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ULTRAVIOLET SURVEY FOR HOT COMPANIONS AMONG NONVARIABLE YELLOW SUPERGIANTS

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ABSTRACT

Twenty nonvariable yellow supergiants have been observed for the first time with the *International Ultraviolet Explorer* satellite, with the aim of discovering hot companions. Two newly discovered systems are announced: HD 74395 (G2 I + B9.5 IV–V) and HD 193469 (later than G0 + B8 IV–V). The Cepheid HD 9250 was also observed, but no hot companion was found. Some stars independently known to have a hot companion were included in order to study the properties of the companions and to compare with previous work. Atmospheric models were used to fit the overall energy distribution of the binary system, allowing an estimate of T_e, log g, and the spectral type of the companion. The magnitude differences, in the V band, between the yellow supergiants and their companions were calculated. We explore the possibility of using this magnitude difference and the spectral type determined for the hot companions to estimate M_V for the yellow supergiants and the distance to the systems. Comparison of the binaries' positions in the H-R diagram with theoretical evolutionary tracks suggests that the masses of the primaries are contained between 5 and 9 solar masses and that, on average, they are about twice as massive as their hot companions.

Subject headings: stars: binaries — stars: Cepheids — stars: supergiants — ultraviolet: spectra

I. INTRODUCTION

It has been suggested in the past (Lloyd Evans 1968) that the cause of the small amplitude of some Cepheids could be the presence of a close companion star which, by gravitational interaction, sufficiently alters the evolution of the star entering the instability strip and may reduce the amplitude or even inhibit the pulsation. In support of this theory Lloyd Evans cited a high proportion of small-amplitude stars among Cepheids known or suspected to be spectroscopic binaries.

A statistical study of the duplicity of classical Cepheids has been carried out most recently by Madore and Fernie (1980). Their results indicate that between 15% and 35% of the Cepheids are binaries. There is also some evidence that a number of nonvariable stars lie inside the instability strip (Fernie and Hube 1971; Schmidt 1972; Bidelman 1985). These results raise the immediate question of what percentage of these stars are binaries as well. Some work has already been done to address such a question (Parsons 1981), and the percentage of binaries among the nonvariable F and G supergiants appears to be similar to that among classical Cepheids. Parsons's results show that in a sample of 50 nonvariable F and G supergiants, 34% are doubles and 20% of the total sample have hot secondaries.

With the goals of discovering new nonvariable yellow supergiant binaries, thereby improving the statistics, and then studying the properties (such as temperature, gravity, luminosity, and mass) of each of the components of the binary systems, we have carried out a new survey for hot companions among a group of nonvariable stars that, because of their spectral types, should be sitting inside or near to the Cepheid instability strip. The present paper reports the results of the survey.

II. THE OBSERVATIONS

The observations were made in the ultraviolet spectral region using the *International Ultraviolet Explorer* (*IUE*) satellite, on 1982 June 4 and 1983 February 17, operated from the NASA Goddard tracking station, Greenbelt, Maryland, and on 1982 August 4 from the VILSPA tracking station, Villafranca, Spain.

Table 1 summarizes the observations of the stars in our sample. Only low-dispersion spectra were obtained with both the short-wavelength (SWP) and the long-wavelength (LWR) cameras. All the primary data reductions, such as image correcting and transforming from raw data into usable absolute intensities, were performed by the *IUE* observatory staff. The secondary data reduction, such as dereddening, continuum flux fitting, etc., was performed by the authors (using the *IUE* Regional Data Analysis package available at the University of Toronto) and will be described in § V.

III. THE SAMPLE

A sample of 19 F and G yellow supergiants was selected to be surveyed. The selection criteria were the following: (*a*) the stars had to have been previously monitored photometrically and found to be nonvariable (see col. [5] of Table 1); (*b*) they had to have not been observed with the *IUE* satellite before (*IUE Newsletter*, Nos. 9 and 11); and (*c*) they apparently had to fall inside or near the Cepheid instability strip, as judged

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TABLE 1

YELLOW SUPERGIANTS SURVEYED FOR HOT COMPANIONS

HD (1)	Name (2)	Spectral Type (3)	M_V (4)	Reference (5)	Image Number (6)	Aperture (7)	Exposure Time (min:sec) (8)	Remarks (9)
9250..........	...	G0 Ib	7.19	VAR	LWR 13836	large	15:00	low-amplitude Cepheid
					SWP 17557	large	60:00	
11544..........	...	G2 Ia	6.80	1	LWR 13835	large	5:00	
					SWP 17556	large	25:00	
16901..........	14 Per	G0 Ib	5.40	1	LWR 13834	large	4:00	
					SWP 17555	large	16:00	
26630..........	μ Per	G0 Ib	4.10	1	LWR 15311	large	1:30	hot companion known
					SWP 19278	large	7:00	(Parsons 1981)
31910..........	β Cam	G0 Ib	4.00	1, 2	LWR 15312	large	1:00	visual binary
					SWP 19279	large	5:30	
57118..........	...	F0 Iab–Ib	6.08	3	LWR 13408	large	2:00	
					SWP 17120	large	10:00	
59067..........	...	G8 Ib + B	5.78	3	LWR 13412	both	0:50, 0:50	hot companion known
					SWP 17125	both	0:10, 0:10	(Parsons 1982)
63700..........	ξ Pup	G3 Ib	3.34	VAR ?	LWR 13409	large	0:30	
					SWP 17121	large	13:00	
67594..........	ξ Mon	G2 Ib	4.30	1, 4	LWR 13410	large	1:00	
					SWP 17123	large	7:00	
70761..........	...	F2 Ib	5.89	3	LWR 13407	large	2:00	
					SWP 17119	large	10:00	
74395..........	...	G2 Ib	4.63	3	LWR 13411	large	1:50	hot companion detected
					SWP 17124	large	7:00	and visual binary
					SWP 17126	both	1:00, 1:00	
77912..........	...	G8 Ib–II	4.60	1	LWR 13401	large	2:03	
					SWP 17114	large	0.46	
90772..........	...	F0 Ia	4.76	VAR	LWR 13833	both	3:12, 1:00	
					SWP 17554	both	5:00, 5:00	
90853..........	...	F0 II	3.82	3	LWR 15321	large	0:18	
					SWP 19285	large	1:30	
96436..........	65 Leo	Sg G7	5.55	3	LWR 13402	large	0:29	
96566..........	...	Sg G5	4.60	3	LWR 13406	large	1:00	
					SWP 17118	large	5:00	
112374..........	...	cF6	6.77	VAR	LWR 13405	large	2:00	
					SWP 17117	large	5:00	
					LWR 15317	large	6:00	
					SWP 19282	large	30:00	
133683..........	...	F9 Ib	5.76	3	LWR 13409	large	3:41	
					SWP 17116	large	2.12	
135345..........	...	G5 Ia + B	5.20	3	SWP 19283	both	0:10, 0:10	hot companion known
					SWP 19286	large	0:20	
155603..........	V915 Sco	G5 Ia	6.22	VAR	LWR 15318	large	15:00	
164584..........	7 Sgr	F5 II	5.35	3	LWR 15319	large	7:00	
					SWP 19284	large	10:00	
172052..........	...	F5 Ib	6.70	5	LWR 15320	large	7:00	
180028..........	...	F6 I	6.92	?	LWR 15316	large	15:00	
187299..........	...	G5 Iab–Ib	7.10	1	LWR 15315	large	15:00	
190113..........	...	G5 I	7.89	?	LWR 15314	large	45:00	
193469..........	...	F5 I	6.47	?	LWR 15313	large	5:00	hot companion detected
					SWP 19281	large	35:00	
223047..........	ψ And	G5 Ib + A0 V	5.0	1	LWR 13837	both	3:00, 3:00	hot companion known
					SWP 17558	both	20:00, 16:00	

REFERENCES.—(1) Fernie, J. D., and Hube, J. O., 1971. (2) Percy, J. R., and Welch, D. L., 1981. (3) Arellano Ferro, A., 1981. (4) Stift, M. J., 1979. (5) Fernie, J. D., 1976.

from their previously published spectral types. In order to check the consistency of our work with previous studies, four stars known to have hot companions (HD 26630, HD 59067, HD 135345, and HD 223047) were also observed. One small-amplitude Cepheid (HD 9250) and three small-amplitude, long-period, yellow supergiants (HD 90772, HD 155603, and HD 112374) were also included. In total, 27 stars were observed. The sample stars, ordered in right ascension, and a summary of their observations are given in Table 1.

The exposure times were based on the sensitivity curves of the SWP and LWR cameras, assuming that a companion would be present. A typical exposure time was calculated for a hypothetical companion seen at 1440 Å, assuming it to be a B3 type star and 4 mag fainter than the program star. This seemed a reasonable assumption considering earlier discoveries, e.g., HR 4511 (F5–G0 Ia + B1) (Parsons 1981) and HR 8752 (G5 0–I + B1 V) (Strickland and Harmer 1978). The star η UMa and its flux at 1440 Å (Code and Meade 1979) were used as the

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TABLE 2

YELLOW SUPERGIANTS WITH HOT COMPANIONS IN THE PRESENT STUDY

		Yellow Supergiant				Hot Companion				
HD	$E(B-V)$	Spectral Type Literature	T_e	log g	Spectral Type Predicted	T_e	log g	Spectral Type Predicted	ΔV (hot-SG)	Remarks
26630..........	0.15	G0 Ib	5500 ± 500	2.0 ± 0.5	G0–GI	10500 ± 500	4.0 ± 0.5	B9–B9.5	3.5 ± 0.2	spectroscopic binary
59067..........	0.15	G8 Ib	5500 ± 500	2.0 ± 0.5	G0–GI	22500 ± 1500	4.5 ± 0.5	B1–B2	1.4 ± 0.2	previously studied binary (Parsons 1982)
74395..........	0.06	G2 Ib	<5500	...	Later than G1	10000 ± 500	4.0 ± 0.5	B9.5	3.2 ± 0.2	newly discovered companion
135345..........	0.30	G5 Ia	6500 ± 500	1.0 ± 0.5	F7	18000 ± 1000	4.0 ± 0.5	B3	1.3 ± 0.2	spectroscopic binary
193469..........	0.26	F5 I	<5500	...	Later than G0	12000 ± 1000	4.0 ± 0.5	B8	5.4 ± 0.2	newly discovered companion
223047..........	0.10	G5 Ib	<5500	...	Later than G1	11000 ± 1000	4.5 ± 0.5	B9	4.6 ± 0.2	spectroscopic binary (Levato 1975)

reference for computing the exposures. Of course, cooler but brighter companions would also be detected. The given exposure times did not always produce a well-exposed spectrum for one of many reasons: (*a*) no hot companion was present; (*b*) the companion was cooler and/or fainter than predicted; (*c*) reddening uncertainties from star to star produced errors in the computed exposure times. The given exposure times are also included in Table 1.

Two new systems, HD 74395 (G2 I + B9.5 IV–V) and HD 193469 (later than G0 + B8 IV–V), were found to have an ultraviolet excess, interpreted as being due to the presence of a hot companion. These and the previously known systems are listed in Table 2 and are discussed further in the following sections.

IV. THE ANALYSIS

a) *Continuum Flux Fitting*

The ultraviolet spectra of the stars with hot companions were reduced in the following manner. First, the original data numbers of the SWP and the LWR images were converted into net fluxes, and the two images were merged at 1975 Å. The full spectrum was then dereddened using an average ultraviolet extinction law (Savage and Mathis 1979). The adopted color excesses were taken from the literature and are listed in Table 2. The dereddened fluxes were averaged in 50 Å bins separated by 100 Å, and were converted into magnitudes on a scale such that $m(\lambda) = 0.0$ mag for a flux of 3.64×10^{-9} ergs s^{-1} cm^{-2} $Å^{-1}$ (Parsons 1981). The ultraviolet magnitudes were combined with *UBVRIJKL* ground-based photometry available in the literature. The latter were dereddened and converted to the same ultraviolet flux-magnitude system, using the absolute flux calibration of Johnson (1966) and the reddening laws of Johnson (1965).

The energy distribution, plotted as the logarithm of the wavelength versus apparent magnitude for the six stars with hot companions in this study, is shown in Figures 1 to 6. The temperature and gravity for each of the components were estimated by fitting the atmospheric models of Kurucz (1979) to

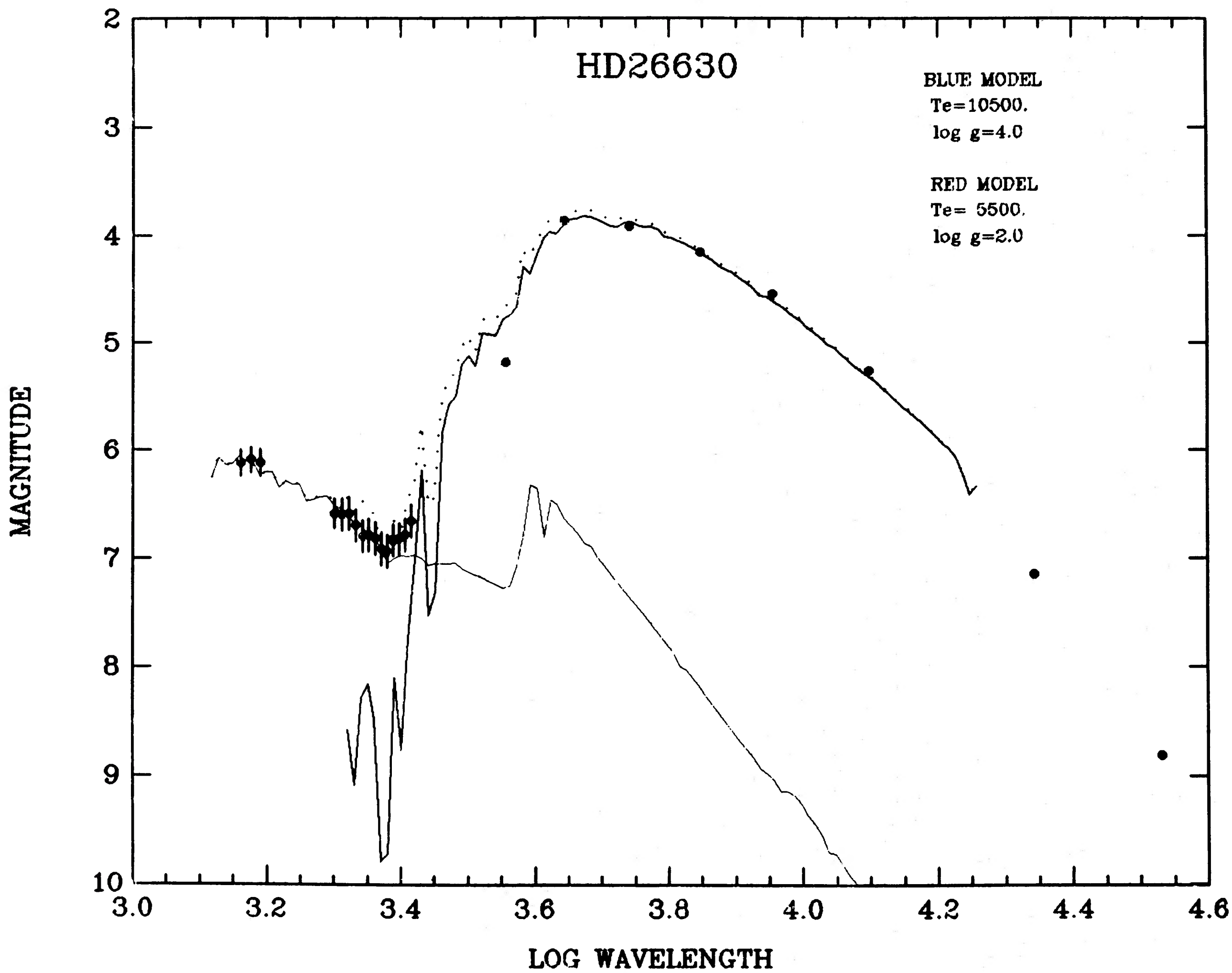

FIG. 1.—Energy distribution of the star HD 26630 and its hot companion in the log λ apparent magnitude plane. Dots in the ultraviolet region (log $\lambda < 3.5$) are the averaged fluxes converted to magnitudes as described in § IV*a*. The error bars are the standard error of the mean. Dots for log $\lambda > 3.5$ are ground-based magnitudes converted to the same magnitude scale as the ultraviolet observations. The continuous curves are individual atmospheric models (Kurucz 1979) which best fit the observations. The dotted curve is the convolution of the blue and red models.

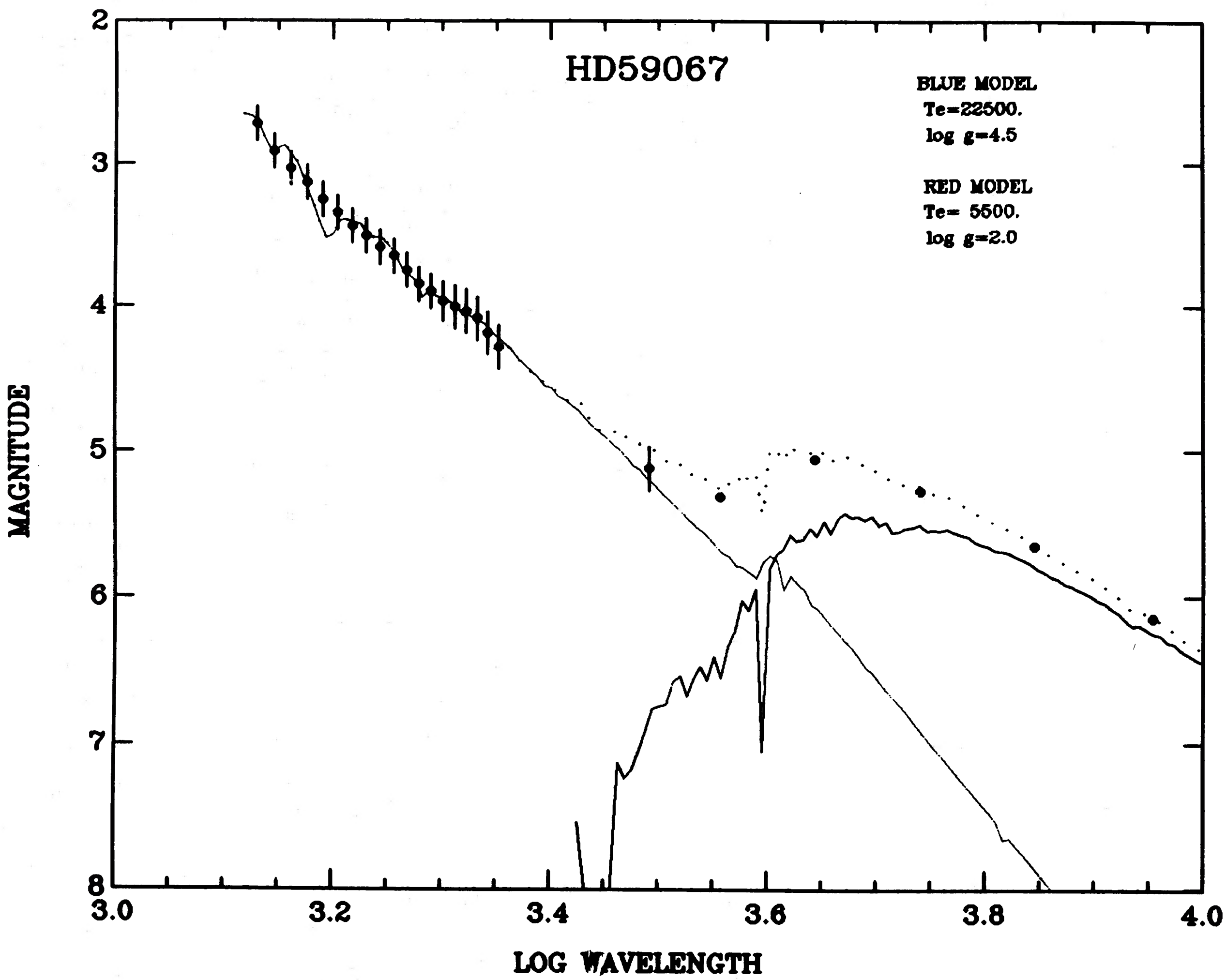

FIG. 2.—Same as Fig. 1 for the star HD 59067

the observed magnitudes. For stars cooler than 5500 K there is no atmospheric model in Kurucz's work, and accordingly the temperature was not estimated. The results are listed in Table 2, where the quoted uncertainties were determined by trial and error for different models. In what follows the predicted spectral types are derived from the adopted temperature by using the calibration of Schmidt-Kaler (1982).

b) *Newly Discovered Systems*

Hot components to the nonvariable yellow supergiants HD 74395 and HD 193469 were discovered. The temperatures, gravities, and spectral types suggested by the composite energy distribution of the binaries (Figs. 3 and 5) are listed in Table 2. The companions are, in all cases, B type stars on or very near to the main sequence. For the star HD 74395, the temperature found for the yellow primary and hence the deduced spectral type, is in good agreement with the MK spectral type found in the literature. The temperature and gravity found for the companions are $T_e = 10{,}000 \pm 500$ K, log $g = 1.0 \pm 0.5$, from which a spectral type of B9.5 IV–V is derived. For the star HD 193469 its energy distribution (Fig. 5) indicates $T_e < 5500$ K and accordingly a spectral type later than G0, in clear disagreement with its F5 I spectral type found in the literature. For the hot companion we found $T_e = 12{,}000 \pm 1000$ K and log $g = 1.0 \pm 0.5$ and then a spectral type of B8 IV–V.

c) *Four Spectroscopic Binaries*

The four spectroscopic binaries HD 26630, HD 59067, HD 135345, and HD 223047 were included in the sample to provide a consistency check with previous studies. HD 59067 and its companion were studied by Parsons (1982). For HD 26630 the temperature of the yellow primary is in good agreement with its MK type. The temperature and gravity for the comparison are $T_e = 10{,}500$ K; log $g = 4.0 \pm 0.5$ (Fig. 1). For the hot companion we find $T_e = 22{,}500 \pm 1500$ K and log $g = 4.5 \pm 0.5$ and then a spectral type of B1–B2 IV–V, in agreement with Parsons's classification of B2 IV or V. The primary star has been classified as G8 Ib, but its energy distribution of Figure 2 suggests $T_e = 5500 \pm 500$ K and then a spectral of G0–G1. This disagreement was already noted by Parsons, who also finds that the color of this star is more consistent with that of a G1–G3 supergiant.

The star HD 135345 can be found in the literature as G5 Ia + B. We find for the companion $T_e = 18{,}000 \pm 1000$ K and log $g = 4.0 \pm 0.5$ and a spectral type of B8 IV–V. There is,

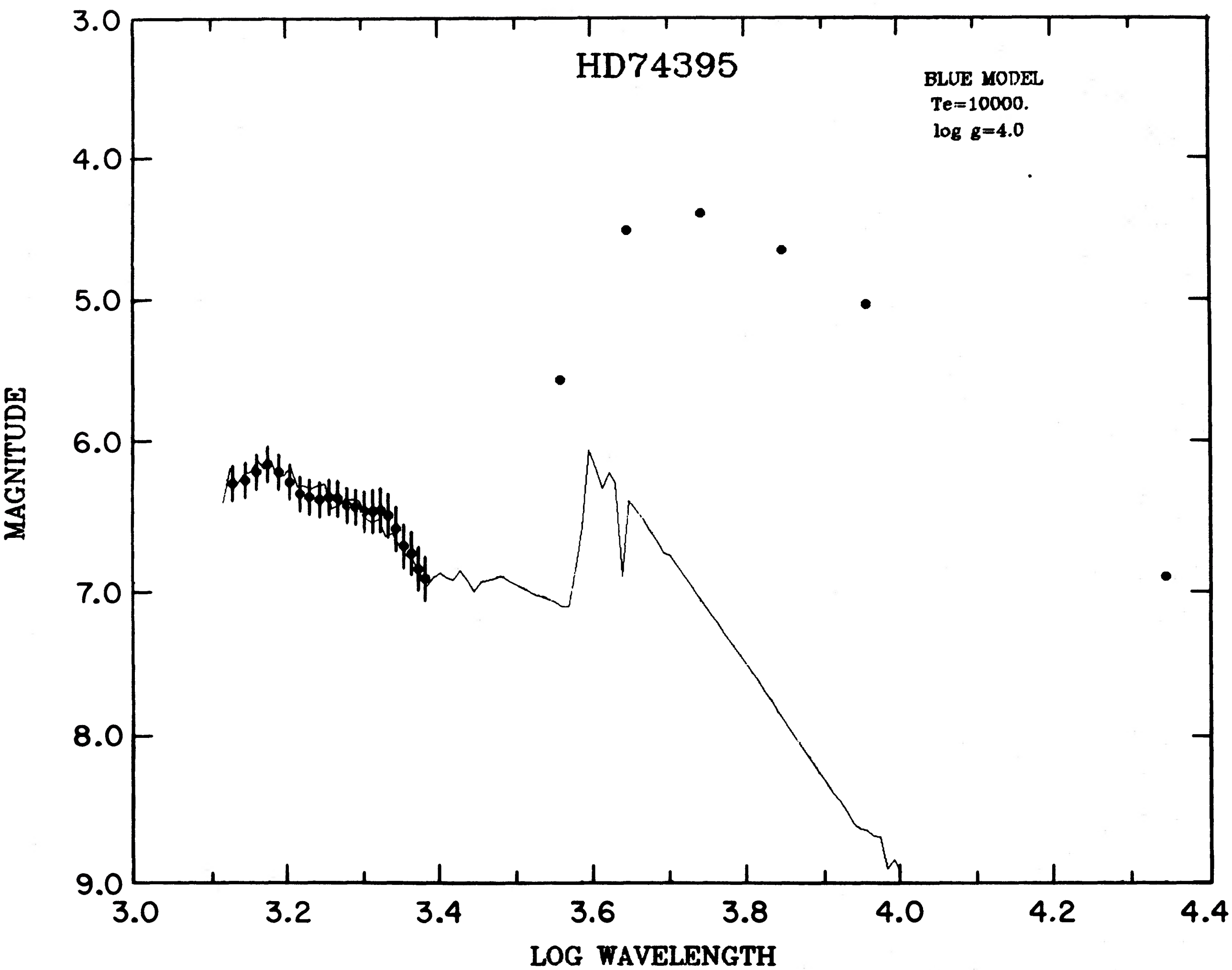

FIG. 3.—Same as Fig. 1 for the star HD 74395. The yellow star is cooler than 5500 K, and no red model was fitted

TABLE 3

LUMINOSITIES OF YELLOW SUPERGIANTS WITH HOT COMPANIONS

HD	Spectral Type of Hot Companion	M_V Hot Companion	ΔV (hot-SG)	M_V Supergiant	D (pc)
26630..........	B9–B9.5	1.0 ±0.3	3.5 ±0.2	−2.5 ±0.4	170 ±31
59067..........	B1–B2	−2.3 ±0.6	1.4 ±0.2	−3.7 ±0.6	640 ±179
74395..........	B9.5	1.0 ±0.4	3.2 ±0.2	−2.2 ±0.4	295 ±54
135345..........	B3	−1.1 ±0.4	1.3 ±0.2	−2.4 ±0.4	219 ±40
193469..........	B8	0.3 ±0.3	5.4 ±0.2	−5.1 ±0.4	1439 ±266
223047..........	B9	0.8 ±0.4	4.6 ±0.2	−3.8 ±0.4	501 ±92

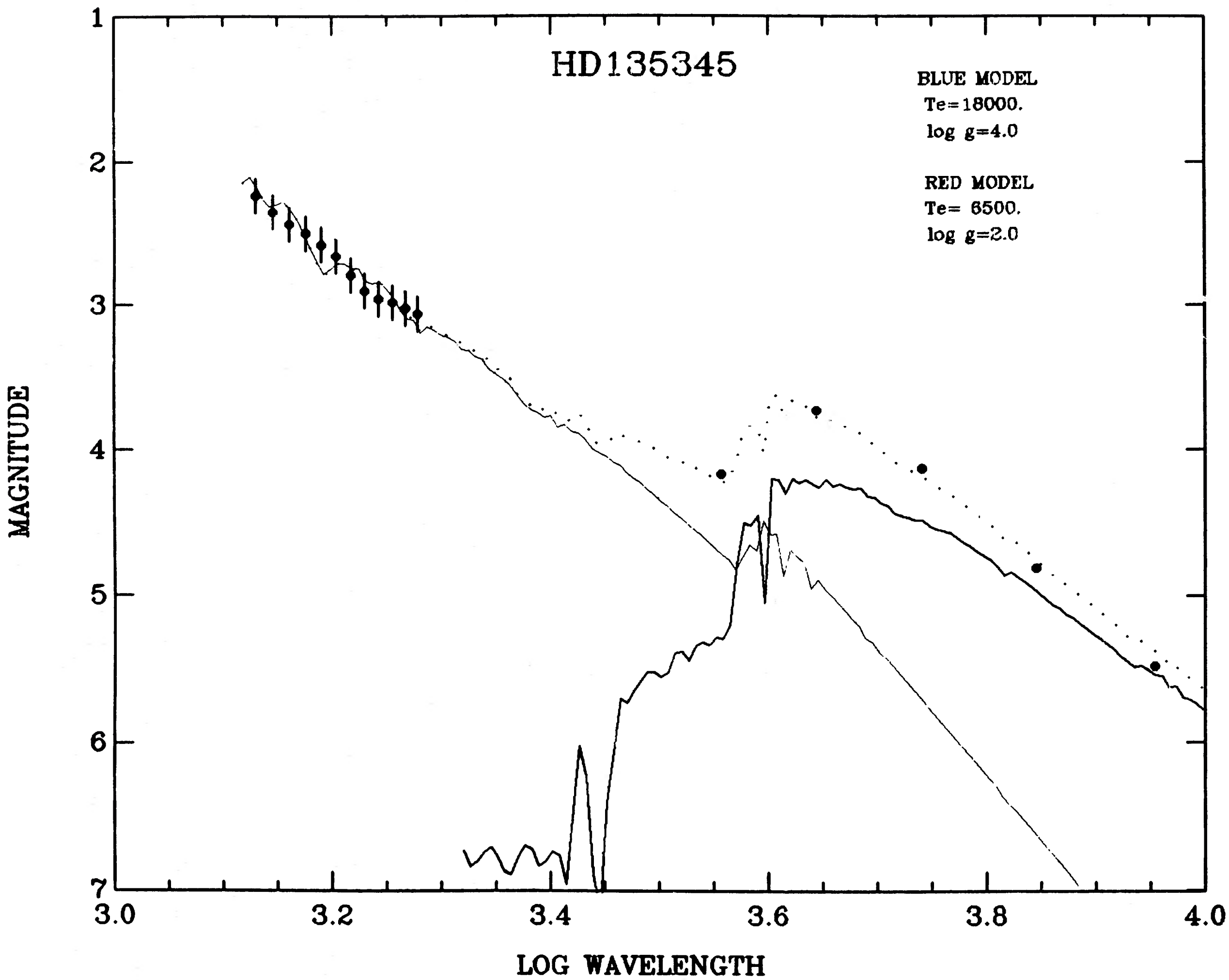

FIG. 4.—Same as Fig. 1 for the star HD 135345

again, a large disagreement between the spectral type of the primary from its energy distribution (Fig. 4 which indicates $T_e = 6500 \pm 500$ K, or a spectral type of $\sim$F7) and the G5 spectral type from the literature.

The star HD 223047 appears in the literature as G5 Ib + A0 V (Levato 1975). Its energy distribution (Fig. 6) suggests $T_e = 10{,}000 \pm 1000$ K and log $g = 4.5 \pm 0.5$ and then a type of B9 IV–V for the companion; for the primary $T_e < 5500$ K and a spectral type later than G1, in good agreement with the previous classification.

V. DISCUSSION

Knowing the absolute magnitudes for luminous stars, such as yellow supergiants, is important in the context of the calibration of cosmic distance indicators. In this section we explore the possibility of profiting from the duplicity of some yellow supergiants to find their absolute magnitudes.

Given the spectral type of the hot companion (Table 2), the main-sequence spectral-type calibration of Garrison (1978) was used to find M_v(hot). The absolute magnitude of the yellow supergiant, M_v(sg), and the distance modulus of the system then follow from M_v(hot) and the visual magnitude difference ΔV between the red and the blue models of Figures 1–6. The results are shown in Table 3. The uncertainties in M_v(hot) were estimated considering the width of the main sequence in Garrison's calibration and allowing for some evolution of the companion and then were increased by a factor of 2 to allow for some plausible intrinsic spread of the main sequence due to evolution. These errors propagate directly into the determination of M_v(sg). One additional source of uncertainty is that the ultraviolet interstellar extinction law may be dependent on the direction in the sky. If this is so, the extinction law may be different for each star; however, we used an average extinction law (Savage and Mathis 1979) to correct the ultraviolet observations. No further effort was put into accounting for this uncertainty since the extinction law for each direction is not well known at this time. Nevertheless, since our stars are relatively near and are only moderately reddened, this uncertainty should not be large.

The stars HD 26630 and HD 223047, in Table 3, are in

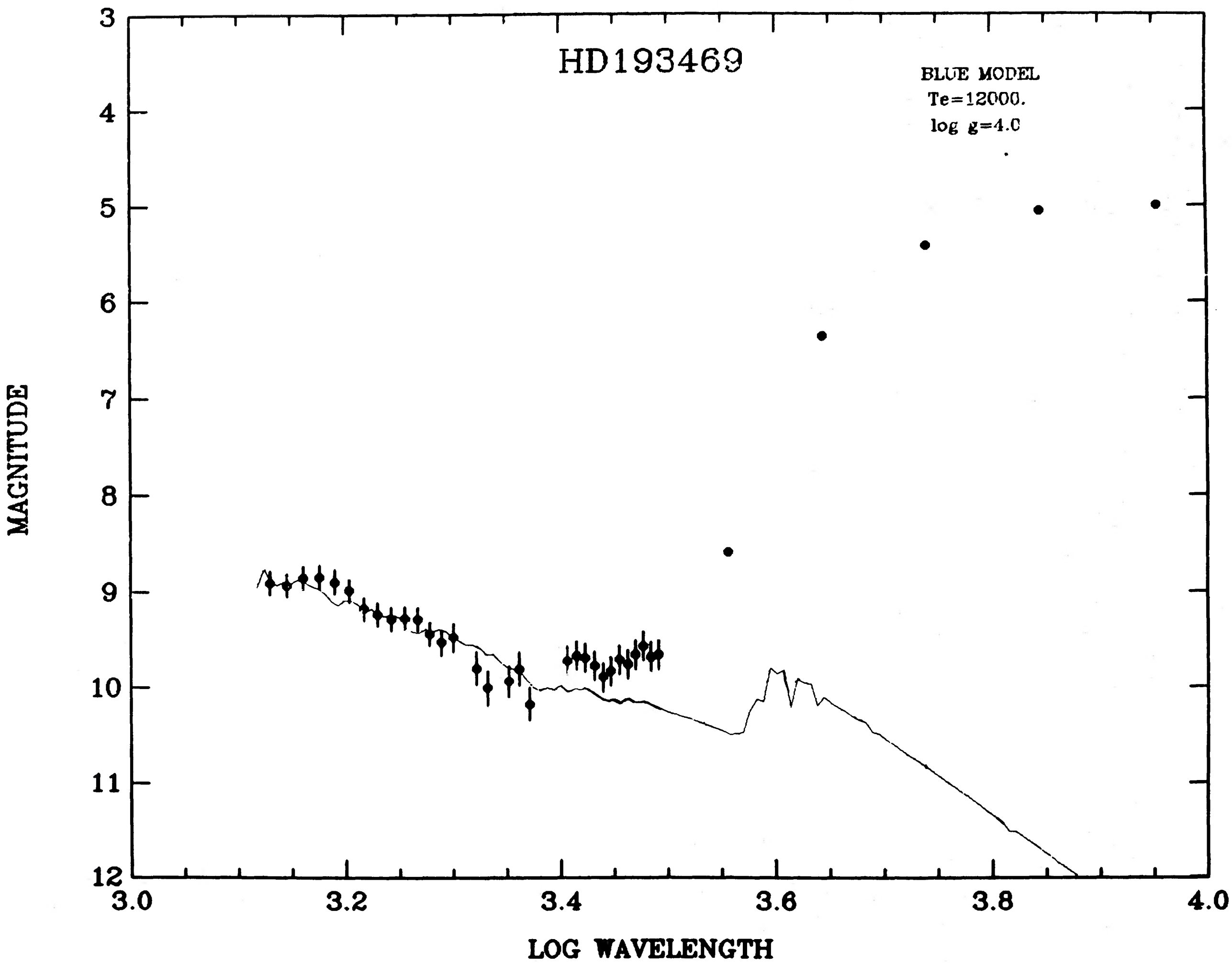

FIG. 5.—Same as Fig. 1 for the star HD 193469. The yellow star is cooler than 5500 K, and no red model was fitted

common with the nonvariable yellow supergiants studied by Schmidt, Rosendhal, and Jewsbury (1974). Unfortunately, there is poor agreement between their absolute magnitudes (determined spectroscopically) and ours, in the sense that their magnitudes are 2.6 and 1.3 mag brighter, respectively. However, if the presence of the companion is not accounted for, the spectroscopic magnitude determination may be biased.

In Figure 7, the six binaries of this study are plotted on the H-R diagram. The star HD 135345 and possibly HD 59067 may be inside the Cepheid instability strip despite their constancy in luminosity. The evolutionary tracks of Iben (1967) are included for comparison. The masses of the primaries seem to be contained between 5 and 9 solar masses, and, on the average, the yellow supergiants seem about twice as massive as their hot companions. The displacement of the hot companions relative to the main sequence of Iben (1967) is due to the known shift between Iben's theoretical main sequence and Garrison's (1978) observational main sequence.

Of 23 nonvariable yellow supergiants searched, 26% $\pm$ 10% are spectroscopic binaries. Although the sample is not complete, this number is certainly consistent with the 34% obtained from the analysis of a larger sample studied by Parsons (1981) and the 31%–38% found by Burki and Mayor (1983). Similar results have been found for the frequency of binaries among classical Cepheids, which is between 15% and 35% (Madore and Fernie 1980; Burki, 1983). These results do not support the idea that nonvariables which may be inside or near the instability strip are preferentially in binary systems, as compared to classical Cepheids. If the presence of the companion is still thought to be responsible for inhibiting the variability, then details of the relative types of orbits for the companions must now be investigated.

We are thankful to the staff members of the Goddard-Greenbelt and Villafranca tracking stations for their professional assistance in the acquisition and preliminary reduction of our observations and for their friendly hospitality. This work was supported by Consejo Nacional de Ciencia y Technologia (Mexico) and by the Natural Sciences and Engineering Research Council of Canada.

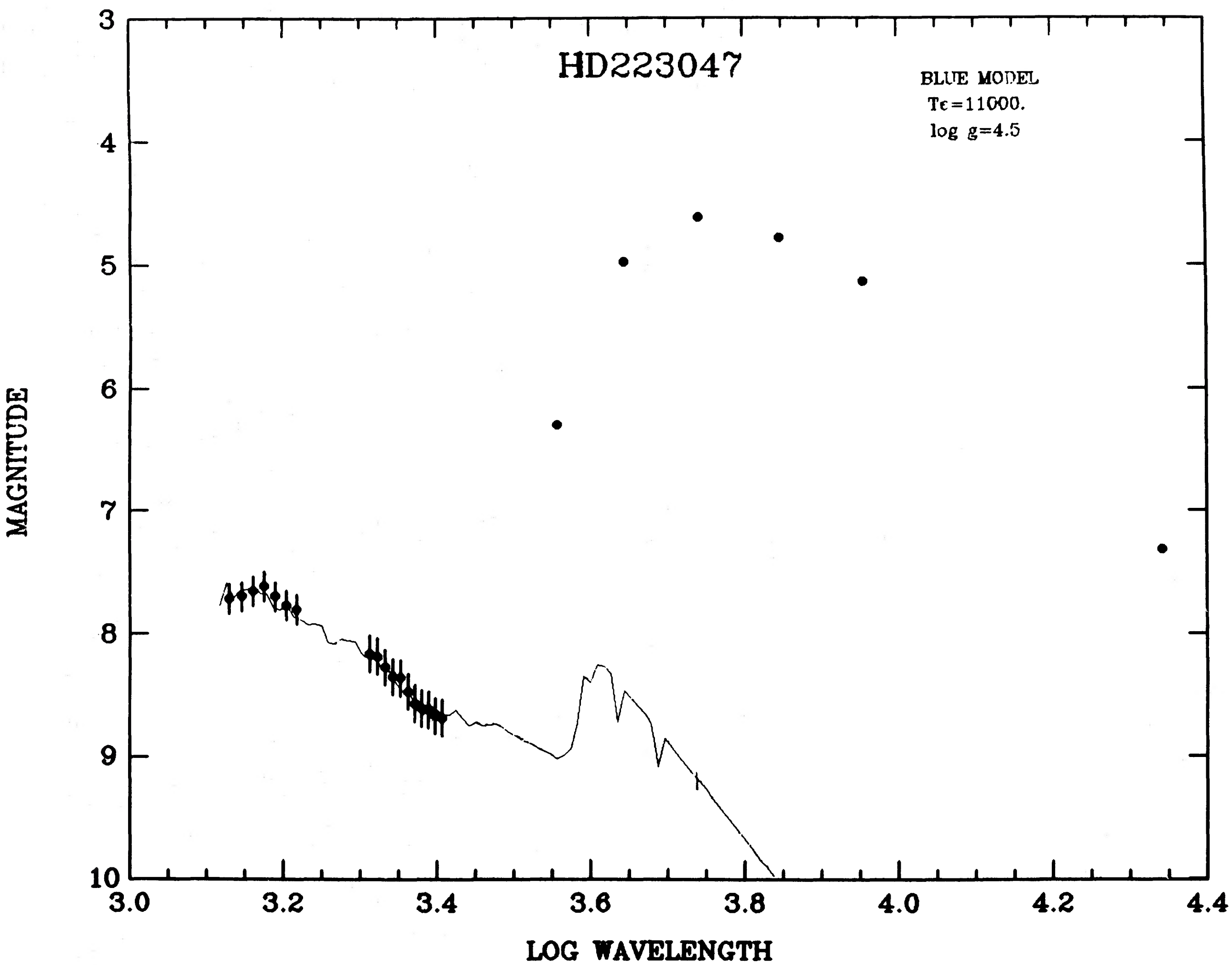

FIG. 6.—Same as Fig. 1 for the star HD 223017. The yellow star is cooler than 5500 K, and no red model was fitted.

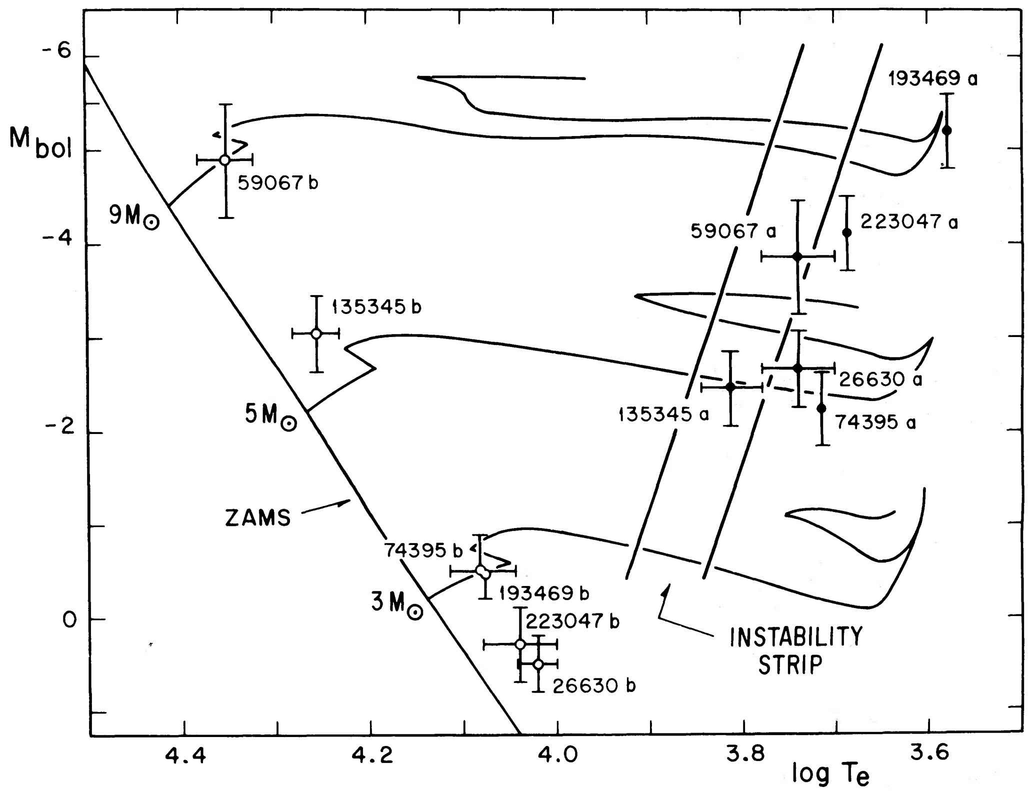

FIG. 7.—Position of the six binary yellow supergiants (*filled circles*) of this study and their companions (*open circles*) on the H-R diagram. The stars HD 59067 and HD 135345 lie inside the Cepheid instability strip despite their constancy. Due to the lack of atmospheric model cooler than 5500 K and to the inconsistency found between its energy dsitribution and its MK spectral type, the star HD 193469 is plotted according to its color. Error bars correspond to the uncertainties quoted in Table 2. The evolutionary tracks are from Iben (1967) and show that the masses of the yellow supergiants are between 5 and 9 solar masses and that, on average, the yellow supergiants are about twice as massive as their hot companions.

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Note added in proof.—While this paper was in press Dr. G. Burki pointed out to us that the star HD 74395 is a visual binary. The separation between HD 74395 and its visual companion is 79″ [H. M. Jeffers, W. H. van den Bos, F. M. Greeby, *Pub. Lick Obs.*, **22**, 310, (1963)]; however, the *IUE* aperture used is 10″ × 20″ (i.e., the visual companion was not included) and this then must be a triple system. Dr. Burki also informs us of the spectroscopic binary nature of HD 70761, HD 187299, and HD 190113 in Table 1. Indeed HD 187299 is a spectrscopic binary whose companion is suspected of being a main-sequence star earlier than B3, and 2.5 mag fainter than the primary [R. F. Griffin and G. A. Radford, *Observatory*, **97**, 169 (1977)]. However, we failed to detect a hot companion in a 15 min exposure; hence the companion may be cooler and/or fainter.

The inclusion of these stars brings the percentage of spectroscopic binaries among the nonvariable stars in our sample to 39 ± 10%.

This result is still in good agreement with the results of S. B. Parsons [*Ap. J.*, **245**, 201 (1981)] and does not change our general discussion in § V.

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