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THIRTEEN-COLOR PHOTOMETRY OF Be STARS

M. Alvarez and W. J. Schuster
Instituto de Astronomía
Universidad Nacional Autónoma de México

RESUMEN

Presentamos fotometría de 13-colores obtenida en el Observatorio de San Pedro Mártir en Baja California, de un cierto número de estrellas espectroscópicamente variables, de tipo Be y con envolvente (shell stars). Varias de ellas también muestran variabilidad fotométrica en el ultravioleta y/o en el infrarrojo, en observaciones tomadas durante un lapso de dos a tres años.

Analizamos las estrellas más interesantes por medio de diagramas color-color, exceso de color, características espectrales y cambios en su distribución de energía. Discutimos algunos aspectos de nuestros próximos proyectos de investigación.

ABSTRACT

Thirteen-color photometry made at the San Pedro Mártir Observatory in Baja California, for a number of spectroscopically variable Be and shell stars is presented. Several of these stars also show photometric variability in the ultraviolet and/or infrared over a time base of two to three years.

We analyze the more interesting stars in terms of color-color diagrams, color excesses, spectral characteristics and changes in their energy distributions. Prospects for future research are discussed.

Key words: **PHOTOMETRY – STARS-Be**

I. TECHNIQUES

For the last four years we have observed with the 13-C photometric systems (Johnson and Mitchell 1975) 86 spectroscopically variable Be and shell stars (Hubert-Delplace 1976). It is known that some Be stars also show large changes in their magnitudes and colors. See, for example, Alvarez and Schuster (1978), Feinstein and Marraco (1979), Ferrer and Jaschek (1971), Feinstein (1968, 1970, 1975). We are studying in detail the photometric variability of these 86 stars in order to obtain a better understanding of the Be star phenomenon.

In Table 1 we give photometric criteria for selecting stars whose 13-C observations show evidence of variability. For each color or magnitude we give two standard deviations; σ(lower) represents a good estimate of the deviation for a non-variable B star while σ(upper) represents a more conservative estimate based on more nights and on stars of widely different spectral types. These criteria were derived from four sets of data: (*a*) 13-C observations of the B0 V standard BS 1855 where the number of blue-red observations is 23/25 respectively, (*b*) 13-C observations of the O9 V standard BS 8622 (95/47), (*c*) standard star residuals from 225 nights, 1973-1979 and (*d*) a subset of these residuals from 83 nights, 1977-1979, some years of the Be star observations. For each night the standard star residuals were squared, summed and divided by n−3 (three coefficients are derived from the standard star reductions) to give a standard deviation. In general the deviations for 1977-1979 are smaller than those for

TABLE 1

PHOTOMETRIC VARIABILITY CRITERIA[a]

	52	*33-52*	*35-52*	*37-52*	*40-52*	*45-52*	*52-58*	*52-63*	*58*	Derived from
σ(lower)	0.011	0.010	0.011	0.010	0.008	0.006	0.009	0.010	0.015	standards BS1855 (B0 V) and BS8622 (O9 V)
σ(upper)	0.022	0.017	0.023	0.019	0.013	0.009	0.012	0.015	0.021	standard-star residuals, 1973-1979.
	58	*58-72*	*58-80*	*58-86*	*58-99*	*58-110*				
σ(lower)	0.015	0.008	0.008	0.008	0.009	0.017	...	...	...	standard-star residuals, 1977-1979 and the standard BS1855 (B0 V)
σ(upper)	0.021	0.014	0.014	0.013	0.016	0.039	...	...	...	standard-star residuals, 1973-1979 and standard BS8622 (O9 V)

a. At unit air mass.

1973-1979 since our observing techniques and equipment have improved in time.

Following Ferrer and Jaschek (1971) we take 2σ criteria to separate variables from non-variables for internal comparison of our data. That is, stars with $\sigma > 2\sigma$ (upper) are variable, stars with $\sigma < 2\sigma$(lower) are non-variable, and all others are possibly variable. All comparisons were done at unit air mass. Twenty-five of these stars were observed previously with 13-C photometry (Johnson and Mitchell 1975; Mitchell and Johnson 1969; Johnson *et al.* 1967). For external comparisons of our data with previous observations we have used 3σ criteria to separate variables from non-variables. That is, stars with $\Delta > 3\sigma$(upper) are variable, where Δ is the difference between the average of our measurements and the average of Johnson and Mitchell (1975).

In Table 2 we list the 86 Be stars separated according to the above criteria; 31 are variable in at least one color or magnitude, 36 are possibly variable, and 19 do not show evidence of variability. In the first column, we give the HD number, in the second column the Bright Star catalogue number (Hoffleit 1964), followed by the spectral type from Hubert-Delplace (1976) and from the BS catalogue (column 3). Columns 4 to 7 give the number of blue and red observations from our work (AS), and from Johnson and Mitchell (1975), (JM), respectively. Finally, columns 8, 9 and 10 indicate whether or not the star is variable.

As described by Johnson and Mitchell (1975), in the 13-C photometric system filter *58* (0.58 microns effective wavelength) ties together the observations obtained with the two different photomultipliers on a purely color basis. Figure 1 shows the changes in the *58*-magnitude (M_{58}), observed for our 31 "variable" stars. On the horizontal axis, we have the Julian Date of

TABLE 2

13-COLOR PHOTOMETRIC VARIABILITY OF Be STARS

			Number of Observations				Variability		
			A S		J M				
HD	BS	Sp	B	R	B	R	Var.	Pos.	No
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
698	...	cB8e/B2-B6 V	0	2	..	..	..	x	..
4180	193	B2 V/B4ne/B8 III	11	7	2	1	x	..	..
6811	335	B9 III/B7 V	10	6	2	2	..	x	..
9709	...	B8 V	4	5	..	..	..	x	..
10516	496	B0ne/B1 III-Vpe	11	4	3	3	x	..	..
13267	627	B3p/B5 Ia	4	3	..	..	..	x	..
13854	654	cB1e/B2 Ia	4	6	..	..	..	x	..
14134	...	cB3e	2	0	..	..	..	..	x
14818	696	cB1e/B2 Ia	3	6	2	2	x	..	..
18552	894	B9/B8 Ve	2	2	..	..	..	..	x
19243	...	B2e	1	0	..	..	..	..	x
21641	...	B9	8	5	..	..	..	..	x
21856	1074	B1n/B1 V	7	3	..	..	..	x	..
22192	1087	B5ne	11	6	2	2	..	x	..
23862	1180	B8n/B8p	3	0	3	3	x	..	..
24534	1209	B0ne/0pe	9	7	..	..	x	..	..
25940	1273	B3 Vpe/B3ne	9	6	3	3	..	x	..
28497	1423	B3ne/B2 V	2	7	..	..	..	x	..
29866	1500	B4ne/B7 V-IV	6	4	..	..	..	..	x
32343	1622	B2 Vpe/B3e	0	4	..	..	..	x	..
33328	1679	B IV/B2.5 III-IV	3	7	2	2	..	..	x
34085	1713	B8 Ia/cB8	1	2	4	2	x	..	..
35439	1789	B3ne/Be III-IV	4	5	2	2	x	..	..
36486	1852	B2 V/O9.5 II	0	2	2	2	..	..	x
37202	1910	B3p/B2 IVp	6	7	2	2	x	..	..
37967	1961	B5 Vpe/B3ne	0	1	..	..	..	..	x
38010	...	B3ne	2	4	..	..	..	x	..
41335	2142	B2e/B2 IV-V nne	3	3	..	..	..	..	x
41511	2148	A2p/A0	2	3	2	2	..	x	..
44458	2284	B IVpe/Be ne	1	3	..	..	..	..	x
45314	...	B2ne	2	3	..	..	x	..	..
45910	...	B3e	2	3	..	..	..	x	..
50083	...	B2e	1	3	..	..	..	..	x
50138	...	B8e	3	2	..	..	..	..	x
50658	2568	B8	2	5	..	..	..	x	..
51480	...	B8e	4	3	..	..	x	..	..
52721	...	B3e	2	0	..	..	..	x	..
53367	...	...	4	2	..	..	x	..	..
58050	2817	B3/B3e	6	5	..	..	..	x	..
60855	2921	B2 IVe/B5	2	2	..	..	x	..	..
62367	...	B9	2	4	..	..	..	x	..
65875	3135	B3p/B2e	4	6	..	..	x	..	..
71072	...	B8	3	4	..	..	..	x	..
89884	...	B5	7	8	..	..	..	x	..
91120	4123	B9/B9ne	6	8	..	..	..	x	..
91316	4133	cB0/B1 Ib	10	8	2	2	..	x	..
109387	4787	B7p/B5e	1	3	3	3	x	..	..
138749	5778	B5ne/B7nn	8	7	2	2	x	..	..
141569	....	B9	8	7	..	..	..	..	x
142926	5938	B8 V	9	8	..	..	..	x	..
142983	5941	Bp/B3p	8	8	1	3	x	..	..
145389	6023	B9p/Ap	7	8	2	3	x	..	..
148184	6118	B2 Ve/B3e	6	7	4	1	x	..	..
149757	6175	O9.5 V	6	7	4	2	..	x	x
162428	....	....	4	5	..	..	x	..	..
162732	6664	Ap/B8	7	8	..	..	x	..	..
164447	6720	B9e/B8 IV	5	5	..	..	..	x	..
168797	6873	Be/B6 IV	7	7	..	..	..	x	..
171406	6971	B3	9	5	..	..	..	x	..
171780	6984	B5/B7 V	8	7	..	..	x	..	..
173371	....	B9	9	4	..	..	x	..	..
174237	7084	B5e/B6.5 V	3	2	..	..	..	..	x
174638	7106	Bpe/B8p/B2p	8	6	1	4	x	..	..
178175	7249	B2 Ve/B3e	4	2	..	..	..	..	x
183362	7403	B2e/B3ne/Be V	4	2	..	..	..	..	x
183656	7415	A0p/A0	3	2	..	..	..	..	x
184279	....	B2 Se	6	5	..	..	x	..	..
187811	7565	B3 Ve/B5ne	5	5	2	2	x	..	..
191610	7708	B3 Ve/B3ne	3	6	2	2	x	..	..
193009	....	....	4	5	..	..	..	x	..
193182	....	A0/B9.5 III	9	10	..	..	..	x	..
193237	7763	Bp/B1e	9	14	2	2	x	..	..
195325	7836	A0pe	7	6	..	..	..	x	..
200120	8047	B1 IVe/B3ne	10	7	1	1	x	..	..
201733	8103	B3e/B5e	6	5	..	..	..	x	..
205060	....	....	6	8	..	..	..	x	..
206773	....	B0ne	5	5	..	..	..	x	..
210129	8438	B7 V/V8ne	9	7	..	..	..	..	x
214168	8603	B1 Ve/B3ne	9	7	..	..	..	x	..
216057	8682	B8ne/B8.5 IV-V	7	3	..	..	..	..	x
217050	8731	B2pe/B3 ne	10	9	..	..	x	..	..
217543	8758	B3ne/B4 V	6	5	..	..	x	..	..
218393	....	A5p/B8 Ia	6	7	..	..	x	..	..
218674	....	B3	4	6	..	..	..	x	..
224544	9068	B5ne/B7 IV	4	2	..	..	..	x	..
224559	9070	B3 IV/B4 V	4	5	..	..	..	x	..

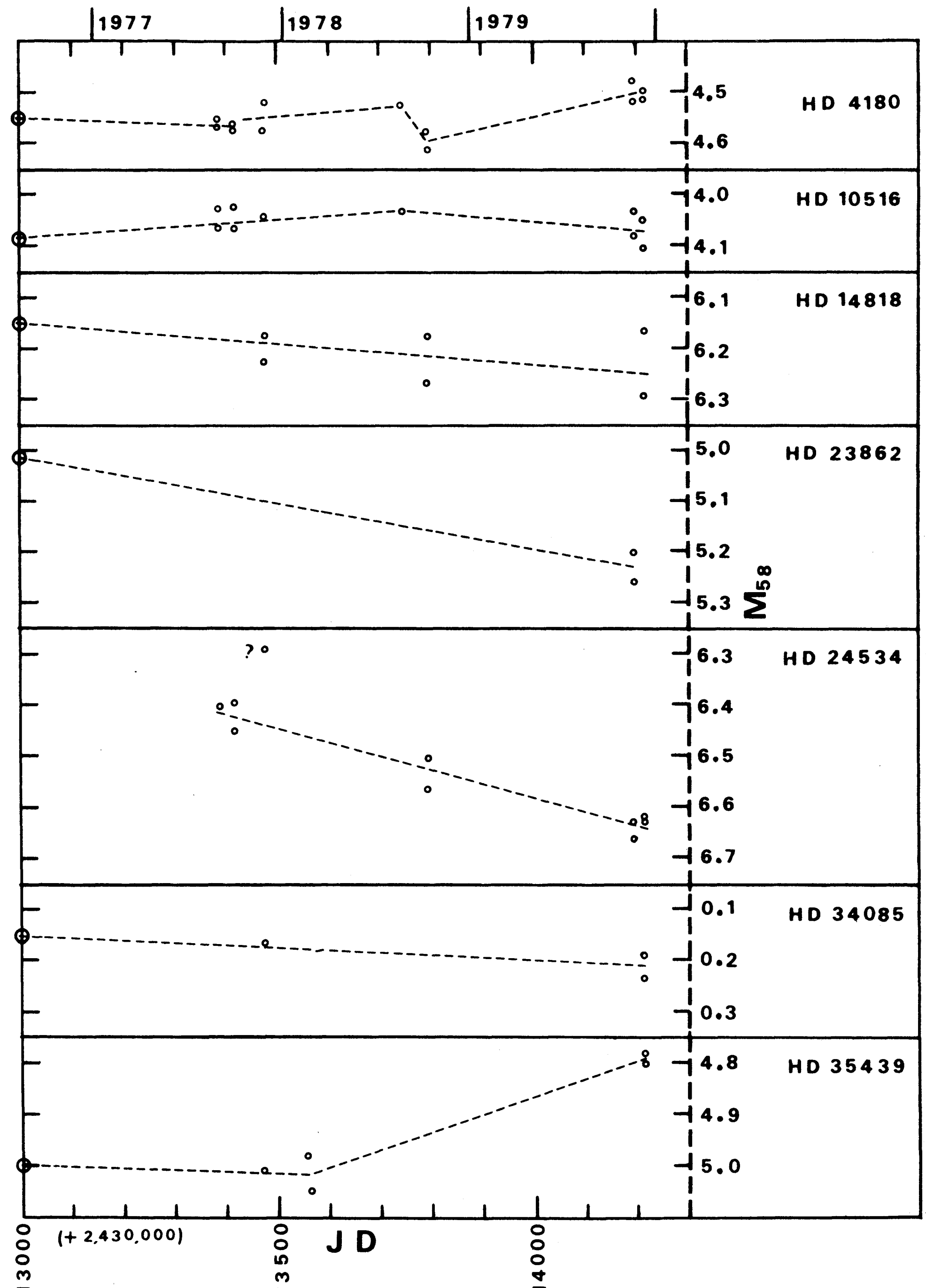


Fig. 1*a*. Changes in the *58* magnitude observed for the variable Be stars. The extreme M_{58} data is plotted in the vertical axis. Julian Date of the observations along the horizontal axis. JM observations are plotted as open circles at the extreme left of the diagram.

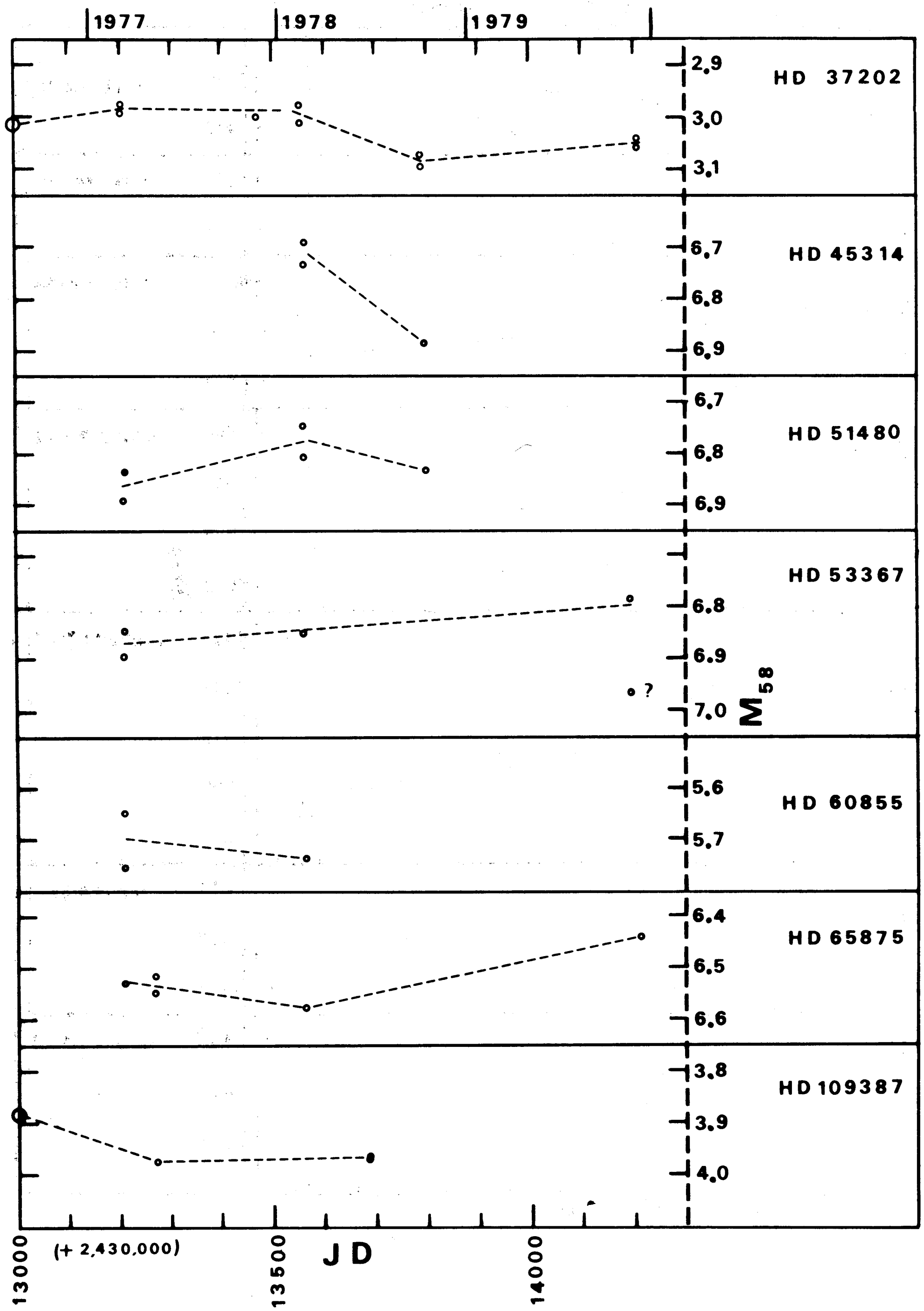


Fig. 1*b*. Same as Figure 1*a*.

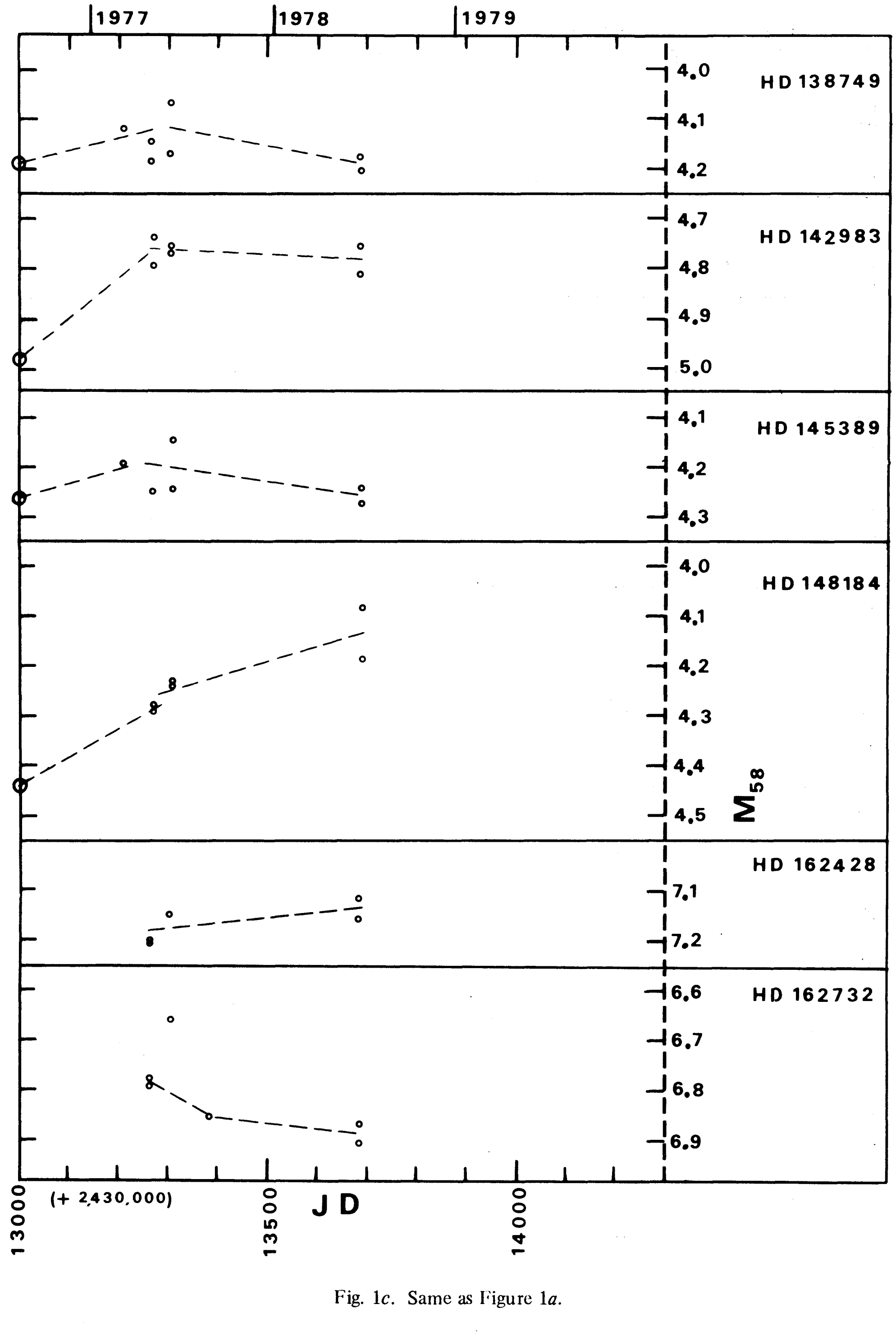


Fig. 1*c*. Same as Figure 1*a*.

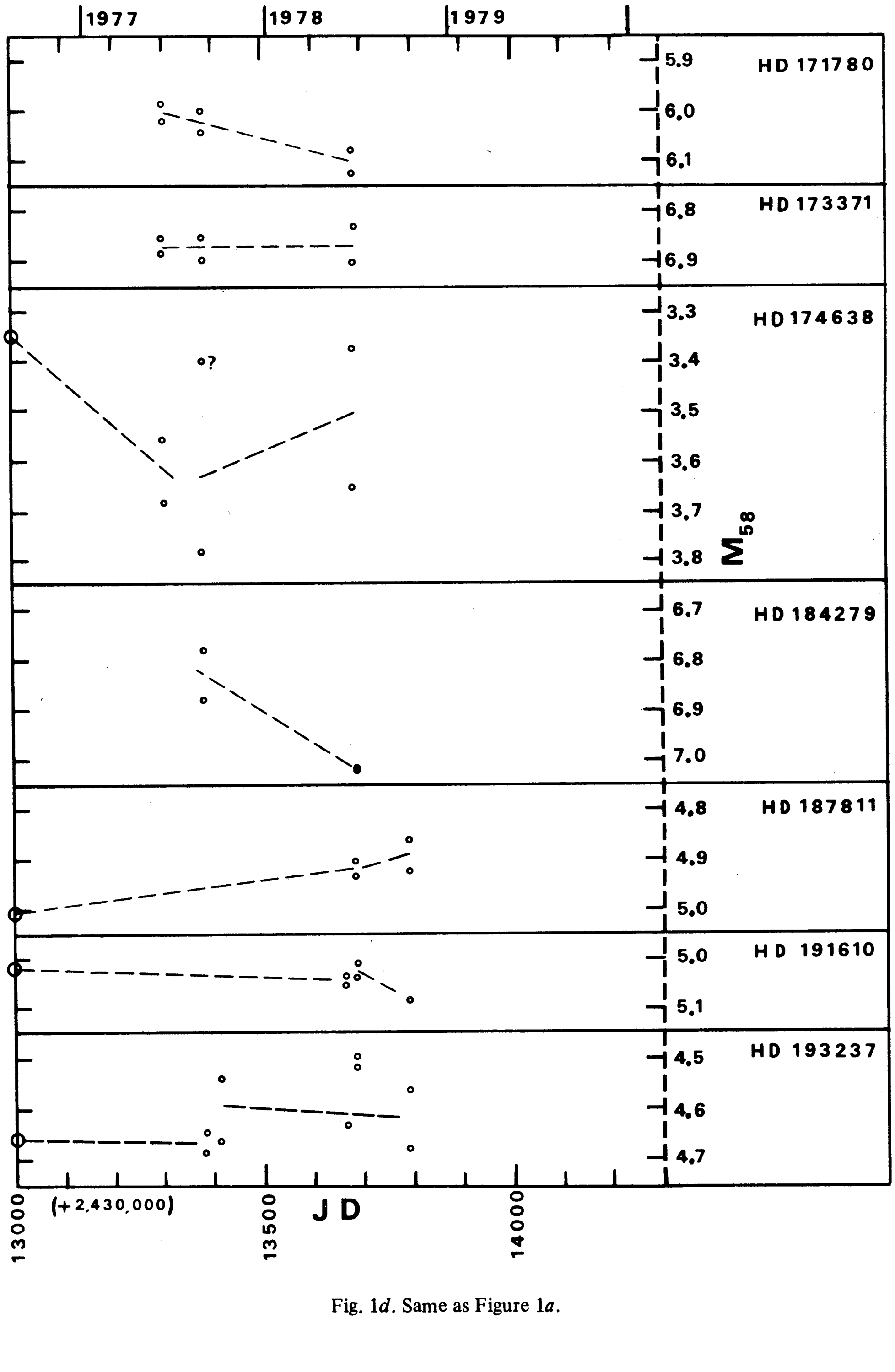


Fig. 1*d*. Same as Figure 1*a*.

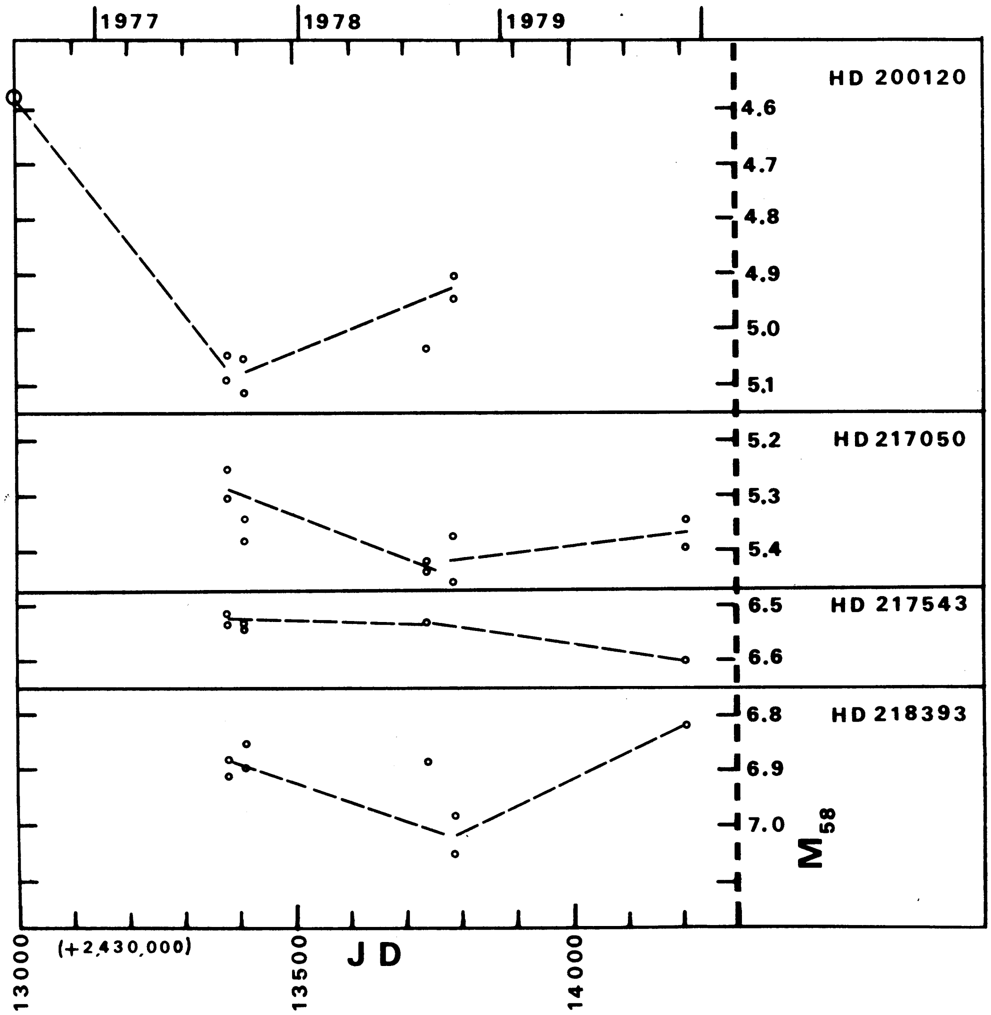


Fig. 1*e*. Same as Figure 1*a*.

our observations. The observations of Johnson and Mitchell were made during the years 1965-1968 and are plotted at the extreme left of the diagram as an open circle. We plot the extreme values of the *58*-magnitude obtained during our observing runs. Some stars show very clear trends, either increasing (HD 35439, HD 53367, HD 65875, HD 148184, HD 187811) or decreasing (HD 23862, HD 24534, HD 45314, HD 162732, HD 171780, HD 184279) in magnitude. None of the curves of Figure 1 show evidence for periodicity, perhaps because the time interval of our work is still too short (2-3 years). Also a number of stars (HD 4180, HD 14818, HD 174638, HD 193237 and HD 218393) show evidence for irregular or short period ($<$ 1 month) variability.

Figure 2 is the two-color diagram (*35-45, 45-52*) for the observed Be stars. The open circles correspond to the supergiants, the plus signs to the giants, the small circles to the main sequence stars and the filled circles to stars of not well established classification. Also, we plot some B standard stars observed repeatedly during our program. The solid line corresponds to the "unreddened" locus obtained as the blue-most envelope of the plotted points, and the arrow shows the change in colors caused by interstellar reddening. Our Figure 2 is very similar to the (*U-B, B-V*) diagram of Feinstein and Marraco (1979, their Figure 1), and as shown by Alvarez and Schuster (1979), the positions of the Be stars in these two-color diagrams are determined not only by interstellar reddening but also by intrinsic ultraviolet excesses.

In Table 3 we give variability information for our 31 variable Be stars broken down according to magnitude and colors. By definition each of these stars is variable in at least one color or magnitude, but most are variable in several colors. The last row of Table 3 shows the percentage of stars in the variable category plus one half the number in the possibly variable. We see that variability in the visible magnitudes, M_{52} and M_{58} is the

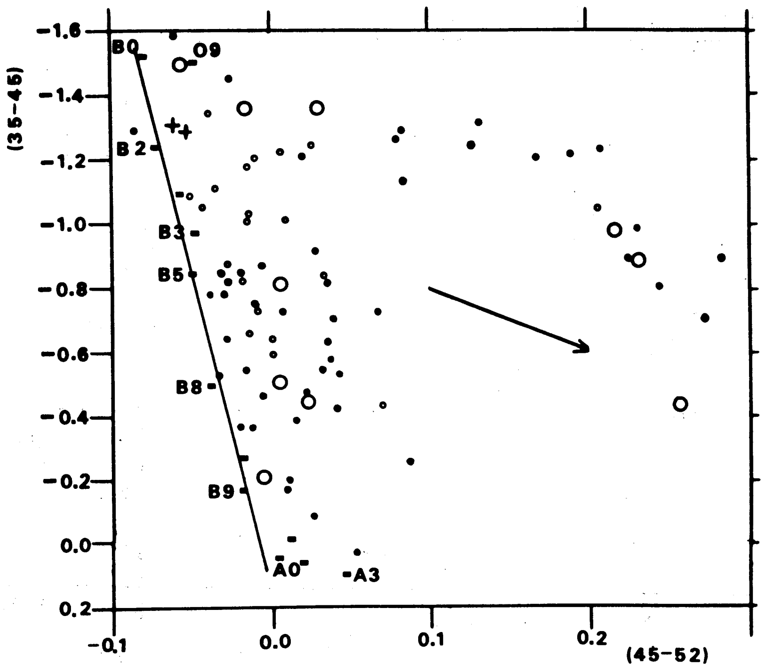


Fig. 2. (*35-45*) versus (*45-52*) diagram for the observed Be stars. Open circles correspond to the supergiants, pluses to giant stars, small circles to the main sequence stars and dots correspond to stars of not well established classification. The solid line is the "unreddened" locus of the Be stars and the arrow shows the change in colors caused by the interstellar reddening. B standard stars are also shown.

TABLE 3

PHOTOMETRICALLY VARIABLE Be STARS
(31 STARS TOTAL)

	52-58	*33-52*	*35-52*	*37-52*	*40-52*	*45-52*	*52-58*	*52-63*	*58-72*	*58-80*	*58-86*	*58-99*	*58-110*
Variable	25	14	12	6	6	4	2	5	8	15	12	9	5
Possibly var.	5	7	6	9	2	0	4	3	10	4	9	12	10
Not variable.	1	10	13	16	23	27	25	23	13	12	10	10	16
% var.	89	56	48	34	23	13	13	21	42	55	53	48	32

most common. Also, significant numbers of Be stars are variable beneath the Balmer jump (colors *33-52* and *35-52*) and between 7000 A and 1.0 micron, Alvarez and Schuster (1978) showed that after correction for interstellar reddening many Be stars have intrinsic photometric excesses for the Balmer continuum and between 6000 A and 1.1 microns.

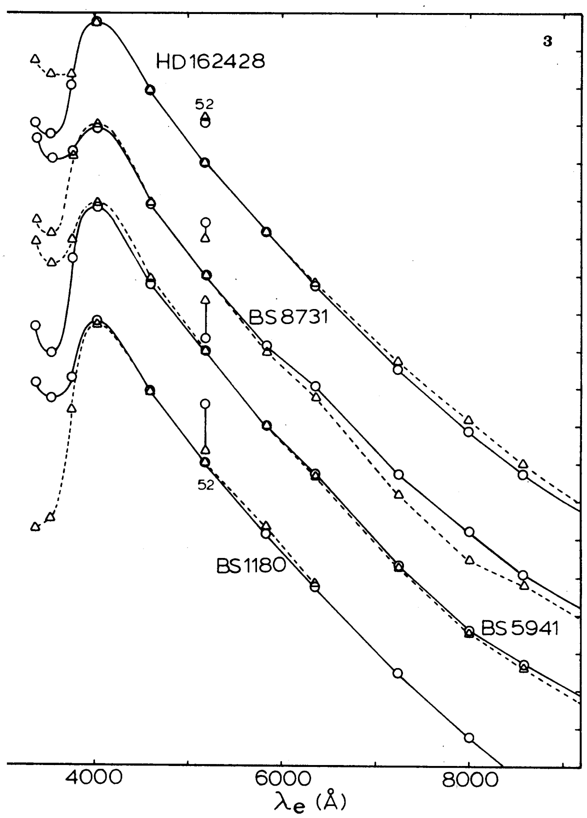
In Table 4 we show the sense of variability for a subset of 16 Be stars with the largest changes. Each star of Table 4 has undergone a change of at least 0.15 mag in at least one color or magnitude. Some really large variations have been observed in these stars; for example: HD 23862, HD 142983, HD 174638 and HD 217050 have shown changes of 0.5 mag or greater. In Table 4, columns 2, 3 and 4 give the photometric changes in the visible (*52, 58*), in the ultraviolet (*33-52, 35-52*) and in the infrared (*58-72, 58-80, 58-86, 58-99*) respectively, where the difference is calculated in the sense (newer – older) observations. A plus or minus without parenthesis indicates a change greater than 0.15 mag; with parenthesis, less than 0.15 mag. A question mark indicates no data, and a zero no significant variation. In column 5 the observers are given; JM stands for Johnson and Mitchell (1975) and AS for the present work. Our observations have been grouped according to observing runs, and so the blue and red observations are approximately simultaneous while the JM data span the years 1965-1968. In Figures 3 and 4 the changes in the relative energy distributions are shown for eight of these stars. The curves are normalized at the *52* filter, and changes in the M_{52} are shown by vertical lines.

From Table 4 we see that when the changes are large (> 0.15 mag), the visible and UV changes have the same sign, whereas the visible and IR changes have opposite

TABLE 4

LARGEST PHOTOMETRIC CHANGES ($\geq 0^{m}.15$)

ID 1)	ΔV (2)	ΔUV (3)	ΔIR (4)	Observers (5)	Approximate time interval (yr) (6)	Variable Star Catalogue (7)
3862	+	+	?	JM/AS	13.0	BU Tau
4534	+	(–)	–	AS/AS	2.2	X Per
5439	–	?	+	AS/AS	1.8	Var?
5314	+	?	(–)	AS/AS	0.6	–
9387	(+)	+	(–)	JM/AS	11.1	Var?
2983	–	–	(–)	JM/AS	10.0	Var?
8184	–	(+)	(+)	JM/AS	11.7	χ Oph
2428	(–)	–	(+)	AS/AS	1.1	–
2732	+	+	(+)	AS/AS	1.1	–
3371	0	?	+	AS/AS	0.0	–
4638	+	+	(+)	JM/AS	11.2	β Lyr
4279	+	(+)	0	AS/AS	0.8	–
3237	–	0	(+)	JM/AS	11.6	P Cyg
0120	+	(–)	–	JM/AS	10.5	V832 Cyg
7050	+	+	(–)	AS/AS	1.1	EW Lac
8393	+	(–)	0	AS/AS	1.0	–



3. Relative energy distributions for four of the cooler Be s of Table 4. Older observations are shown by circles and a l line; newer observations by triangles and a dashed line. The ervers are the same as indicated in Table 4. The vertical scale).2 magnitude per mark. The abscissas are the effective elengths of the 13-C filters.

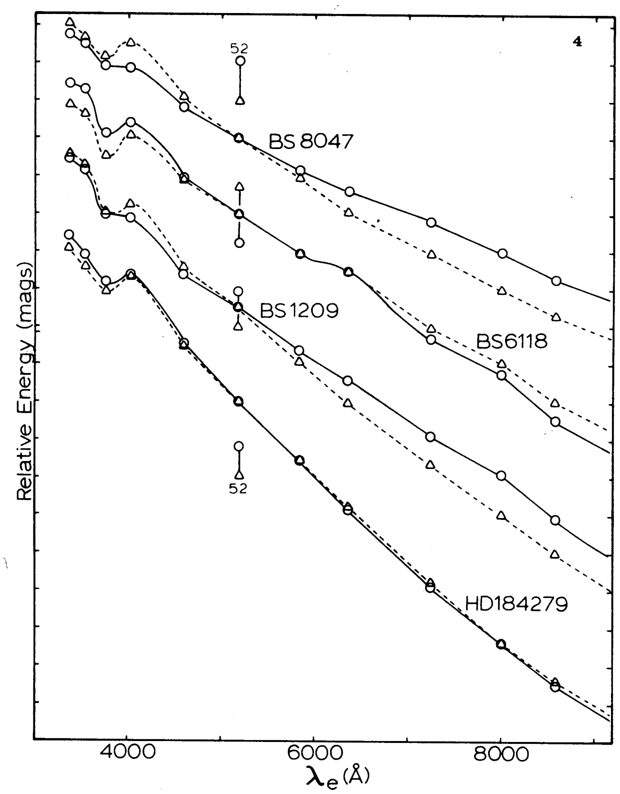


Fig. 4. Relative energy distributions for hotter Be stars. Same symbol meanings as Figure 3. The vertical scale is 0.2 magnitude per mark, except for BS 8047 for which is 0.4 magnitude per mark.

signs. This correlation between the visible and UV changes is the same one noted by Feinstein (1968, 1970). However, a more general pattern can be derived by analyzing Table 4 and Figures 3 and 4 in detail. The cooler Be stars, with large Balmer jumps, such as in Figure 3, sometimes undergo very large changes in the UV, and these changes have the same sign as the changes in the visible. The hotter Be stars, such as the ones shown in Figure 4, only show small changes in the UV, and these changes have the opposite sign as the changes in the visible. The only exception to this general rule among the stars of Table 4 is HD 184279 (and perhaps HD 218393), which is plotted in Figure 4.

In Figure 2, the hotter variable stars change position very little, while the cooler ones may move significatly along nearly vertical lines. Such large UV variations show that the Be star positions in Figure 2 may be produced by both unusual intrinsic colors as well as interstellar reddening and support the idea that at least some of the UV excesses found by Alvarez and Schuster (1979) are intrinsic to the star and its envelope and are not caused by incorrect reddening corrections.

II. CONCLUSIONS

Of our 86 Be stars, 31 (36%) show definite evidence of variability and 36 (42%) are possibly variable. Variation in the visible magnitudes (*52, 58*) is the most common form of variability; of the 31 definite variables, 25 (81%) are variable in *52* or *58*, and 5 (16%) are possibly variable. Our time base is not yet long enough to make any definite conclusions about periodicity, but a few Be stars do show evidence of irregular of short-period (< 1 month) variations.

Also, variations in the Balmer continuum and in t near infrared (7000 A – 1.0 micron) produce the m common color changes among our 31 variables. ' found photometric excesses in these same wavelengt This supports the idea that the excesses are intrinsic the star and its envelope, and suggests that whate physical processes are important in explaining th excesses, may also be responsible for the variability.

Finally, definite correlations between variations in t visible magnitudes and the UV and IR colors have be found for the 16 Be stars with large photomet changes, and the ΔV versus ΔUV correlation seems depend upon the stellar temperature or the size of t Balmer jump.

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DISCUSSION

Mendoza, E.: ¿Cuáles son las causas de variación en las estrellas Be?
Alvarez: Los objetos tipo Be están formados por una estrella rodeada de una envolvente constituida por material a temperatura elevada y con campos de velocidad que pueden ser perturbados por efectos de la fotósfera. También hay estrellas Be formadas por sistemas dobles en las que hay intercambio de materia.
Ringuelet: Deseo comentar que las variaciones observadas en el UV y en el IR son de distinto carácter. Las primeras son de igual monto a ambos lados de la discontinuidad de Balmer, de manera que ésta permanece invariable. En el rojo e IR la variación (que se verifica en las más luminosas) podría corresponder a modificaciones en el material circunestelar.
Sahade: Una de las estrellas estudiadas y que experimenta grandes variaciones es β Lyrae, la famosa binaria cerrada. ¿Han tratado de ver si esas variaciones son las esperables según la fase del movimiento orbital?
Alvarez: Aún no hemos determinado con suficiente precisión esta variación pero continuaremos observando este objeto.
Niemela: ¿Tiene idea de la escala de tiempos para las variaciones?
Alvarez: Hemos encontrado estrellas que presentan variaciones en magnitud en el intervalo de 3 ó 4 años que ha durado este programa. Hay otras estrellas que tienen períodos menores del orden de un mes. Pensamos que requerimos aún un número mayor de observaciones para determinar sus períodos.

Manuel Alvarez and William J. Schuster: Observatorio Astronómico Nacional, UNAM, Apartado Postal 877, 228 Ensenada, B.C., México.