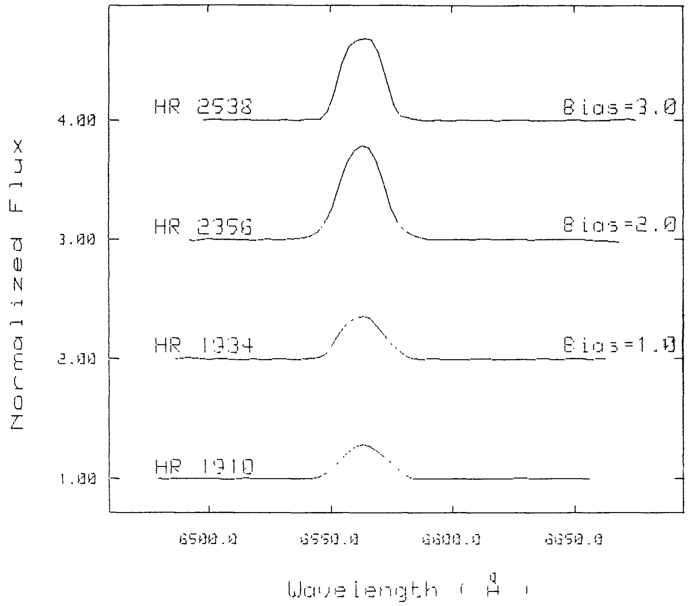

FIG. 2*b*

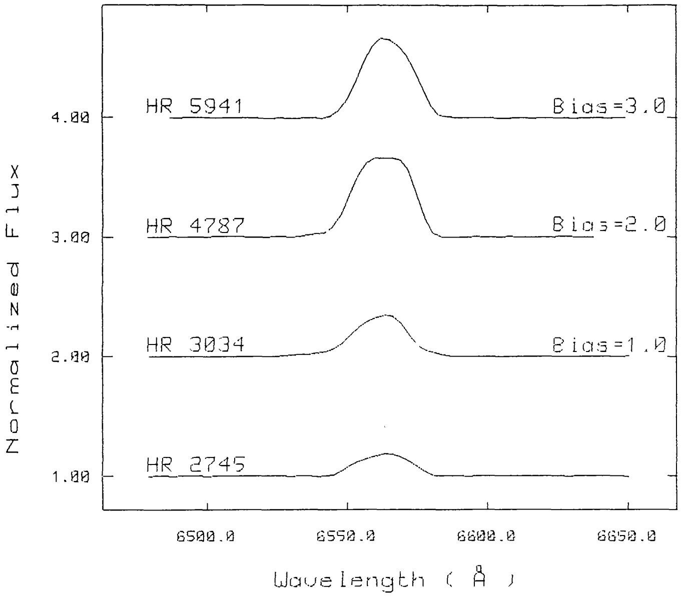

FIG. 2*c*

FIGS. 2*a*–2*c*.—Observed Hα profiles of the program Be stars. Name of the individual star is given to the left and the bias values to the right.

served F_c variations are not due to the random noise, and they may be considered as intrinsic phenomena of the stars.

From Table 1 it can be seen that the five Be stars, which have shown rapid F_c variations in their spectra, are hotter than B2. This is an interesting result which shows that the Be stars later than B2 do not display rapid variations of their continuum level whereas these variations are present in Be stars earlier than B2 (at least this statement is valid for our sample of stars). The above statement should not be considered literally as a generalized statement for all Be stars, because we have not observed a large number of stars with homogeneous distribution of all spectral types.

Now the question is why only Be stars earlier than B2 have displayed rapid and irregular variations of F_c. Rapid and irregular variability of emission lines of Be stars were explained by Huang (1972) in the framework of the hydrodynamical model of Be stars. He suggested that when the density distribution in the gaseous ring (lumps of gas), which will be in circular motion around a star lacks circular symmetry, the emission profile becomes not only asymmetric with respect to the center of the line, but also time dependent. According to Huang, rapid and irregular variations of the profiles can be observed if the number of lumps of gas on different circles is large, i.e., the addition of more and more lumps of gas on different circles will lead to rapid (even on the time scales of minutes) and irregular profile variations. This type of situation will practically arise if the stellar wind is variable.

From ultraviolet observations (UV) of Be stars (survey of absorption lines of highly ionized species), it was found that these stars have displayed strong and dramatically variable stellar winds (for detail references see Sonneborn *et al.* 1988). Even rapid variation was observed on the time scale of hours (1.5 hr) in the highly ionized stellar wind of ω Ori (Sonneborn and Wu 1982; Grady *et al.* 1985). Therefore, UV observations support the basic assumption of Huang's hydrodynamical model which can explain rapid and irregular variations of Be stars, but his model is not capable of representing variations of spectral subtypes of Be stars.

Results of UV observations for main-sequence B type stars have shown that winds are present in stars earlier than B2 and absent in cooler stars (Barker, Landstreet, and Marlborough 1984). The UV spectra of Be stars however, indicate the

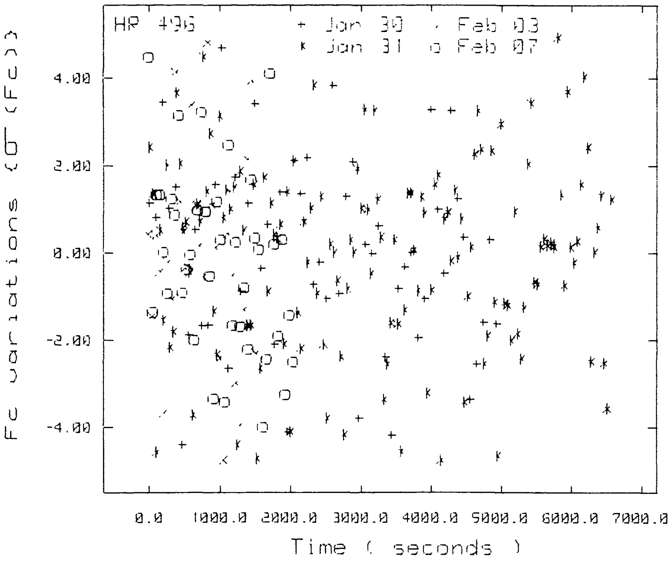

FIG. 3*a*

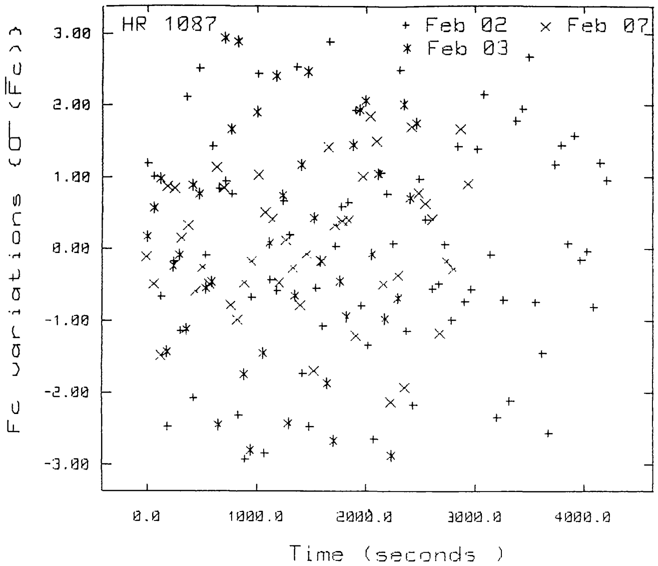

FIG. 3*b*

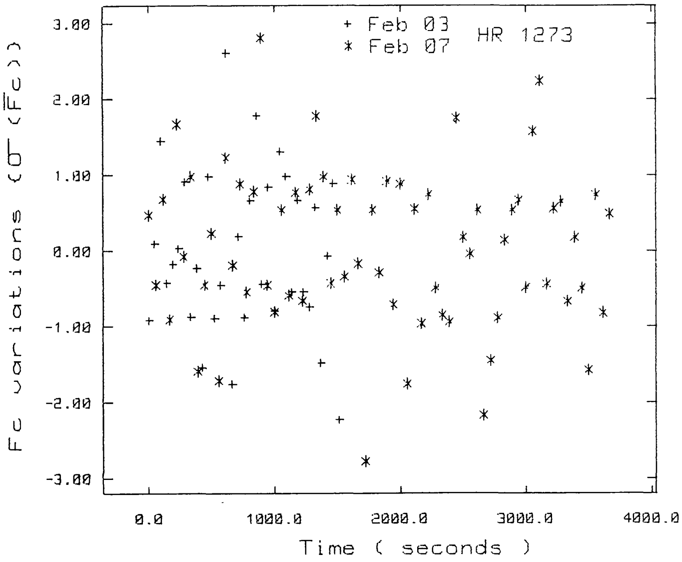

FIG. 3*c*

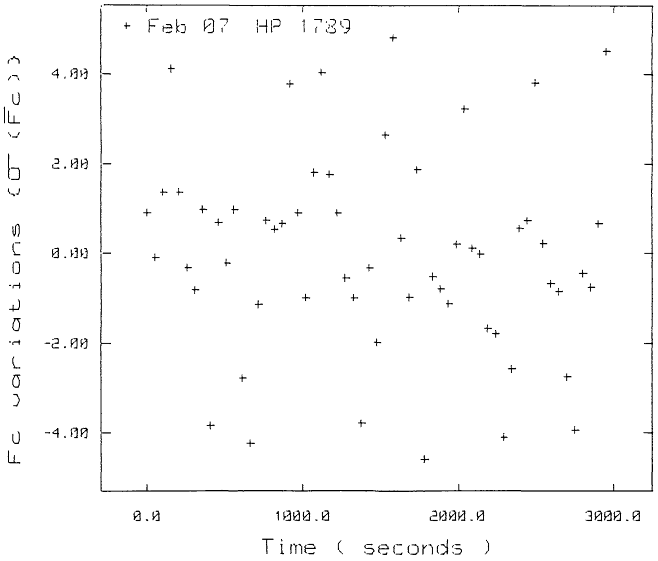

FIG. 3*d*

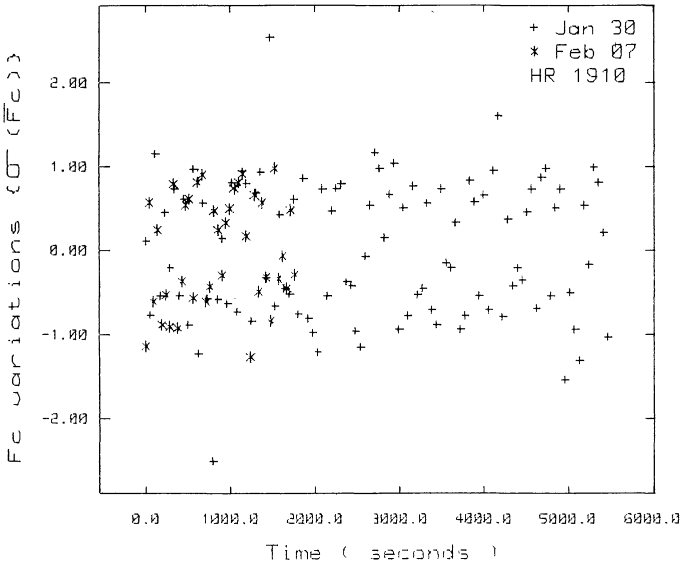

FIG. 3*e*

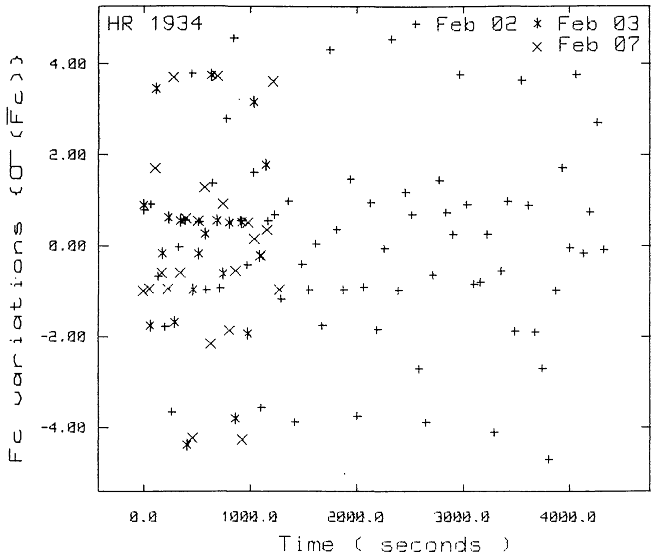

FIG. 3*f*

FIGS. 3*a*–3*l*.—Same as Fig. 2, but for Be stars.

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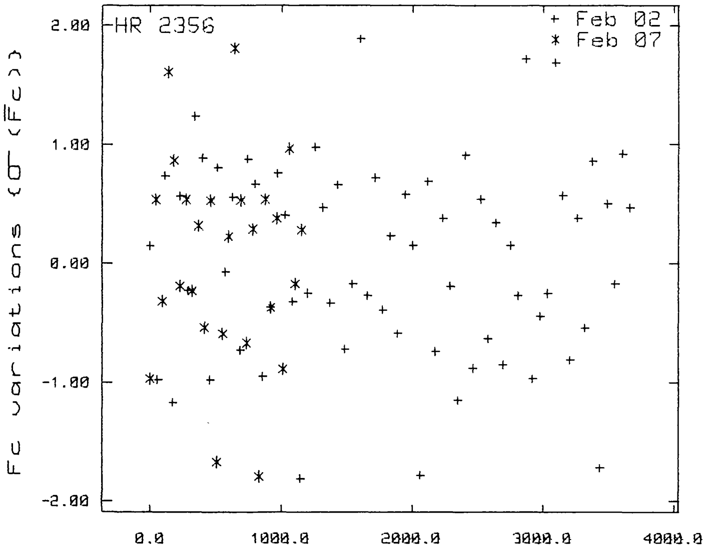

FIG. 3*g*

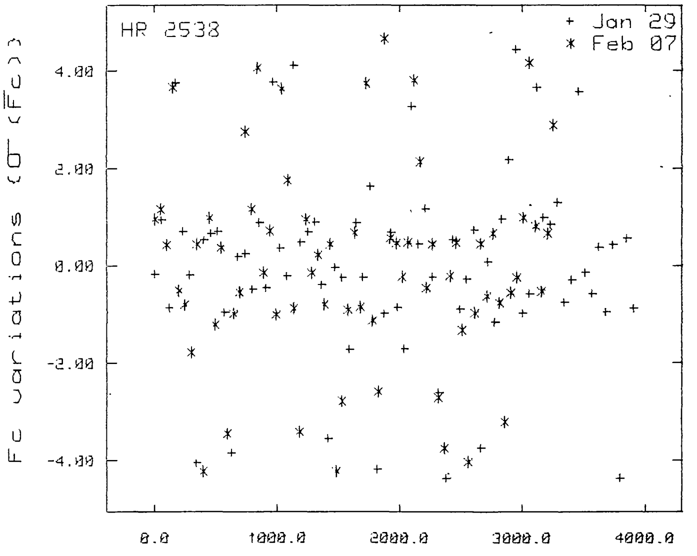

FIG. 3*h*

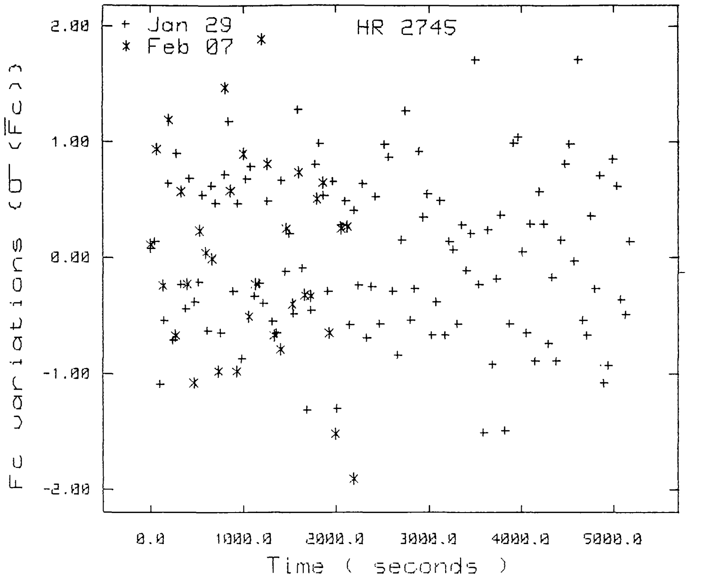

FIG. 3*i*

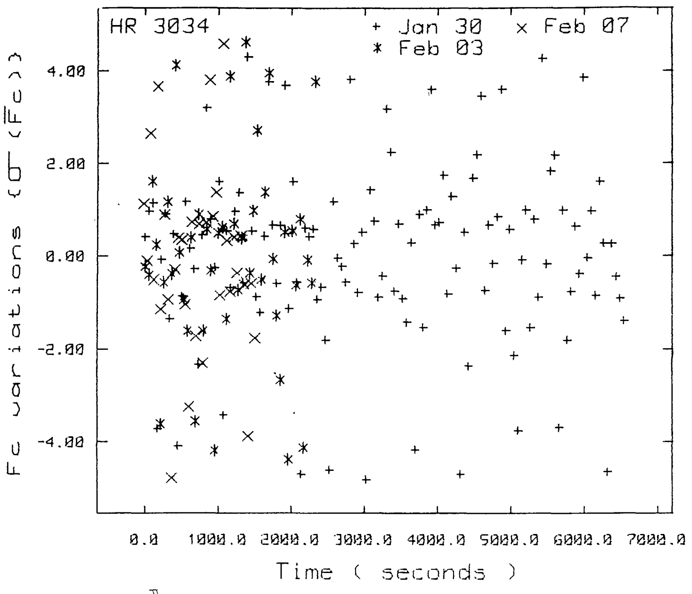

FIG. 3*j*

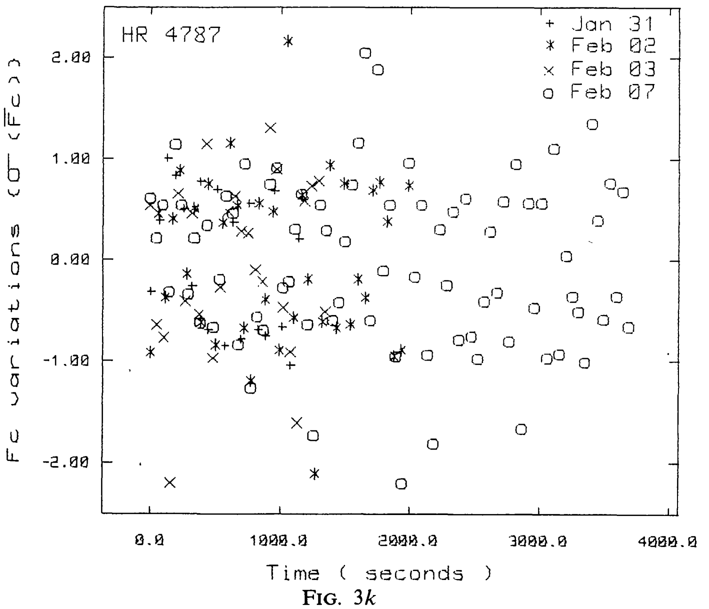

FIG. 3*k*

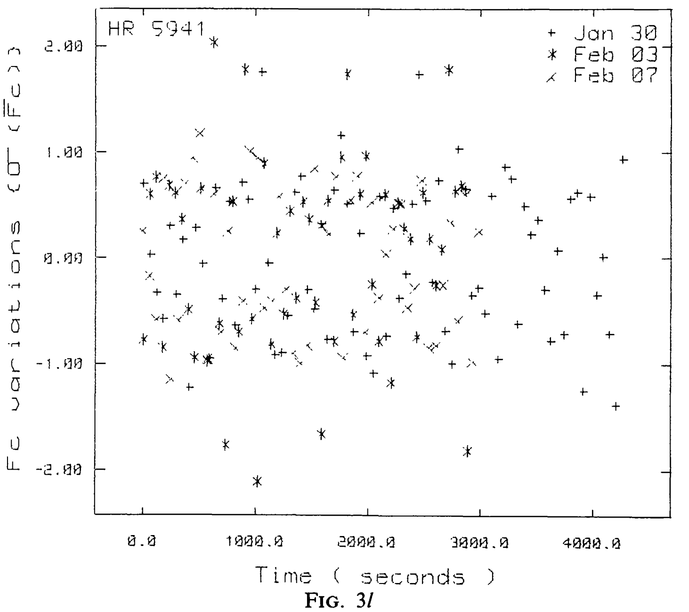

FIG. 3*l*

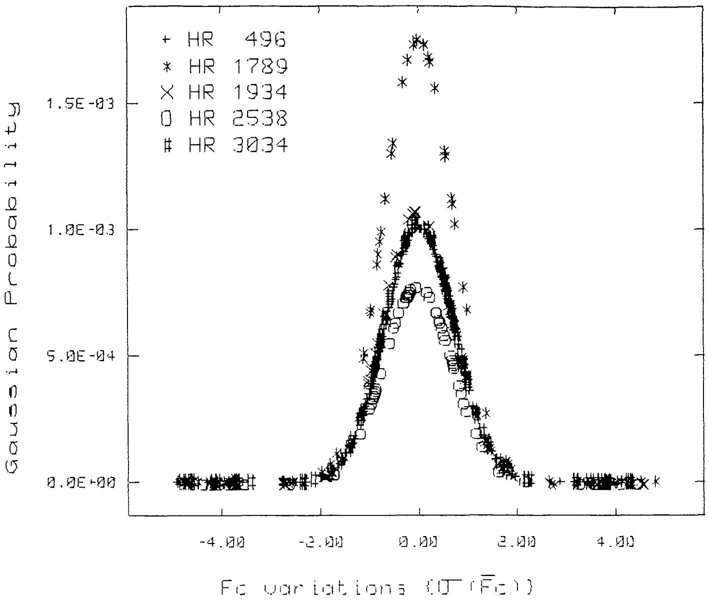

FIG. 4.—Gaussian probability distribution of F_c variations of five Be stars. X-axis represents the variation of F_c in units of $\sigma(\bar{F}_c)$.

presence of winds through the entire B range of spectral subtypes (Barker, Landstreet, and Marlborough 1984). Therefore, there must be some additional mechanism in Be stars cooler than B2 to initiate the acceleration of the wind. Whatever process is responsible for the initial acceleration of the wind in stars later than B2, also contributes to the total wind (a background wind which arises from all parts of the surface of the star) in stars hotter than B2, and probably is the cause for time variations (Marlborough 1987). Recently, it has been recognized that nonradial pulsation (NRP) is a common phenomenon in Be stars (Baade 1987 and references therein). The changing character of NRP of Be stars earlier than B2, which may have background radiation-driven wind, adds matter to the circumstellar envelope (CE), with nonuniform density to the equatorial region depending on the modes of oscillations, and in a time varying way (Marlborough 1987). Marlborough (1987) also suggested that since the line and continuum emission, in the optical and infrared regions, is roughly proportional to the square of the density, therefore even modest mass ejection will produce dramatic spectral changes at optical and infrared wavelengths.

Chalabaev and Maillard (1983) have shown that variable plasma, injected into the circumstellar envelope, will lead to continuum level variability, because the arising variations of the bound-bound emission will be smoothed because of the large optical thickness of the envelope, while the variations of the free-free and free-bound emissions will not be affected by transfer effect as the envelope is optically thin in the continuum.

Therefore, in the summary it may be concluded that our observed continuum level variations of Be stars earlier than B2, may be due to the interactions between NRP and background radiation driven wind (for Be stars earlier than B2) which may inject variable plasma into the circumstellar envelope, leading to continuum level variability.

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