THE ASTROPHYSICAL JOURNAL, 279:237–251; 1984 April 1.

THE BLUE STRAGGLERS OF M67[1]

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Received 1983 May 16; accepted 1983 September 2

ABSTRACT

We report infrared photometry and echelle spectroscopy for the five bluest stragglers in the old open cluster M67. The photometry indicates the presence of a post–main-sequence companion for two stars, F190 and F280. The former star is also found to have radial-velocity variations with an amplitude of 30 km s^{-1} or more. The average velocities determined from our data for F156 and F280 depart by 5–7 km s^{-1} from the cluster mean, which is more than twice the 1 sigma uncertainty in each determination. Our rotational velocity values range from less than 10 to 120 km s^{-1}, somewhat lower than average for stars of this temperature in other, necessarily younger, open clusters.

In our view these results strongly support the idea that blue stragglers have their origins in mass transfer from an evolved companion. We suggest that orbits may be eccentric, which would diminish somewhat the amplitude of velocity variations and substantially increase the length of the expected periods, thus making detection difficult. Also, postulating that moderately wide pairs rather than close binaries are the straggler progenitors helps to explain the distribution of blue stragglers among clusters.

Subject headings: clusters: open — stars: binaries

I. INTRODUCTION

A significant by-product of the theoretical understanding of the principal phases of stellar evolution, and their relation to the Hertzsprung-Russell diagram, has been the determination of cluster ages by comparisons of the luminosity and/or temperature of a cluster's main-sequence turnoff with stellar evolution calculations. In most old open clusters and in an occasional globular cluster, however, a few stars lying on or near the main sequence are hotter and brighter than the turnoff. These "blue stragglers" thus pose a direct contradiction to the classical evolutionary models.

Several proposed explanations of their presence have been reviewed by Wheeler (1979*a*, *b*) and Trimble (1980). Since the stars appear to lie on the main sequence (Breger 1982) and have the appropriate masses (e.g., Strom, Strom, and Bregman 1971), they are probably not post–main-sequence stars in a phase analogous to the horizontal branch of globular clusters, as espoused by Sargent (1968). Unfortunately, it is difficult to obtain explicit confirmation of the recent star formation hypothesis championed by Hintzen, Scott, and Whelan (1974), but we feel that the ubiquity of blue stragglers in old open clusters tends to rule it out. Mass transfer from an evolved companion (McCrea 1964) remains a controversial hypothesis. Strom and Strom (1970) reported indirect evidence for velocity variations in NGC 7789, from a large scatter in velocity determinations, but subsequent studies such as those of Hintzen, Scott, and Whelan (1974) and Hrivnak and Stryker (1982) find few unarguable cases of velocity variations. Also, McNamara (1980), Breger and Wheeler (1980), and Breger (1982) have argued that the brightest blue stragglers in NGC 7789 may have masses slightly exceeding the mass-transfer limit of twice that of the cluster turnoff stars; Wheeler (1979*b*) has made the same point concerning F81 in M67. Membership is a crucial issue in both cases. A novel suggestion, by Wheeler (1979*a*, *b*) and Saio and Wheeler (1980), is that main-sequence lifetimes may be prolonged, perhaps by internal mixing.

The purpose of our work is to explore observationally, in the five bluest stragglers in the old open cluster M67, the empirical basis for the mass-transfer hypothesis, which demands specifically that a straggler have a companion in a post–main-sequence evolutionary phase. Some evidence for its current presence should remain, for the compact core characteristic of post–main-sequence phases makes it extremely difficult to accomplish total transfer, disruption, or coalescence. To this end we have obtained new photometry and high-resolution spectroscopy, to search for anomalous colors and the presence of radial-velocity variations. At the same time we have determined rotational velocities from the spectra, to check for abnormally high values which might argue for a prolonged main-sequence lifetime, if this is triggered by mixing that arises from meridional circulation.

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In a previous investigation (Carney and Peterson 1981), we obtained such data for a pair of metal-poor blue stragglers of the field halo population. We found both stars to be radial-velocity variables. As pointed out by Bond and MacConnell (1971), this strongly supports the binary hypothesis for the origin of blue stragglers, since the halo population is generally deficient in binaries (though perhaps not as severely as previously believed, according to Harris and McClure 1983 and Carney 1983). Rotational velocities were found to be $v \sin i = 9$ and 31 km s^{-1}, higher than in metal-poor dwarfs generally but typical for Population I stars of the same temperature. Because all field straggler candidates were required to have a $B-V$ color bluer than the main-sequence turnoff of globular clusters, it is not too surprising that the field stragglers' photometric indices were not unusual. However, the normal blue-infrared colors demand that the companion be at least 3 mag fainter.

Except for the question of the membership of F81, which we cannot resolve, our new data on M67 also provide strong evidence for the binary hypothesis. Our photometry indicates the presence of companions in two cases, as discussed in § II. Spectral observations, rotational velocities, and line strengths are taken up in § III. Radial velocities are determined from Fourier cross-correlation analysis in § IV, where peak-to-peak variations of 30 km s^{-1} are noted in one case. Following a summary in § V of the evidence for binaries among the M67 stragglers, we discuss in § VI related issues concerning binary frequencies and mass-transfer orbits. In § VII the case is made that wide pairs, rather than very close ones, may be the most common progenitors of blue stragglers, which consequently should be formed in globular clusters only where low-density environments are present. The paper concludes with a summary of the results and a discussion of the main hypothesis and its ramifications for future work.

II. PHOTOMETRY

One of the major uses of photometry which spans a long baseline in wavelength is the detection of binary companions, as discussed in detail by Carney (1982, 1983) with respect to the Hyades and field halo dwarfs. In the case of a single cluster of homogenous composition, it makes little difference which blue color is chosen for comparison with an infrared color, since the only quantity varying from one main-sequence star to the next is the temperature. Here we will be comparing several clusters, however, and colors insensitive to composition changes should be selected. As described by Carney (1983), $V-K$ satisfies this condition extremely well. For hot stars, $b-y$ does also. When changes in metallicity amount to an order of magnitude (1.0 dex), the synthetic colors of Kurucz (1979, 1980) show that $b-y$ changes by less than 0.004 mag for effective temperature $T_{\rm eff} > 7000$ K at a fixed gravity.

Therefore, *JHK* photometry of the five bluest M67 stragglers was obtained in 1982 January with an InSb system ("Hermann") attached to the 1.3 m telescope of Kitt Peak National Observatory. A 20″ diaphragm was used with a variable throw, usually 60″ but modified occasionally to avoid beam contamination. Standard beam-switching practices were followed, and integration was continued in each filter until repeatability errors declined to less than 1%. Standard stars were taken from the list of Frogel *et al.* (1978), so that the data are on the "CIT" system.

TABLE 1

PHOTOMETRY

Star	V	$b-y$	J	H	K	No.
M67:						
F81	10.03	−0.011	10.23	10.22	10.26	2
F153	11.31	+0.060	11.09	11.06	11.00	1
F156	10.99	+0.056	10.79	10.74	10.75	2
F190	10.98	+0.145	10.42	10.33	10.29	1
F280	10.70	+0.048	10.45	10.39	10.38	2
Pleiades:						
158	8.23	+0.151	7.71	7.62	7.58	1
232	8.06	+0.117	7.67	7.60	7.56	1
541	5.65	−0.022	5.78	5.81	5.84	1
652	8.04	+0.132	7.56	7.47	7.45	1
869	6.43	+0.001	6.45	6.45	6.47	1
1284	8.37	+0.189	7.81	7.66	7.64	1
1362	8.25	+0.153	7.77	7.68	7.65	1
1380	6.99	+0.014	6.94	6.92	6.92	1
1397	7.26	+0.047	6.96	6.88	6.86	2
1993	8.37	+0.177	7.82	7.68	7.63	1
2195	8.12	+0.131	7.72	7.61	7.58	1
2220	7.52	+0.056	7.33	7.30	7.29	1
2263	6.60	−0.010	6.65	6.66	6.67	1
2289	7.97	+0.093	7.62	7.56	7.56	1
2415	8.10	+0.116	7.74	7.67	7.64	2
2425	6.17	−0.012	6.23	6.24	6.27	1
2488	7.54	+0.033	7.43	7.40	7.39	1

Data for the Hyades dwarfs were obtained during the same and previous observing runs with the same equipment (Carney 1982). However, to compare the colors of the unusual blue stragglers with normal main-sequence stars, it was necessary to extend blueward the Hyades main-sequence observations using a younger cluster. Seventeen stars in the Pleiades cluster were observed.

The new data are given in Table 1. Several stars were observed twice, as noted in the last column. Carney (1982, 1983) has established errors per measure, in *JHK*, respectively, to be ±0.017, ±0.014, and ±0.011, for these observing runs.

Previously determined V magnitudes and $b-y$ colors are included with the *JHK* photometry in Table 1. Such data for the Hyades members were discussed by Carney (1983). For the Pleiades, we have taken V magnitudes from Johnson and Mitchell (1958), and $b-y$ colors from Crawford and Perry (1976) and McNamara (1976), as summarized by Hauck and Mermilliod (1979). We chose $E(b-y) = 0.040$ and $E(V-K) = 0.150$ mag, following Johnson and Sandage (1955), Mendoza V. (1967), and Crawford and Perry (1976). V magnitudes for M67 were taken from Eggen and Sandage (1964), and $b-y$ data from Bond and Perry (1971) and Strom, Strom, and Bregman (1971), as summarized by Hauck and Mermilliod (1979), plus Eggen (1981). For the controversial reddening of M67 (Taylor 1983), we have adopted $E(b-y) = 0.037$ mag and $E(V-K) = 0.135$ mag.

In Figure 1 we have plotted $(b-y)_0$ versus $(V-K)_0$ colors for the stars of Table 1 and the hotter Hyades stars of Carney (1982). Little meaningful comparison can be made for M67 F81, because it is significantly hotter than any other star. Of the four remaining M67 blue stragglers, two, F190 and F280, are displaced from the mean relation by more than 3 sigma.

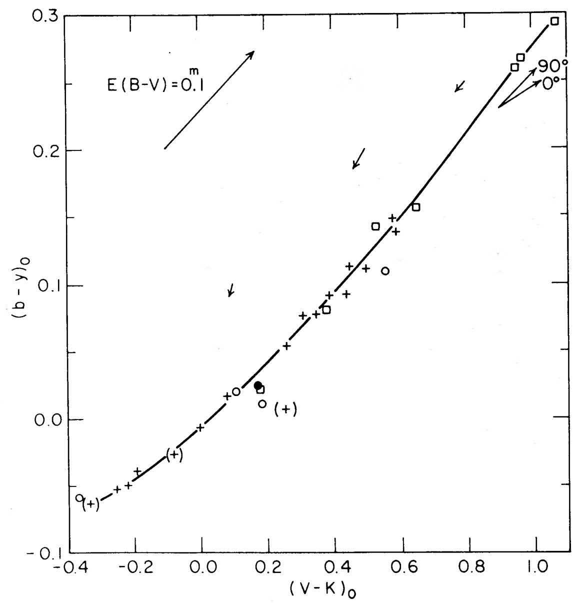


FIG. 1.—A color-color diagram for the M67 stars (○) and Pleiades stars (+) of Table 1, along with the hotter Hyades stars (□) of Carney (1982). Symbols in parentheses represent systems known to be multiple. The reddening vector is indicated by the long arrow; gravity vectors are indicated by the three short arrows; and rotation vectors, by the arrows labeled 0° and 90° Note that these displacements move stars only along the sequence and thus cannot explain the perpendicular displacement of two of the M67 stars, F190 and F280.

What effect might cause such a displacement? As discussed by Carney (1983), reddening is not the answer. This is illustrated in Figure 1 by the reddening vector for $E(B-V) = 0.1$, twice that adopted for M67 and the Pleiades. Gravity also affects colors, but according to the model surface fluxes of Kurucz (1979, 1980), the displacement is mainly along the mean relation. The short arrows in Figure 1 illustrate the changes expected for a change of 0.5 in log g, an amount greater than indicated by the Strömgren photometry of Strom, Strom, and Bregman (1971) and of Eggen (1981).

Rotation may also distort colors, particularly when aspect ratios vary. In Figure 1 we show the effect, at inclinations $i = 0°$ and 90°, of an F2 star with equatorial rotation velocities 20% and 50% that of the break-up velocity, as computed by Collins and Sonneborn (1977). Although rapidly rotating stars will be generally displaced to cooler temperatures in a color-magnitude diagram, the displacements in the color-color diagram of Figure 1 are generally along the mean relation.

The best remaining explanation for the deviant stars is that they are binaries. Colors and magnitudes dictate that the system cannot include a giant or a white dwarf, but that the companion must reside somewhere in the subgiant domain. Numerical experiments with the Pleiades and Hyades main-sequence stars indicate that for the hot stars under consideration, main-sequence companions will not displace a double from the mean color-color relation of Figure 1, but rather along it. This is illustrated by two of the Pleiades binaries (Abt *et al.* 1965; Pearce and Hill 1974). Only a redder star, one above the main sequence, can cause

TABLE 2

ECHELLE OBSERVATIONS

Star	UT Date	Telescope	Disk No.	Exposure (min)	Region
			M67		
F81	1979 Dec 7	1.5 m	355-26	30	Mg *b*
	1979 Dec 8	1.5 m	356-14	40	N I
	1980 Apr 5	1.5 m	463-29	40	O I
	1983 Jan 12	MMT	605-3	8	Mg *b*
F153	1979 Dec 7	1.5 m	355-27	30	Mg *b*
	1979 Dec 8	1.5 m	356-15	60	N I
	1980 Apr 5	1.5 m	463-30	60	O I
	1982 Apr 8	1.5 m	1276-5	10	Mg *b*
	1982 Apr 8	1.5 m	1276-8	30	Mg *b*
	1983 Jan 12	MMT	605-5	5	Mg *b*
	1983 Apr 2	MMT	699-29	5	Mg *b*
	1983 Apr 3	MMT	701-21	8	Mg *b*
	1983 Apr 4	MMT	703-1	11	Mg *b*
	1983 May 21	MMT	768-18	20	Mg *b*
	1983 May 22	MMT	772-5	2	Mg *b*
F156	1979 Dec 7	1.5 m	355-28	30	Mg *b*
	1979 Dec 8	1.5 m	356-16	45	N I
	1982 Apr 8	1.5 m	1276-23	30	Mg *b*
	1983 Jan 12	MMT	605-6	10	Mg *b*
	1983 May 22	MMT	772-10	10	Mg *b*
F190	1979 Nov 6	1.5 m	324-32	26	Mg *b*
	1979 Dec 7	1.5 m	355-29	30	Mg *b*
	1979 Dec 8	1.5 m	356-17	35	N I
	1982 Apr 8	1.5 m	1276-17	30	Mg *b*
	1982 Apr 8	1.5 m	1276-20	30	Mg *b*
	1983 Jan 12	MMT	605-8	8	Mg *b*
	1983 Apr 2	MMT	699-30	8	Mg *b*
	1983 Apr 3	MMT	701-22	15	Mg *b*
	1983 Apr 4	MMT	703-2	17	Mg *b*
	1983 May 21	MMT	768-20	20	Mg *b*
	1983 May 22	MMT	772-6	10	Mg *b*
	1983 May 23	MMT	775-19	10	Mg *b*
	1983 May 24	MMT	779-24	10	Mg *b*
	1983 May 25	MMT	784-9	12	Mg *b*
	1983 May 26	MMT	787-22	15	Mg *b*
F280	1979 Dec 7	1.5 m	355-20	20	Mg *b*
	1982 Apr 8	1.5 m	1276-11	35	Mg *b*
	1982 Apr 8	1.5 m	1276-14	35	Mg *b*
	1983 Jan 12	MMT	605-9	8	Mg *b*
	1983 Apr 4	MMT	703-4	30	Mg *b*
	1983 May 22	MMT	772-8	20	Mg *b*
		Hyades			
HD 26462	1980 Jan 8	1.5 m	390-8	15	O I
HD 27459	1979 Nov 6	1.5 m	324-26	15	Mg *b*
	1979 Dec 7	1.5 m	355-22	15	Mg *b*
	1979 Dec 8	1.5 m	356-10	16	N I
	1980 Jan 7	1.5 m	390-6	15	O I
HD 27819	1979 Nov 6	1.5 m	324-23	18	Mg *b*
	1979 Dec 7	1.5 m	355-24	10	Mg *b*
	1979 Dec 8	1.5 m	356-12	15	N I
	1980 Jan 8	1.5 m	390-5	10	O I
	1980 Mar 1	1.5 m	427-2	15	O I
HD 27934	1979 Nov 6	1.5 m	324-29	15	Mg *b*
	1979 Dec 7	1.5 m	355-20	15	Mg *b*
	1979 Dec 8	1.5 m	356-9	11	N I
	1980 Jan 8	1.5 m	390-4	10	O I
HD 27962	1979 Nov 6	1.5 m	324-14	10	Mg *b*
	1980 Jan 8	1.5 m	390-7	10	O I
HD 29388	1979 Nov 6	1.5 m	324-17	17	Mg *b*
HD 29488	1979 Nov 6	1.5 m	324-20	15	Mg *b*

the deviations seen for F190 and F280. However, we cannot rule out the presence of a triple system which includes two cool main-sequence members; such is the case for the third Pleiades star flagged in Figure 1, H-II 1397 (ADS 2767). Pre-main-sequence companions are also possible photometrically, though unlikely given the age of M67. We feel that the photometry indicates at the 3 sigma level the presence of a post-main-sequence companion for both F190 and F280; either normal or abnormal subgiants might be expected if mass transfer has taken place.

III. SPECTROSCOPY

a) *Observations*

The spectroscopic data (Table 2) were obtained at the Multiple Mirror Telescope and the Whipple Observatory's 1.5 m telescope (both at Mount Hopkins, Arizona) using the echelle spectrograph (Chaffee 1974) and the intensified Reticon (I-Ret) detector (Latham 1982). The observations were made over a period of 3 yr, generally in conjunction with other programs. One of these, the measurement of line breadths in field horizontal-branch stars, has been discussed by Peterson (1983), who gives additional details of the spectroscopic configurations and the data-reduction procedure.

The slit width set the resolution at 10 km s^{-1} in 1979–1980, 12 km s^{-1} in 1982, and 8 km s^{-1} in 1983, given the dispersion of 2.1 Å mm^{-1} at 5200 Å of both spectrographs.

Because spectral coverage is restricted to a single echelle order (about 50 Å), some selection is necessary. The order most frequently chosen was that centered at 5190 Å, which includes the Mg *b*-lines. Additional orders were involved in an attempt to measure high-excitation lines of CNO elements: one centered at 7770 Å for the O I triplet, and one at 7450 Å for several extremely weak N I and C I lines. For radial-velocity determinations, these orders proved virtually useless. The 7450 Å region was devoid of detectable stellar features in all but the most sharp-lined stars, while in the 7770 Å region, only three Th-A comparison lines could be detected, an insufficient number for an accurate dispersion solution.

The hottest straggler, F81, failed to show any detectable lines in the Mg *b* region. As a result, neither rotational nor radial velocities could be determined for it from our Mg *b* data. However, the single O I spectrum of F81 shows blended O I lines whose profile (and overall strength) is a good match for the O I lines of HD 27934. This suggests that $v \sin i = 80 \pm 20$ km s^{-1} for F81, as deduced for HD 27934 below. The dearth of lines in the Mg *b* order of F81 is probably due to its high temperature. It is excluded from the following discussion and from that of radial velocities in § IV.

b) *Rotational Velocities*

Among the remaining M67 straggler spectra, only one appeared sharp-lined at this resolution, that of the Am star F153. The three additional M67 blue stragglers are moderately rapid rotators.

To evaluate their rotation quantitatively, software written by Neal Burnham of the CfA (see Stauffer *et al.* 1984) was used to rotationally broaden the observed sharp-lined spectrum of F153. This was done at several values of $v \sin i$: 3 km s^{-1}, from 10 to 100 km s^{-1} in increments of 10 km s^{-1}, and 120 km s^{-1}. Rotational velocities for all other stars were then determined by a visual comparison of the spectra in this grid against the observed spectrum of the star in question.

The procedure is illustrated in Figure 2 for the four M67 stars. The resulting values, listed in Table 3 along with those

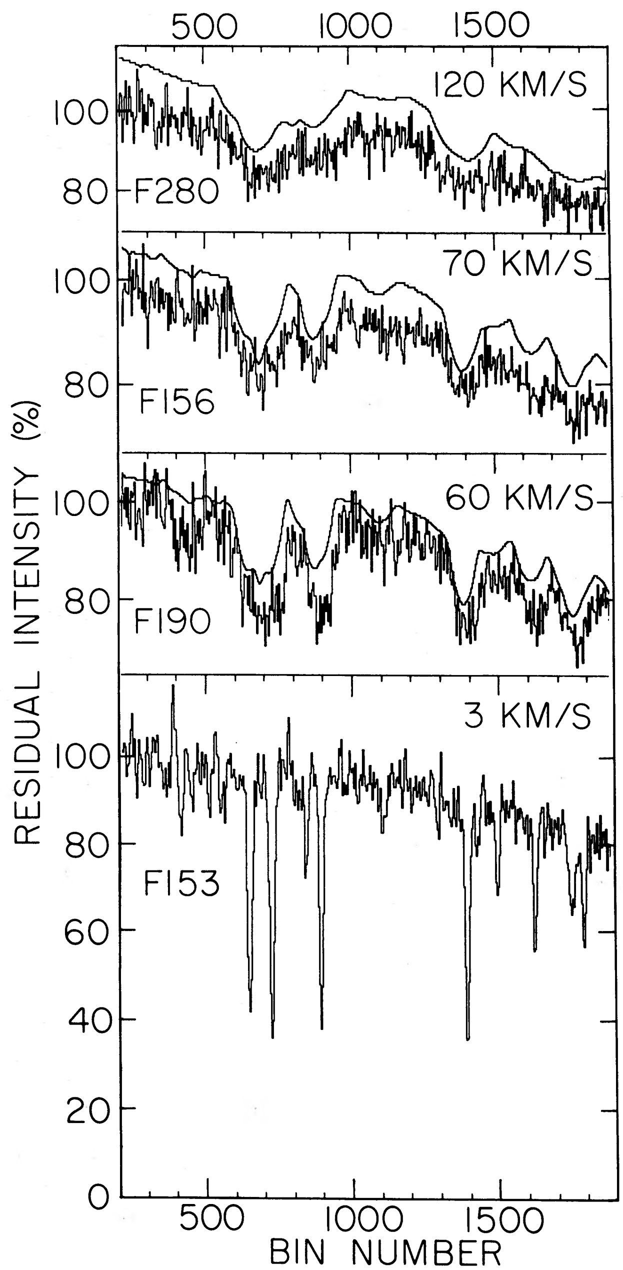


FIG. 2.—A comparison of the observed spectrum of M67 F153, artificially broadened by rotation, with the observations of three broad-lined M67 stars. All are arranged on a logarithmic wavelength scale; one unit = 1.3 km s^{-1}. The bottom portion shows the F153 spectrum broadened by $v \sin i = 3$ km s^{-1}. The remaining panels illustrate, from bottom to top, respectively, the observed spectra for F190, F156, and F280 compared with the F153 spectrum broadened by $v \sin i = 60$, 70, and 120 km s^{-1}. In each case the F153 spectrum is scaled to a level 10% higher to avoid confusion. Its similarity to the unbroadened data is striking.

for the Hyades, range from 60 to 120 km s^{-1}. This refines the earlier conclusion of Deutsch (1966, 1968), based on 20 Å mm^{-1} spectra of the seven brightest M67 blue stragglers, that the M67 rotational velocities are in the neighborhood of 50–100 km s^{-1}.

On the whole, these M67 rotational velocities are not particularly large for stars of this temperature, at least not the young ones found in other clusters. The determinations listed by Anderson, Stoeckly, and Kraft (1966) for Pleiades stars in this temperature range usually exceed 150 km s^{-1}, except for known or suspected binaries. Stars in this latter cluster are only about 25% more rapidly rotating, on average, than those in the field or in other clusters, so that the M67 stragglers would appear to be rotating more slowly than average. (The advanced age of M67 probably doesn't affect the discussion, since the slowdown proportional to the square root of age inferred for field stars (Kraft 1970; Soderblom 1982) is believed to be due to the magnetic fields associated with a convection zone. The M67 stragglers are sufficiently hot that the convection zone has all but disappeared, so that such spin-down should not be a factor.)

TABLE 3

ROTATIONAL AND RADIAL VELOCITIES

Star	Rotational Velocity (km s^{-1})	JD (2,440,000+)	Radial Velocity (km s^{-1})	r
		M67		
F153	<10	4214.97	30.9 ± 1.1	7.9
		5067.62	33.1 ± 1.6	5.1
		5067.66	33.6 ± 0.8	template
		5336.92	30.9 ± 1.7	4.1
		5426.76	33.4 ± 0.7	11.2
		5427.77	31.7 ± 0.8	9.5
		5428.63	32.8 ± 0.5	17.2
		5475.67	32.5 ± 0.5	16.0
		5476.63	31.6 ± 0.6	12.0
F156	70 ± 10	4215.01	37.4 ± 2.7	4.4
		5067.78	37.9 ± 1.8	7.2
		5336.92	38.9 ± 4.1[a]	2.2
		5476.66	41.0 ± 1.8	6.1
F190	65 ± 8	4184.00	34.9 ± 1.9	6.6
		4215.04	35.1 ± 2.0	6.4
		5067.74	48.5 ± 2.0	6.5
		5067.75	43.2 ± 3.0	3.9
		5336.93	20.6 ± 3.0	3.5
		5426.77	51.6 ± 1.2	9.8
		5427.78	45.8 ± 1.6	7.1
		5428.65	32.7 ± 0.8	15.1
		5475.68	21.0 ± 1.1	10.6
		5476.63	33.1 ± 1.0	12.0
		5477.64	46.2 ± 1.4	8.0
		5478.64	32.3 ± 1.3	8.4
		5479.65	23.0 ± 1.5	7.6
		5480.64	30.6 ± 1.4	8.0
F280	120 ± 20	4215.05	43.1 ± 7.5[a]	1.6
		5067.69	42.2 ± 7.0[a]	1.8
		5067.71	39.2 ± 5.3	2.7
		5336.94	36.4 ± 7.0[a]	1.4
		5428.67	24.5 ± 4.1	3.1
		5476.65	41.2 ± 5.1[a]	2.3
		Hyades		
HD 27459	60 ± 10	4183.93	37.9 ± 1.3	9.9
		4214.88	39.9 ± 1.5	8.6
HD 27819	30 ± 20	4183.91	40.5 ± 1.5	7.8
		4214.89	47.1 ± 1.0	9.1
HD 27934	70 ± 10	4183.96	40.9 ± 1.3	10.2
		4214.86	39.4 ± 1.9	6.6
HD 27962	<10	4183.83	37.4 ± 0.9	9.4
HD 29388	65 ± 10	4183.85	52.1 ± 1.3	10.4
HD 29488	110 ± 20	4183.89	42.1 ± 3.7	4.2

[a] Lower limit (see text).

c) *Line Strengths*

From the standpoint of exploration of the metallic-line phenomenon, it is interesting to compare line strengths in the (presumably) old Am star M67 F153 with those of the (presumably) younger Am star HD 27962 in the Hyades, whose colors are similar (Table 1). In the top panels of Figures 3*a* and 3*b*, each spectrum is shown. The observed spectrum is plotted against geocentric wavelength (in Å). The label beneath gives the disk number of the observation, the name of the program star, the right ascension and declination (1950) recorded at the telescope and used in going from geocentric to heliocentric velocity, and the time of observation expressed as the day of the current year and the Julian Date.

The spectra of the two Am stars are almost indistinguishable. Close inspection reveals that one line at 5200.41 Å, due to Y II, is notably stronger in M67 F153 than in HD 27962. However, the O I triplet is weaker in M67 F153 than in HD 27962. In the latter, the residual depths of the triplet lines are 0.42, 0.39, and 0.33 ± 0.02, while in F153, the depths are 0.32, 0.28, and 0.34 ± 0.09.

All this is in excellent accord with two primary conclusions of the study of the Am phenomenon by Smith (1971), namely, (1) that the overall enhancement of iron is independent of age, but rather determined by position in the H-R diagram, and (2) the degree of relative element enhancement is a smooth function of atomic number and is very uniform even in stars of different overall iron enhancements, except for the light elements and the rare earths. With respect to iron, excesses are seen in the rare earths, and deficiencies in many light elements (including oxygen, according to Lambert, Roby, and Bell 1982). The amount of the anomaly depends on the overall degree of iron enhancement at a given temperature. These conclusions are particularly strengthened if one assigns an old age and a low metallicity to M67.

Because of the Am effects, though, we are unable to discern whether CNO abundance anomalies due to mixing are present in the M67 stragglers, as was attempted for the field halo blue stragglers by Carney and Peterson (1981) with null results.

IV. RADIAL-VELOCITY MEASUREMENTS

a) *Procedure*

The determination of the radial velocities listed in Table 3 used the cross-correlation software developed for galaxy redshift measurement by Tonry and Davis (1979, 1981). Previous studies (e.g., Peterson 1983) have outlined the details of the procedure as applied to echelle data recorded with the I-Ret. The approach followed here differed from that of Peterson (1983) only in the independent determination of rotational velocities as discussed above, in the choice of templates discussed here, and in the calculation of random

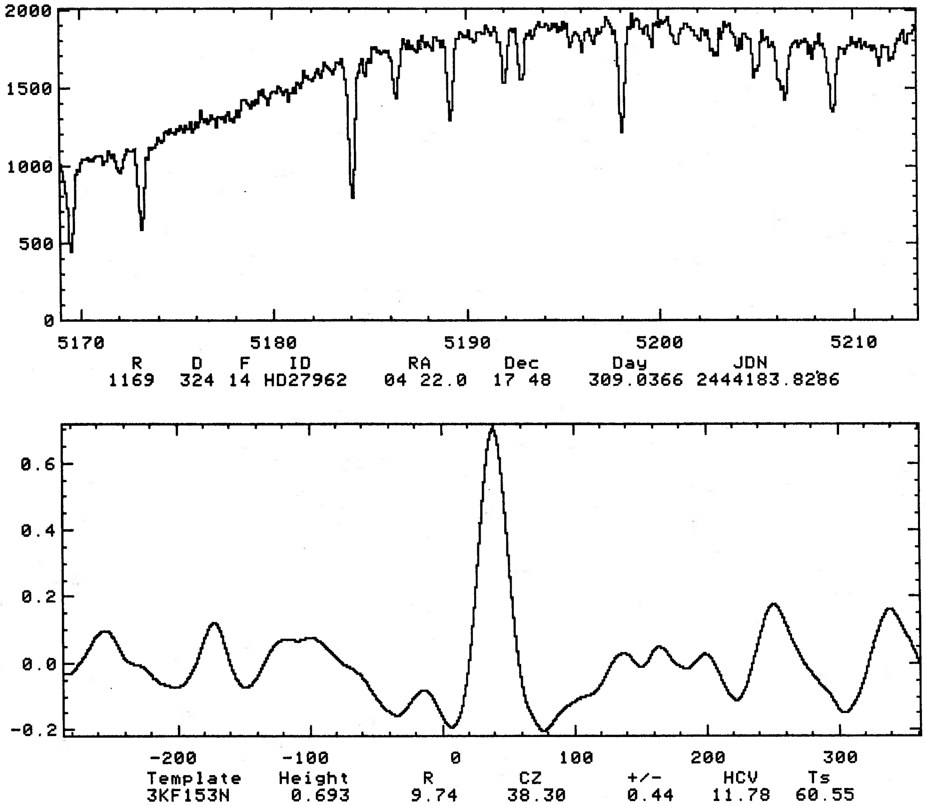


FIG. 3*a*

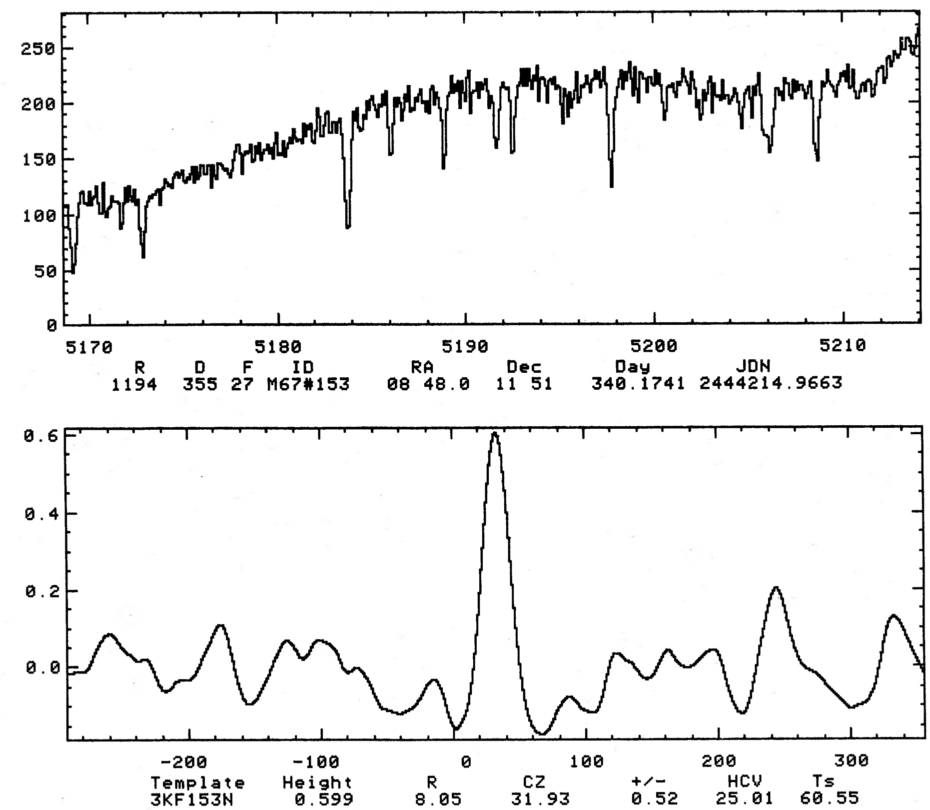


FIG. 3*b*

FIG. 3.—Sample spectra and cross-correlation functions are presented in this and the following figures for groups of stars with similar line broadening. The first star in each figure is a Hyades member; the remainder are M67 stragglers. Spectra are shown as counts per pixel vs. terrestrial wavelength. Beneath each one are the reduced file and raw-data file numbers, the star's name, its right ascension and declination (epoch 1950), and the date of observation: the day of the current year and the Julian Date. All the correlation functions except that shown in Fig. 4*d* represent cross-correlation against a template of optimal rotational broadening. The fractional correlation is plotted as a function of heliocentric radial velocity in the vicinity of the peak. The template employed is identified in the bottom line of the lower panel: the number preceding the letter K gives $v \sin i$ in km s^{-1}. Also listed are the peak height and the height ratio r, along with the deduced heliocentric velocity, its 1 sigma uncertainty, and the geocentric and template velocity corrections used in this deduction, all in km s^{-1}. Fig. 3 shows two sharp-lined Am stars: (*a*) the Hyades star HD 27962; (*b*) M67 F153.

errors in velocities determined from broad-lined spectra as discussed below.

Templates of standard spectral type were generally unsuitable here, because the majority of stars are rotating so fast that adjacent lines are blended. This situation is serious in that the spectrum in this region is dominated by only four lines: the three Mg *b* features at 5167.32, 5172.70, and 5183.62 Å, and that of Fe II at 5169.04 Å. Since the bluest pair is spaced 100 km s^{-1} apart, they begin to overlap when $v \sin i$ exceeds 50 km s^{-1}. In the region of overlap, high-frequency components appear (as may be seen in Fig. 2), which introduce noise into the correlation function.

Consequently, we chose to capitalize on the similarity evident in Figure 2 between the broadened F153 spectrum and those of the other M67 stragglers. Templates were generated directly from the broadened F153 spectra. Spectra of all stars were correlated against templates broadened by the appropriate amount, the rotational velocities having been previously determined.

This approach amounts to filtering the template to match the spectrum, as opposed to the normal technique of filtering the spectrum to reduce its high-frequency noise. Filtering the template seems appropriate here since essentially the same filter, that of rotational broadening, has already been applied to the spectrum.

Figures 3–5 illustrate the application of the correlation procedure to a variety of observational data. In each lower panel, the correlation function is plotted against heliocentric radial velocity in km s^{-1} in the vicinity of the peak. Beneath appear the name of the template used in this particular correlation, the peak height, the height ratio r, the deduced heliocentric velocity, its uncertainty as calculated without the corrections noted below for line broadening or velocity step, and the geocentric and template velocity shifts that were incorporated (all in km s^{-1}).

Figure 3 displays the spectra and the narrow, well-defined correlation peaks obtained for the two Am stars, the Hyades member HD 27962 and M67 F153.

Figure 4 demonstrates that the use of broadened templates is necessary for stars with $v \sin i$ near 70 km s^{-1}. The Hyades member HD 27459 is shown first, followed by the M67 stars F156 and F190, each correlated against an optimally broadened template. The correlation peaks are smooth and well defined, though broader than for narrow-lined stars. The peaks have the same breadth and the same shape in all correlations, despite the substantially lower signal-to-noise level of the M67 observations. What happens if a narrow template is used instead is shown in Figure 4*d*, where the same F190 spectrum is correlated against a template broadened by 3 km s^{-1}. The serious difficulty in estimating the center of the peak, and therefore the radial velocity, is evident.

The applicability of the technique to the broadest lined stars is shown in Figure 5. Spectra and correlation peaks obtained with the 120 km s^{-1} template are shown for HD 29488 in the Hyades and M67 F280. Again, the peak is rather broad but well defined, and has the same shape and width for both stars. Even though spectral lines are almost undetectable by eye, the correlations appear to give satisfactory velocities, at moderate signal-to-noise levels as well as at high ones, provided the rotational velocity is predetermined from the spectral lines directly.

b) *Random Errors*

Random errors in the radial velocities were calculated from the Tonry and Davis (1979) formula $CN/(1 + r)$, where r is the peak height ratio (a measure of the significance and accuracy of the correlation), and N is the velocity step per pixel (1.3 km s^{-1} at the MMT, and 1.5 km s^{-1} at the 1.5 m). As discussed by Peterson (1983), the value of the coefficient for echelle measurements is found to be $C = 6.5 \pm 2.0$, based on an intercomparison of multiple velocity measurements for three sharp-lined stars. It must be increased for broad-lined stars to account for the smearing of the spectrum, which limits the power spectrum of the cross-correlation function to lower wavenumbers than in the sharp-lined case.

The size of this effect was evaluated here by measuring the FWHM of the power spectrum of each F153 template as a function of the $v \sin i$ value used in its broadening. At $v \sin i = 70$ km s^{-1}, the FWHM dropped to $\frac{2}{3}$ that at 3 km s^{-1}, and to $\frac{1}{2}$ at $v \sin i = 120$ km s^{-1}. For stars rotating at 70 and 120 km s^{-1}, then, factors of 1.5 and 2, respectively, were applied to the results of the above formula to derive the 1 sigma random errors in velocity. These are listed in the penultimate column of Table 3.

To determine the error in the deduced radial velocities due to the uncertainty in $v \sin i$, many spectra were correlated against several templates. The results appear in Table 4.

High signal-to-noise data are usually well behaved, in the sense that the change in radial velocity between two correlations with different $v \sin i$ is typically smaller than the theoretical uncertainty calculated from r. For $r < 2$, however, very much larger errors can arise. Exactly this behavior was seen by Tonry and Davis (1979) in their galaxy correlations. Following Peterson (1983), we adopt $r = 2.5$ as the point below which radial velocities are more uncertain than the stated errors, and we note this in Table 3.

The behavior of r as a function of template broadening generally lends support to our determinations of $v \sin i$, made from a visual comparison of observed and artificially broadened data. The 80 km s^{-1} template generally gives the lowest r values; no star in Table 4 has $v \sin i$ this high. Based on r, it is hard to choose between the 60 and 70 km s^{-1} correlations, just as our eye estimates have indicated.

c) *Systematic Errors*

The zero point of the velocity scale depends on the determination of the velocity displacement of the broadened templates with respect to the absolute zero point established by one or more standards.

For the zero-point standards, both the A type and G type CfA standard templates were used. (The A type standard is HD 27962, the sharp-lined Am star in the Hyades which was observed here as a program star.) For observations made at the MMT, the appropriate template shifts T_s were established directly from observations of the twilight or dawn sky. The result for the A template was $T_s(A) = -0.15$ km s^{-1} on JD 2,445,336, and $+0.06$ km s^{-1} during JD 2,445,426–29. The uncertainty is less than 0.2 km s^{-1}, given the excellent agreement among the sky exposures obtained during a given run and the accord between the A and G type correlation results.

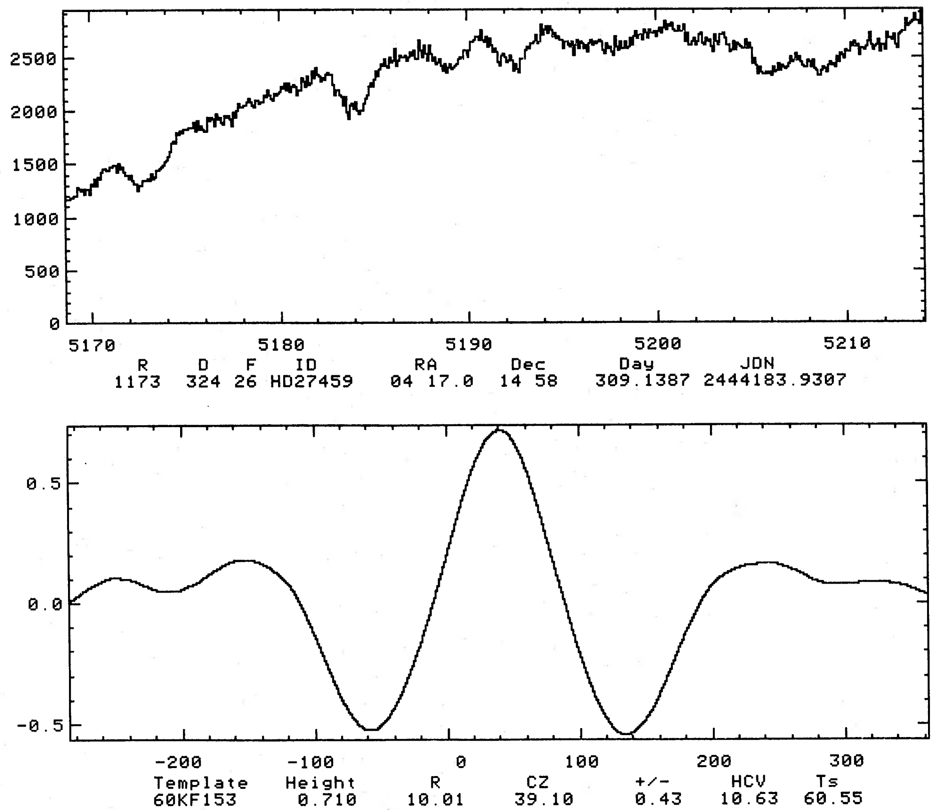


FIG. 4*a*

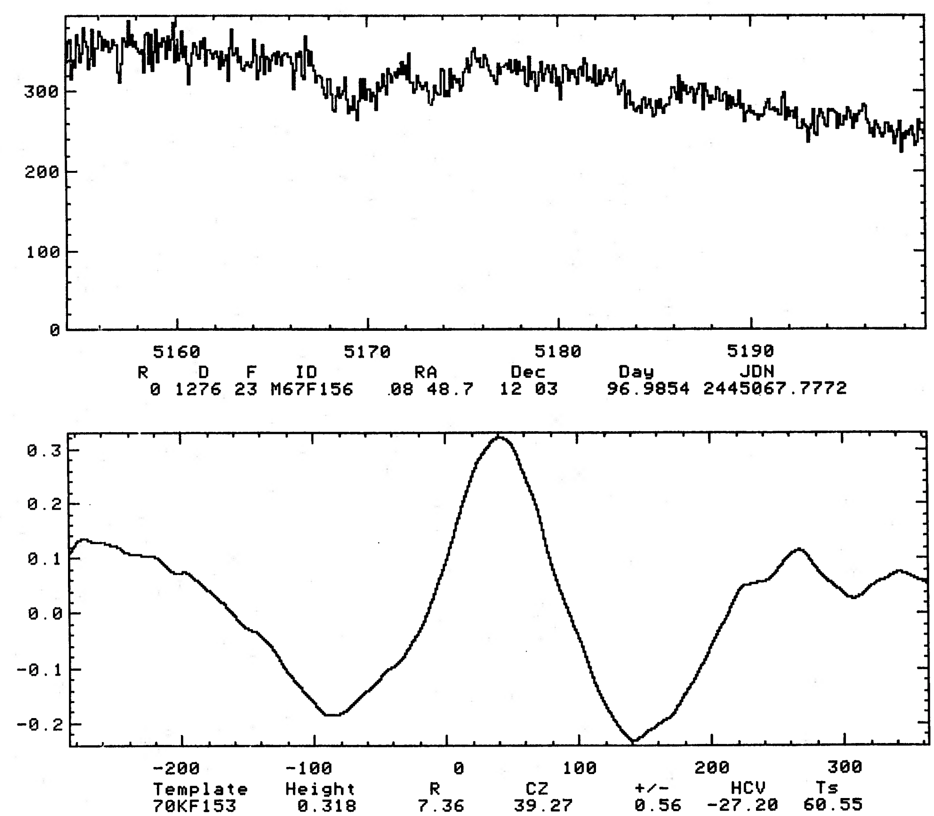
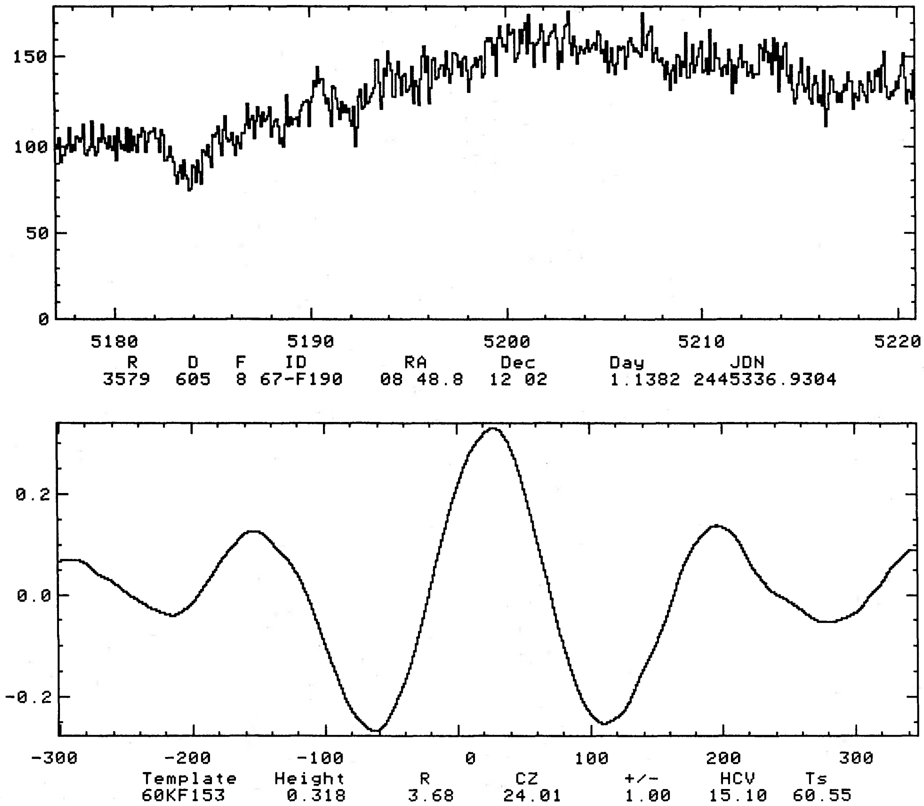


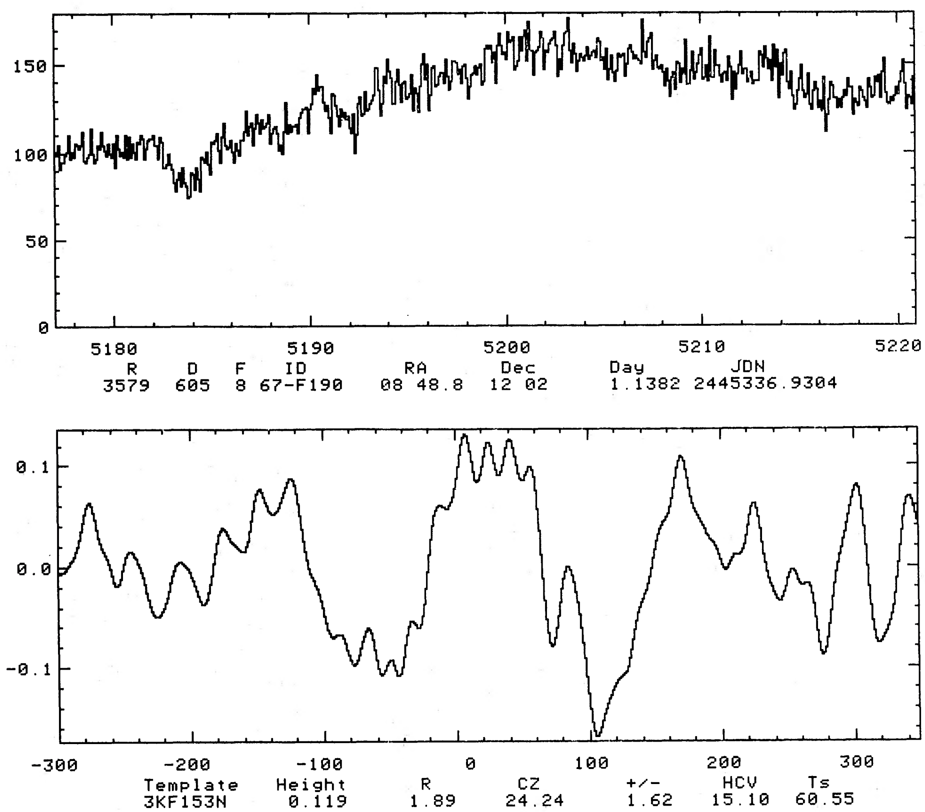
FIG. 4*b*

FIG. 4.—Same as Fig. 3 for three stars of moderate line broadening. (*a*) HD 27459. (*b*) M67 F156. (*c*) M67 F190. (*d*) The same spectrum of M67 F190 correlated against the spectrum of M67 F153 broadened by 3 km s^{-1} instead of 60 km s^{-1}. Note the degradation in the definition of the peak.



R D F ID RA Dec Day JDN
3579 605 8 67-F190 08 48.8 12 02 1.1382 2445336.9304
Template Height R CZ +/- HCV Ts
60KF153 0.318 3.68 24.01 1.00 15.10 60.55

FIG. 4c



R D F ID RA Dec Day JDN
3579 605 8 67-F190 08 48.8 12 02 1.1382 2445336.9304
Template Height R CZ +/- HCV Ts
3KF153N 0.119 1.89 24.24 1.62 15.10 60.55

FIG. 4d

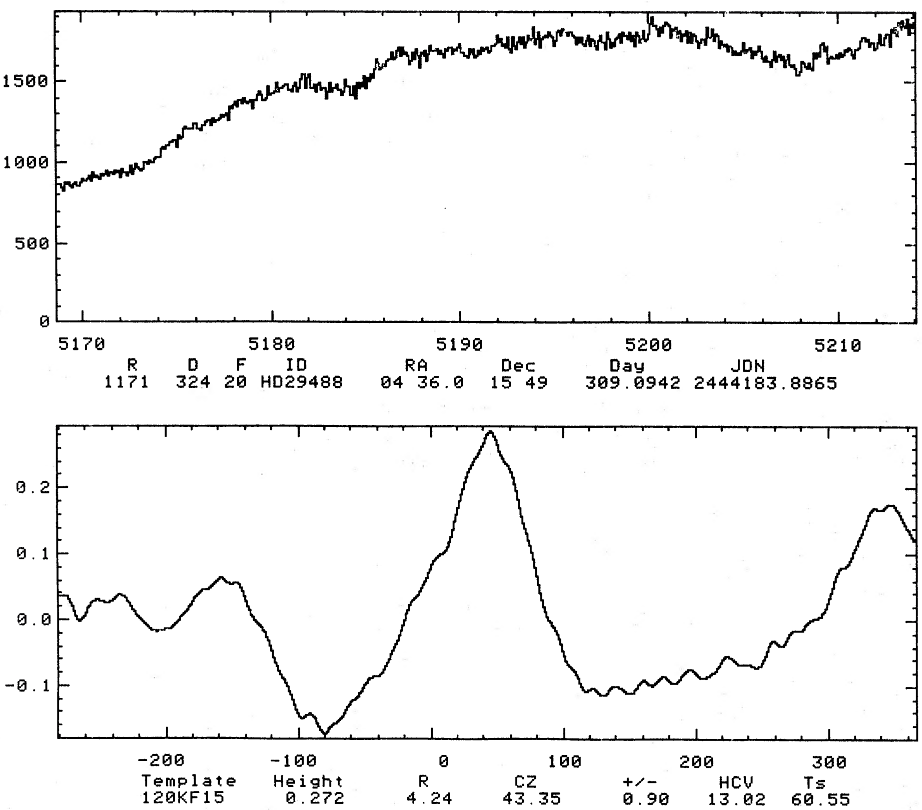


FIG. 5*a*

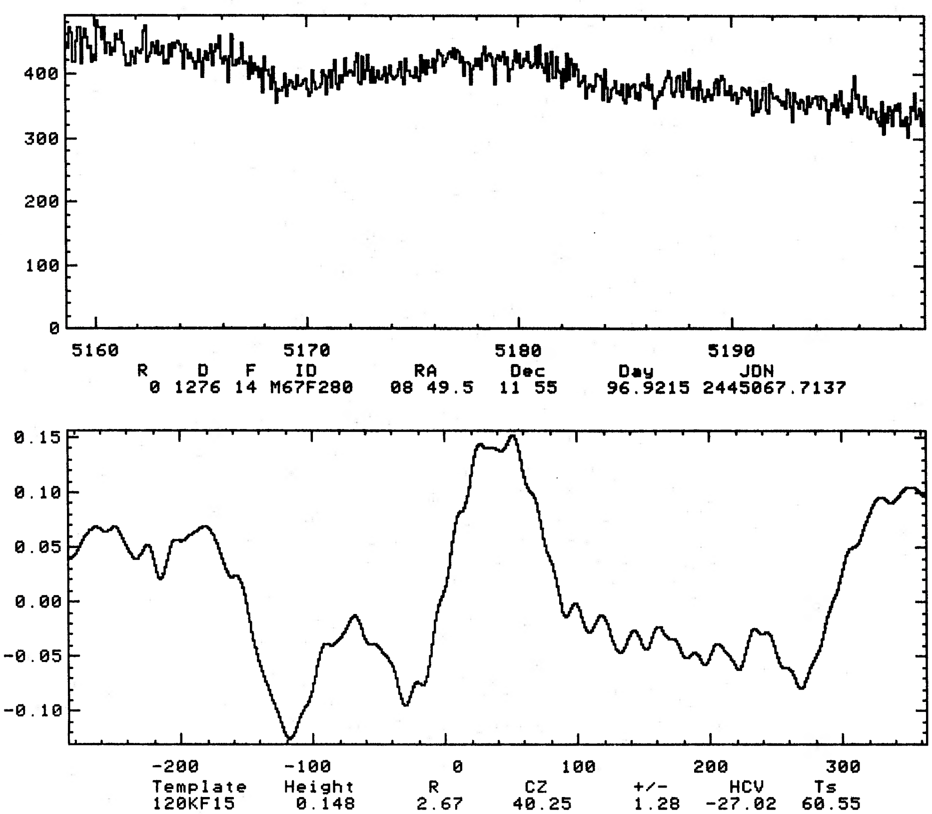


FIG. 5*b*

FIG. 5.—Same as Fig. 3 for the two stars with the broadest lines. (*a*) HD 29488. (*b*) M67 F280.

TABLE 4

RADIAL VELOCITY AND PEAK RATIO AS A FUNCTION OF TEMPLATE ROTATION

		Radial Velocity (km s^{-1})			r		
Star	JD (2,440,000+)	60	70	80	60	70	80
M67 F153	4214.97	30.5	32.2	30.7	5.4	4.8	3.9
	5067.62	37.2	57.0	69.2	1.4	1.9	2.2
	5067.66	33.4	−2.4	76.5	19.4	−5.6	1.7
	5336.92	28.7	28.6	29.0	4.8	3.9	2.4
	5426.76	34.6	32.9	69.8	7.9	5.5	1.6
	5427.77	23.3	37.2	−8.7	5.6	2.0	1.5
	5428.63	33.5	33.0	63.0	8.5	4.7	1.3
	5475.67	34.4	32.5	66.6	7.3	3.2	1.6
	5476.63	28.7	25.2	7.8	7.0	3.9	1.6
M67 F156	4215.01	39.4	37.4	37.8	3.7	4.4	4.4
	5067.78	40.3	38.0	35.6	6.5	7.2	6.0
	5336.92	35.4	38.9	43.9	2.2	2.2	1.7
	5476.66	39.4	41.0	41.6	4.8	6.1	6.9
M67 F190	4184.00	35.0	34.9	34.3	6.2	6.9	6.2
	4215.04	35.0	35.2	34.8	6.4	6.4	5.7
	5067.74	48.8	48.1	47.4	6.5	6.6	6.2
	5067.75	45.0	41.4	40.6	3.4	4.4	4.3
	5336.93	20.9	20.3	19.6	3.7	3.4	2.8
	5426.77	51.4	51.9	51.8	9.5	10.1	8.6
	5427.78	44.1	47.4	51.7	6.4	7.8	6.9
	5428.65	33.0	32.4	...	14.3	15.9	...
	5475.68	21.0	20.9	20.9	10.9	10.2	9.1
	5476.63	32.8	33.5	35.7	11.2	12.8	11.1
	5477.64	46.3	46.0	46.0	7.5	8.4	7.4
	5478.64	31.4	33.2	34.5	7.6	9.2	10.0
	5479.65	24.1	22.0	21.1	7.2	8.0	7.1
	5480.64	30.2	31.1	31.1	7.7	8.3	7.9
HD 27459	4183.93	37.9	36.9	36.3	9.9	9.5	8.1
	4214.88	39.9	39.9	40.5	8.6	8.4	7.2
HD 27819	4183.91	40.7	42.4	43.8	11.5	12.3	8.3
	4214.89	48.9	50.0	52.4	7.9	6.4	4.3
HD 27934	4183.96	42.5	40.9	39.9	11.3	10.2	7.6
	4214.86	41.3	39.4	39.2	6.6	6.6	5.8
HD 27962	4183.83	39.2	41.4	44.3	8.5	6.9	4.1
HD 29388	4183.85	52.8	51.4	50.4	10.2	10.9	9.2

For the 1.5 m data, no sky exposures were obtained, and we must rely on T_s determinations from sky exposures made during different observing runs by one of us (D. W. L.) in conjunction with other velocity programs. One such run took place the week before that during which the majority of our M67 1.5 m data were obtained, with the result of $T_s(A) = +1.93 \pm 0.16$ km s^{-1} from seven sky exposures. This compares favorably with the value $T_s(A) = +2.01 \pm 0.15$ derived from 50 sky exposures in the 7 months preceding our M67 run. This latter value is adopted here, and its uncertainty is estimated at ± 0.4 km s^{-1}, which is the run-to-run standard deviation of T_s.

The relative velocity displacements of the broadened F153 templates with respect to the standard A template are intrinsically devoid of run-to-run variations, these being taken into account by $T_s(A)$. Since all broadened templates were prepared from the same F153 spectrum in exactly the same way, all displacements should be equal. The value was established by correlating the nine sharp-lined spectra against the standard template as well as the F153 spectrum broadened by 3 km s^{-1}, and demanding that the same stellar velocities, on average, result from each. The uncertainty in this displacement is estimated at ± 0.25 km s^{-1} from the internal scatter of the nine individual measurements. The overall 1 sigma uncertainty in the zero point of these observations is then ± 0.3 km s^{-1} for the MMT data, and ± 0.4 km s^{-1} for the 1.5 m data.

d) *Variability among M67 Stragglers*

With more extensive observations of the M67 stragglers, we are in a better position to identify velocity variables. Both explicit variations in velocity and large departures from the cluster mean may be used.

For F280, the two velocity determinations with $r > 2.5$ differ by more than twice their combined standard deviation, a highly suggestive result which supports the photometric evidence for duplicity.

For F190, velocity variations are unmistakable. It has previously been identified as a velocity variable by Deutsch (1968), who gave a period of 4.198 days and a peak-to-peak amplitude of 18 km s^{-1}. Our measurements confirm a period near 4 days but indicate a full amplitude of at least 30 km s^{-1}. This is completely consistent with a separation of the components that is at least several times the expected radius of the blue straggler. (According to Abt and Bidelman 1969, a main-sequence A star with a 4 day period is generally metallic-lined. However, Abt and Moyd 1973 suggest that the definitive Am characteristic is a low rotational velocity. The rather large $v \sin i$ value we find for F190 is presumably the reason that the star is not metallic-lined.)

As outlined below, the mean velocity of M67 has been recently redetermined by Mathieu (1983) and Mathieu and Latham (1983) as 33.5 ± 0.12 km s^{-1}. The average of our F153 velocities, 32.3 ± 0.4 km s^{-1}, probably does not depart significantly from this mean, given the ± 0.7 km s^{-1} uncertainty of our error and the cluster velocity dispersion, combined in quadrature. Also, the 1 sigma standard deviation of an individual measurement, 1.0 km s^{-1}, agrees well with the theoretical values listed in Table 3. On the other hand, our three reliable measurements for F156 average 38.8 ± 1.4 km s^{-1}, which places it 2.6 standard deviations from the cluster mean. The ± 0.4 km s^{-1} uncertainty in the zero point of the 1.5 m data is not sufficient to reduce this significantly.

V. EVIDENCE FOR BINARIES AMONG M67 BLUE STRAGGLERS

The evidence is considerable for binaries among the blue stragglers we have investigated in M67. For F190 and F280, photometry points toward light contamination by cool, non-main-sequence companions. Both stars also show radial-velocity variations from our measurements alone, and F190 was previously noted as a velocity variable by Deutsch (1968).

Two stars have velocities rather far from the cluster mean. For F156, our average value of 38.8 ± 1.4 km s^{-1} lies 3.6 standard deviations from the cluster mean. It is even farther from Deutsch's velocity of 26 ± 3 km s^{-1} cited by Pesch (1967), whose own mean value is 38 ± 5 km s^{-1}, in accord with ours. For F81, the average velocity measured by Pesch (1967) differs by ~ 7 km s^{-1} from the cluster mean. If these stars are members of M67, they probably have variable radial velocities.

Lastly, for F153, we see no variation greater than that expected from the combined uncertainties. However, this star is an Am star, and Abt (1961, 1965) has shown that these are so frequently found in binaries that it is reasonable to assume all have companions.

A conservative approach would be to reject these stars from membership in M67. However, this does injustice to the stragglers' membership probabilities tabulated by Sanders (1977), all in excess of 90%. Interestingly, the same membership dilemma pertains to the hot straggler K1211 in NGC 7789. Breger (1982) calls it a "certain cluster member" on the basis of both its proper motion and its polarization. Yet Hrivnak and Stryker (1982) question its membership on the grounds that their measurement of its radial velocity is unexpectedly far from the cluster mean. In general, it seems unwise to us to exclude from membership in a cluster those candidates whose membership is probable on the basis of proper motions, but improbable on the basis of radial velocities. Such a procedure will systematically remove legitimate stragglers which are velocity variables, and so may seriously underestimate the likelihood that stragglers are binaries.

Our working hypothesis, then, is that all five blue straggler candidates are members of M67. If so, all are almost surely members of binary or multiple systems. In our view, these findings constitute strong support for the binary/mass-transfer origin of blue stragglers.

Unfortunately, the semiamplitudes inferred for the M67 stars in our sample average less than 10 km s^{-1}. If such small velocity variations are characteristic of stragglers in other clusters, they could well have escaped detection at the resolution used in many previous studies.

VI. BINARY FREQUENCY AND MASS-TRANSFER ORBITS

Several issues remain to be resolved. Is the mass of F81 attainable by mass transfer? Is the binary frequency of M67 stragglers truly high? Do straggler progenitors exist; i.e., are there M67 giants in binary orbits which could give rise to mass transfer? Are the stragglers' velocity variations consistent with post-mass-transfer orbits?

Granting F81 membership in M67 admits the possibility of a straggler which explicitly violates the mass limit of twice the turnoff mass allowed for stragglers created from binaries, but this does not pose insurmountable difficulties to the mass-transfer hypothesis as a whole. For example, the existence of a system which is multiple may distort photometric indices, leading to errors in the derived masses. If violations such as F81 were common among stragglers, the transfer hypothesis would have to be abandoned, but since such a case is uncommon, the hypothesis can survive it.

Among metal-poor stars, binaries are rather infrequently detected, so that it is significant that both metal-poor field blue stragglers examined by Carney and Peterson (1981) proved to be radial-velocity variables. The significance of radial-velocity variations in our sample remains to be seen, since binaries are rather common among normal main-sequence stars in young open clusters, and their frequency varies somewhat from cluster to cluster (see Abt 1979).

We can examine M67 itself in some detail thanks to the work of Mathieu (1983) and Mathieu and Latham (1983). In two observing runs spaced 9 months apart, they obtained three to six radial-velocity measurements, each good to ± 0.5 km s^{-1}, of 29 M67 giants. For the mean cluster velocity, they found 33.5 ± 0.12 km s^{-1}, and for the 1 sigma intrinsic velocity dispersion, less than 0.5 km s^{-1}. Of the 23 giants in their sample for which the probability of membership is greater than 50%, according to the proper-motion study of Sanders (1977), four showed definite velocity variations. The most extreme case varied by 23 km s^{-1} from one night to the next; the others showed changes of 16, 8, and 5 km s^{-1} over 9 months. Among the remaining stars included by Sanders (1977), Mathieu and Latham found none with a mean velocity displaced by more than 1.2 km s^{-1}, twice the cluster dispersion.

These results are encouraging for the mass-transfer hypothesis. Binaries are neither extremely rare nor extremely common—though more may be discovered as the survey continues. The size of the giants' velocity variations suggests orbital separations which are appropriate for mass transfer, as we now show,

Assume that orbits are initially circular. Then the velocity variations of the most extreme star suggest an orbit with a semimajor axis $a_0 < 0.2$ AU and a period $P_0 = 20$ days or so, while the next has $a_0 \leq 1$ AU and $P_0 \leq 1$ yr. In old systems, binaries with separations in just this range are those identified as undergoing "case B" mass transfer (from an evolving giant to a main-sequence companion), according to the calculations of Renzini, Mengel, and Sweigart (1977).

The effect of mass transfer on period and velocity amplitude in the case where total mass and angular momentum are conserved has been discussed by Batten (1973). When matter flows from the less massive to the more massive component, the period increases; the ratio of the final period to the initial one varies as the cube of the ratio of the products of initial and final masses. For M67, then, postulating a pair of stars each 0.9 $M_\odot$ initially, which undergoes transfer to the extent that one gains 80% of the other's mass, would result in a new period 20 times the original, i.e., roughly half a year and several years for the two cases above. Indeed, periods of 100–500 days were calculated explicitly for blue stragglers in old clusters by Renzini, Mengel, and Sweigart (1977).

Although this is a consistent scenario, it is by no means a certain one. In particular, it is an open question whether mass is actually conserved during transfer. Empirically, it seems that a system cannot afford to lose too much mass and still produce stragglers as massive as those frequently encountered. Theoretically, however, Packet (1981) has shown that mass exchange in a close binary is accompanied by a transfer of angular momentum sufficient to spin up the accreting star to a critical level after gaining only a few percent of its total mass. At this point, further accretion at the stellar surface ceases, and subsequent accretion depends on whether enough angular momentum can be fed back into the orbit by tidal forces.

The unknown but possibly critical effect of tidal interactions might place stringent limits on the range of initial parameters of a binary orbit within which substantial mass transfer is accomplished rather than mass loss. Such a restriction might explain the observed fact that, if blue stragglers do originate in binary systems, only a small fraction of binaries in open clusters actually produce blue stragglers. For the straggler frequency is much lower than the binary frequency in all open clusters observed to date.

VII. THE CASE FOR INITIALLY ECCENTRIC ORBITS AND LOW-DENSITY ENVIRONMENTS

Because these constraints are not yet specified theoretically, we have explored empirical means of establishing the restrictions in the orbital parameters of those binaries which give rise to stragglers. Several observational considerations suggest that it is advantageous to relax the assumption that orbits are initially circular.

The favored orbits are postulated to have a periastron of about 1 AU, in order to accomplish mass transfer, but a semimajor axis that is much larger. This is more consistent with the distribution of orbital eccentricities and secondary masses among solar-mass binaries of the field; with the low frequency of detection of radial-velocity variations among stragglers in open clusters; with the spatial distribution of stragglers in NGC 7789; with their scarcity in globular clusters versus their ubiquity among old open clusters; and with their preference for low-density environments in those globular clusters where they do occur. The remainder of this section is devoted to a discussion of each of these points in turn.

Consider the solar-mass main-sequence and subgiant binaries of the field studied by Abt and Levy (1976). When periods exceed 10 days or so (and so the components are separated by more than a few stellar radii, or a few hundredths AU), the frequency of eccentric orbits becomes high. Our postulate of rather eccentric orbits for the straggler progenitors is in keeping with this. It also removes a statistical objection to the binary/mass-transfer hypothesis raised by Wheeler (1979*b*). He pointed out that the approximate mass function observed for the blue stragglers cannot be explained using the mass function of secondary stars of short-period binaries given by Abt and Levy (1976). We note that the secondaries of the long-period systems of Abt and Levy (1976) obey a much steeper mass function, and this does give the approximate distribution required for the stragglers.

Following mass transfer, an initially eccentric orbit would presumably retain a substantial eccentricity. If so, the effect of eccentricity on velocity and period would render such a straggler more difficult to detect as velocity variable than one in a circular orbit, but it would still be likely to show a velocity displacement from the cluster mean. Since the velocity semiamplitude varies as $(1+e)^{-1/2}$, it is decreased only slightly as eccentricity e increases, and peak-to-peak amplitudes of 10 km s^{-1} should not be uncommon. The period, however, goes as $(1-e)^{-3/2}$ and so may be increased by several orders of magnitude. In consequence, a straggler in an eccentric orbit would reveal a displacement of a few km s^{-1} from the cluster mean velocity, with little change in radial velocity except during the brief time near periastron. It might be expected, then, that studies such as ours which span 3 yr or less would result in a small or zero sample of stars with variable radial velocities, but a significant fraction with velocity displacements. This aspect highlights the need to determine whether straggler candidates are cluster members by a method other than radial velocities, at least among open clusters (see § V).

A more fundamental effect of invoking eccentric pairs as blue-straggler progenitors arises from the consequently larger mean separation. Wide pairs are more prone to disruption by distant encounters with other stars in the cluster, and so the survival of progenitors of blue stragglers becomes more sensitive to the stellar density. Stragglers would tend to form from stellar populations of low density.

This might account for the point made by Breger (1982), concerning the discovery by MacNamara (1980) of new stragglers in the remote regions of NGC 7789. "The large distance from the cluster center of these new blue stragglers would suggest a statistical preference of blue stragglers for outlying areas of the cluster." However, given the sparseness of open clusters, wide pairs should survive at any radial distance.

The truly dramatic difference in binary disruption is seen in going from open clusters to globulars. Hills (1975) has calculated the maximum separation of pairs with a 50% chance of surviving throughout a Hubble time in several environments. He gives 100–1000 AU as this distance in a rich open cluster, versus about 35 AU in a typical globular.

The survival of wide pairs would then provide an explanation for the prevalence of stragglers in old open clusters and their comparative absence in globular clusters. Of the many populous old open clusters whose color-magnitude diagrams (Hagen 1970) reach the main sequence, every one has a prominent group of blue stragglers. Fifteen globulars now have such color-magnitude diagrams, as portrayed by VandenBerg (1983). Excluding the three with $E(B-V) > 0.15$, for which contamination by field stars is a serious problem, only M3 has a substantial number of stragglers, though Palomar 12 might have a few (see also Renzini, Mengel, and Sweigart 1977 and the discussion following the presentation of Trimble 1980).

To account for the exceptional presence of stragglers in M3, we note that Hills's results apply strictly only in the regions of a cluster which are "relaxed," i.e., where the cumulative effect of moderate stellar encounters has thermally redistributed the kinetic energy of the stellar particles. In the primordial outer regions of a globular, this equilibrium may not yet have been attained. Although such regions have probably been stripped by now from most globular clusters during their passage near the galactic center, a cluster with little such contact might still retain a low-density, non-equilibrium environment, which allows the survival of rather wider pairs.

M3 is a strong candidate for such a cluster. Measurements by Peterson and King (1975) show that M3 has a substantially larger tidal radius than any of the other globulars for which main-sequence photometry has been published. Also, the detailed study of the radial velocities of M3 giants by Gunn and Griffin (1979) supports equilibrium conditions only in the central half (by mass) of the cluster. Models which fit both star counts and velocities demanded an anisotropic velocity distribution function beginning about 15 core radii from the center. Furthermore, the deflection relaxation time there was found to be 10 times longer than the Hubble time.

Indeed, the M3 blue stragglers are commonly found at this distance and are not concentrated toward the center. As we are about to show, this appears certain despite the fact that more interior regions are extremely difficult to search because of crowding problems, so nothing is currently known about the presence or absence of stragglers there.

Fifteen core radii amounts to 7$'$.5 in M3 (Peterson and King 1975; Gunn and Griffin 1979). Six of the eight stragglers identified by Sandage and Katem (1982) have radial distances between 4′.2 and 10′.7, and only two between 2′.5 and 4′.2, though roughly equal total numbers of stars were measured in each region. Also, Ables (1983) has undertaken the construction of a color-magnitude diagram in a region centered 13′ from the cluster center, exterior to those surveyed in previous work, and he has identified another star whose *UBV* colors and *V* magnitude are those of a blue straggler.

Sandage and Katem (1982) note that their M3 stars in the blue-straggler region "may be field stars because . . . they are not concentrated toward the cluster center." That these stars (and the one of Ables) do belong to M3 is supported by *UBV* colors, where available: all these objects fall in the natural extension of the region occupied by metal-poor turnoff stars in Figure 1 of Sandage and Luyten (1969), 0.1 mag bluer in $U-B$ than Population I main-sequence stars of the same $B-V$ color, yet 0.3 mag redder than the reddest white dwarfs. Furthermore, a Population I main-sequence interloper is highly unlikely since M3 lies about 10 kpc above the galactic plane. Indeed, membership has recently been confirmed for five straggler candidates by Chaffee and Ables (1983), from radial-velocity measurements good to ± 20 km s^{-1} which agreed with the cluster mean velocity of -147 km s^{-1} (Webbink 1981).

Possible progenitors of the M3 stragglers are somewhat more difficult to isolate. Interestingly, Gunn and Griffin (1979) have uncovered two M3 giants with constant radial velocities which depart from the cluster mean by 17.0 and -22.9 km s^{-1}, i.e., by 3.5 and 4.5 times the cluster velocity dispersion. Assuming these stars are single, Gunn and Griffin (1979) could not fully explain their existence. It is perhaps more plausible that they are binaries. If so, they could be considered blue-straggler progenitors.

Other globular clusters whose overall density is low might also be expected on these grounds to have stragglers. Such clusters tend to be very far from the galactic center, and so generally do not have color-magnitude diagrams which reach the main sequence. One which does is Palomar 12; as noted above, it may have stragglers. Also, Carney and Inman (1982) have recently extended to faint limits the color-magnitude diagram of another remote cluster, Palomar 13. They found four or five blue main-sequence stars that are up to 1 mag brighter than turnoff stars are expected to be, based on the magnitude of the horizontal branch. Most recently, the vidicon photometry of Frogel and Twarog (1983) of the extremely sparse globular E3 confirms the preliminary conclusion of van den Bergh, Demers, and Kunkel (1980) that a significant group of stragglers is present.

Finally, we note that Cudworth (1983) has completed a proper-motion study of the field of M71 and finds several straggler candidates in this nearby globular of low concentration.

VIII. SUMMARY AND DISCUSSION

Through photometry and echelle spectroscopy, we have shown in this paper that at least two, and probably all, of the five brightest blue stragglers in the open cluster M67 are binaries. This constitutes strong support for the hypothesis that stragglers owe their current existence beyond the main-sequence turnoff to mass transfer from an evolving companion. Several previous observational results, considered in § VII, suggest that stragglers arise preferentially from pairs in initially eccentric orbits rather than circular ones, and therefore that the ease of disruption of the rather widely separated components of the progenitor systems is the dominant cause of the scarcity of stragglers in globular clusters. In this scenario, stragglers are produced only in globulars where binaries, despite their doubled mass, may spend almost all their time in an extremely low-density environment, either because the cluster density is everywhere low (as with the Palomar-type clusters) or because tenuous regions were retained whose stars rarely venture into the dense regions (as in M3).

Arguments which also advance low-density environments as production sites of blue stragglers have been made by Renzini, Mengel, and Sweigart (1977) to account for the presence of anomalous Cepheids. As discussed by these authors and by Zinn and King (1982), such objects are clearly the result of mass transfer among metal-poor stars; if blue stragglers also arise from mass transfer, they themselves are almost surely the progenitors of the anomalous Cepheids and should be found in conjunction with them. Unfortunately, anomalous Cepheids usually are found in external dwarf spheroidal systems such as Draco. Only one is known in the Galaxy, and it has been shown by Zinn and Dahn (1976) and Zinn and King (1982) to belong to the cluster NGC 5466.

Using the core and tidal radii tabulated by Peterson and King (1975) for 41 globular clusters, Renzini, Mengel, and Sweigart (1977) computed the critical separation (defined by Aarseth and Hills 1972) above which binaries are expected to be dissociated. They noted that NGC 5466 is characterized by one of the largest values of this parameter of any galactic globular. They stressed the need to search for blue stragglers in the cores of other globulars with a high value of this parameter.

Our emphasis differs in that we are suggesting that it is the presence of very low-density regions, and not necessarily the mean properties, which determines the probability of finding stragglers in a given globular cluster. M3 does not have an exceptional mean critical binary separation, according to Renzini, Mengel, and Sweigart (1977); about 20 of the 41 clusters have larger ones. In contrast, a ranking based on tidal radius lists M3 fourth and NGC 5466 sixth.

Our criterion for continued straggler searches in globulars would be the presence of low-density regions, where collisional disruption has not proceeded extensively. As a result, the locales we recommend searching are the extremely sparse Palomar-type globulars and the exterior portions, not the cores, of more populous clusters. Dwarf spheroidal galaxies would be an appropriate future target also. If blue stragglers are in fact common in these systems, some confusion could arise in assigning an age to a dwarf spheroidal from the turnoff of a color-magnitude diagram.

Other suggestions for future work include an effort to measure very accurate radial velocities for the M3 stragglers. A meaningful upper limit might be placed on variable velocities by comparing the straggler velocity dispersion with that of the giants, and repeated measures might produce actual detections of variability.

Much lower limits can be placed on the variability of the velocities of red giants of M3, which have many sharp lines and are 3–5 mag brighter than the stragglers. Gunn and

Griffin (1979) have established that binaries with a large semiamplitude are rare on the giant branch, but Harris and McClure (1983) have argued that they cannot be ruled out entirely. A continued effort to monitor the M3 giants would be very worthwhile. These arguments apply equally to M67.

Clearly, it is essential to establish with certainty that the stragglers F81 and F156 are members of M67 undergoing velocity excursions, and a more thorough examination of their velocity behavior is in order. It is also desirable to extend such work to stragglers in other clusters. Given the small size of the upper limits and of the variations seen or inferred to date, an uncertainty in an individual velocity measurement of ± 3 km s^{-1} or less seems needed to make further progress.

For a complementary look at whether binaries are common in other clusters, photometry should be carried out to extend the wavelength baseline. Infrared photometry is particularly recommended for NGC 7789, where post–main-sequence companions might be evident. Such efforts might provide the most immediate detection of the presence of large numbers of companions among blue stragglers.

We are grateful for the support for this project of the staff of the Harvard-Smithsonian Center for Astrophysics, where R. C. P. was a Visiting Scientist during 1982 April–June. Our special thanks go to Neal Burnham for instruction in the use of the program he developed to rotationally broaden observed spectra, a crucial part of our determinations. Both he and Lee Hartmann provided considerable insight through discussions of mutual experiences with the cross-correlation analysis of broad-lined spectra. The extremely capable software support of Bill Wyatt was also indispensable. Discussions of the M3 stragglers with Dr. Harold Ables of the U.S. Naval Observatory, Flagstaff, were very helpful. At the Fred L. Whipple Observatory, the 1.5 m telescope observations were competently carried out by Ed Horine, Jim Peters, and Fred Chaffee. We express our thanks for generous time allocations at both Mount Hopkins telescopes and at Kitt Peak National Observatory. Financial support to R. C. P. from NSF grants AST 79-25880 and AST 81-15555 and to B. W. C. from NSF grant AST 81-11938 to the University of North Carolina is gratefully acknowledged.

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