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THE EVOLUTIONARY STATE AND PULSATION CHARACTERISTICS OF RED VARIABLES IN GLOBULAR CLUSTERS

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ABSTRACT

Infrared photometry, effective temperatures, and bolometric magnitudes for more than 50 red giant variables in globular clusters are assembled and discussed. The main conclusions are:

1. All of the long-period variables (LPVs) in the clusters have luminosities greater than that corresponding to core helium flash, so they must be asymptotic giant branch (AGB) stars. With three possible exceptions, all other cluster variables have luminosities less than that corresponding to core helium flash.

2. Why luminous AGB stars (the LPVs) are *only* in metal-rich clusters is not understood. Part of the explanation probably lies in higher red giant masses in clusters of higher metallicity. Considerable uncertainty in the mass loss rate for giants and its dependence on metallicity and other physical parameters could mask the remainder of the explanation. A lower age for the metal-rich clusters relative to the metal-poor ones may play an important role.

3. Red $K-L$ colors for the LPVs are probably indicative of relatively high mass loss rates compared to the non-LPV variables.

4. A comparison of empirical Q values with theoretical ones for fundamental and first harmonic pulsators is not particularly enlightening. Uncertainties in the temperature scale for the cooler stars seriously affects any such comparison.

5. Those red variables which lie at considerably warmer temperatures than the giant branches of their clusters could be AGB stars, and some may have circumstellar shells.

Subject headings: clusters: globular — photometry — stars: abundances — stars: long-period variables — stars: pulsation — stars: variables

I. INTRODUCTION

The study of red giant variables in globular clusters is important, first because their presence in clusters permits reasonably accurate values of their absolute luminosities and temperatures (via reddening-corrected colors) to be obtained. These parameters are necessary in any examination of the evolutionary state and pulsation characteristics of these stars. Second, such a study is important as a means of exploring the history of the clusters themselves.

Feast (1973) provided a summary of what was known about the cluster red variables, which knowledge at that time was based primarily on observations shortward of 6000 Å. These data are basically incapable of yielding useful information about temperatures and luminosities of the stars, particularly the coolest and most luminous of the variables. However, Feast noted a fact which is important for the discussion contained in this paper—namely, that the long-period variables (LPVs) are found *only* in metal-rich globular clusters.[2] Eggen's (1972) extensive R, I photometer, bands in which blanketing problems are considerably less severe than in U, B, or V, gave the first solid evidence that the long-period variables in 47 Tuc were significantly brighter, bolometrically, than the rest of the stars in the clusters. His work and the extensive program of R, I photometry begun by Lloyd Evans and Menzies (1973 and references therein) began to clarify the observational situation so that the problems concerning these stars could be put into more precise questions.

The first published infrared observations of cluster red variables (for 47 Tuc and ω Cen) by Glass and Feast (1973) showed the great value of such observations.

Basically, though, in the past 10 years not a great deal has been learned about red giant cluster variables. This is due at least in part to a lack of sufficient data. For three recent reviews of both observational and theoretical aspects of work on these stars, the reader is referred to relevant parts of articles by Feast (1981), Willson (1981), and Wood (1981).

In the present paper infrared observations are presented of more than 50 red variables in globular clusters which have been obtained as part of a larger program to study the cool giants in these objects. Clusters included in the study are 47 Tuc (Frogel, Persson, and Cohen 1981, hereafter GC 5), ω Cen (Persson *et al.* 1980, hereafter GC 3), NGC 7006 (Cohen

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[2] It is useful to quote Feast's (1973) definition of cluster LPVs as "red giants with long periods (generally greater than 100 days), large amplitudes (Δm greater than about 2.5 mag), and Me spectra." This is consistant with the classification criteria of Hogg (1973) which are followed in the present paper.

and Frogel 1982, hereafter GC 7), and 26 others (Frogel, Persson, and Cohen 1983, hereafter GC 8). The purpose of this paper is to examine these data for the variables insofar as they pertain to three topics: their location in the H-R diagram and implications for their evolutionary state; evidence for mass loss; and the mode of pulsation. Particular attention is drawn to seven variables which lie considerably to the blue of their cluster giant branches and which may be in an advanced evolutionary state. Other topics related to cluster variable stars are discussed in GC 5 and Frogel, Cohen, and Persson (1983, hereafter GC 9).

II. DATA AND PHYSICAL PARAMETERS

Reddening corrected colors and magnitudes for the cluster variables are given in Table 1. These are taken from the papers referred to in the Introduction. Values at maximum and minimum light are given for the long-period variables (LPVs) V1–4 in 47 Tuc for which extensive data are available (GC 5). The four LPVs in other clusters were observed only once (GC 8), although additional data are given by Robertson and Feast (1981). Multiple observations of a few of the shorter period variables (e.g., those in M4 and M22) show that the amplitudes of their infrared color and magnitude variations are small—typically less than 0.2 mag.

Bolometric magnitudes in Table 1 are taken from the same papers as the data. In all cases they were obtained either by integrating under the energy distribution curves or from the well established correlation between $J-K$ and BC_K, the bolometric correction to the K magnitude (GC 5).

The effective temperatures in Table 1 are, with the exception of those for the ω Cen variables, given in the references cited in the Introduction. As discussed extensively in GC 5 and GC 8, these temperatures are derived from $V-K$ colors and the calibrations of Ridgway *et al.* (1980) and Cohen, Frogel, and Persson (1978, hereafter GC 1) for $V-K<7.0$ and the Dyck, Lockwood, and Capps (1974) scale for $V-K \geq 7.0$. Although it is derived from observations of nonvariable metal-rich stars, application of the Ridgway *et al.* scale to the warmer cluster variables seems to be the best of several alternatives because (*a*) it is a well determined scale, (*b*) for $V-K<3.7$ it is in close agreement with the model atmosphere scale of GC 1 which exhibits only a small sensitivity to metallicity, and (*c*) at its cooler end an uncertainty of ± 0.5 mag in $V-K$ translates into an uncertainty of only ± 100 K in T_e. The Dyck *et al.* scale fits smoothly onto the Ridgway *et al.* scale at $V-K=7.0$ (see Fig. 12 of GC 5) and is based in part on observations of LPVs. As is argued in GC 5 and 8, $J-K$ was not used to obtain temperatures for the cool variables because of its near insensitivity to temperature changes in the region of interest and the relatively large and unpredictable effects of blanketing in $J-K$ compared to $V-K$. It may well be that when sufficient occultation data become available, a blackbody scale calibrated against *JHKL* colors will be shown to be satisfactory for the derivation of effective temperatures of the coolest stars. Until such time, results based on the presently available occultation data, e.g., the Q values (which depend on the third power of the temperature) derived by Fox (1982) for LPVs must be interpreted with caution.

Values of T_e of the coolest ω Cen variables in Table 1 are from the Ridgway *et al.* calibration and thus are somewhat hotter than the values in GC 3 which were derived solely from the model atmosphere in GC 1.

III. THE H-R DIAGRAM AND THE EVOLUTIONARY STATE OF THE LPVS

Figure 1 plots the bolometric magnitudes and effective temperatures of the variables in Table 1. The metal-rich clusters are those in Group A of GC 8 and 9, i.e., with an $[Fe/H] > -0.8$ on Zinn's (1980) scale. For the 47 Tuc LPVs the points plotted are luminosity means. *VJHKL* colors and CO and H_2O indices for the other LPVs are quite similar to the values for those in 47 Tuc. Because of the very limited data available for these other LPVs, though, it cannot be ascertained if there is a dependence of M_{bol} on period of metallicity (cf. Robertson and Feast 1981).

With the exception of V4 in 47 Tuc (which in fact is not usually classified as an LPV; cf. Hogg 1973), all of the LPVs in Figure 1 have luminosities significantly brighter than the tips of the first giant branches of the globular clusters, almost all of which are within 0.1 mag of the predicted luminosity for core helium flash—the

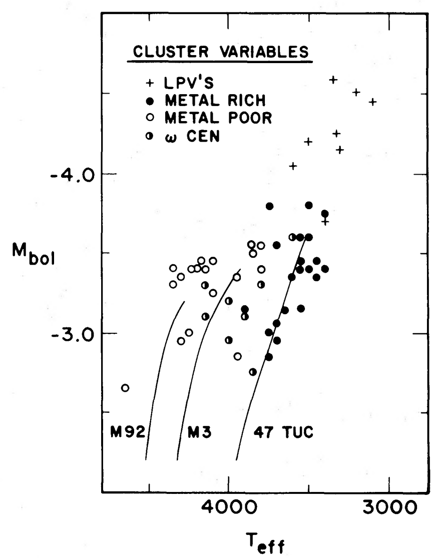

FIG. 1.—An H-R diagram for all globular cluster variables with infrared data from GC 3, GC 5, GC 7, and GC 8. The four LPVs in 47 Tuc are plotted at their average luminosities and temperatures from Table 7 of GC 5. The four newly observed LPVs were measured only once or twice. The metal-rich clusters are *only* those in group A of GC 8 and 9 ([Fe/H] on Zinn's 1980 scale, greater than −0.8). All of the LPVs are members of these clusters only. Variables from ω Cen (GC 3) are shown with a distinct symbol to emphasize the broad range in metallicity possessed by this cluster. The temperatures of the coolest variables in ω Cen (Table 2 of GC 3) were increased as noted in Table 1 of this paper. Fiducial giant branches are from Table 8 of GC 5.

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TABLE 1

PROPERTIES OF CLUSTER VARIABLES[a]

Cluster	Star	K_o	$(V-K)_o$	$(J-K)_o$	$(H-K)_o$	$(K-L)_o$	H_2O	CO	M_{bol}^{c}	T_e^{c}	P	Q^{b}	Notes
NGC 104	V1	5.74	4.1	1.09	0.33	0.50	0.31	0.115	-4.71	3780	212	0.072	LPV, 1
(47 Tuc)	V1	6.63	8.3	1.18	0.54	0.65	0.78	0.04	-3.44	2870		0.076	
	V2	5.86	4.0	1.10	0.35	0.44	0.44	0.135	-4.60	3810	203	0.076	LPV, 1
	V2	6.67	7.1	1.09	0.52	0.61	0.86	0.12	-3.47	3190		0.098	
	V3	6.00	3.9	1.04	0.30	0.38	0.32	0.16	-4.50	3840	192	0.079	LPV, 1
	V3	6.49	8.7	1.19	0.44	0.48	0.54	0.08	-3.56	2760		0.056	
	V4	6.40	5.5	1.07	0.30	0.41	0.36	0.14	-3.85	3490	82	0.040	LPV?, 2
	V4	6.57	6.7	1.15	0.34	0.42	0.49	0.11	-3.58	3280		0.040	
	V5	7.46	4.2	1.00	0.18	0.15	0.06	0.09	-2.99	3760	60	0.066	3
	V6	7.43	4.3	1.01	0.20	0.17	0.09	0.105	-3.03	3720	48	0.050	3
	V7	6.96	4.8	1.07	0.19	0.20	0.07	0.115	-3.37	3600	52	0.039	3
	V8	6.66	5.3	1.12	0.30	0.33	0.225	0.13	-3.60	3530	155	0.093	1
	V11	6.68	5.4	1.06	0.23	0.22	0.14	0.18	-3.58	3510	52	0.031	3
	V13	7.65	4.25	0.97	0.19	0.13	0.09	0.12	-2.83	3740	40	0.048	3
	V15	7.26	4.5	0.99	0.18	0.16	0.06	0.20	-3.17	3660	38	0.034	3
	V18	7.44	4.45	1.00	0.21	0.18	0.06	0.16	-2.96	3680	...	...	
	V19	7.49	3.7	0.98	0.19	...	0.135	0.09	-3.14	3910	...	...	Pec, 4
	V21	6.74	5.7	1.21	0.27	...	0.22	0.16	-3.45	3460	...	...	
	A19	6.79	5.1	1.20	0.25	...	0.125	0.15	-3.47	3560	...	...	
NGC 288	V1	8.47	3.97	0.97	0.18	...	0.115	0.21	-3.53	3820	103	0.082	1
NGC 362	V2	8.64	3.9	0.95	0.22	...	0.035	0.03	-3.52	3850	90:	0.074	1
NGC 1851	V24	9.32	3.83	0.94	0.14	...	...	0.10	-3.53	3865	183:	0.150	9
NGC 1904	V2	10.00	3.10	0.79	0.14	...	...	...	-3.31	4330	...	...	
NGC 4833	V9	8.10	2.96	0.64	0.09	...	0.01	0.00	-3.34	4320	87.7:	0.115	Pec, 1
	V16	8.42	3.07	0.71	0.12	...	...	-0.03	-2.98	4240	...	...	
NGC 5024	V49	10.99	3.00	0.73	0.11	...	...	...	-2.96	4280	111.6	0.185	1
	V50	10.42	3.26	0.79	0.13	...	0.05	0.015	-3.42	4140	55.4	0.06	1
NGC 5139	V6	7.09	4.8	1.14	0.30	...	0.15	0.095	-3.6	3600	73.5	0.047	1, 8
(ω Cen)	V17	7.54	4.1	1.00	0.22	...	0.10	0.17	-3.3	3800	64.7	0.059	1, 8
	V53	8.14	3.46	0.82	0.14	...	0.05	0.085	-2.95	4000	32.7	0.044	1
	V138	7.88	3.23	0.78	0.15	...	0.01	0.005	-3.30	4150	74.6:	0.089	1
	V148	7.89	3.51	0.85	0.16	...	0.03	0.075	-3.18	4000	90:	0.104	1
	V162	8.09	3.20	0.76	0.13	...	0.015	0.01	-3.10	4150	...	...	
	V164	8.19	3.83	0.94	0.15	...	0.035	0.095	-2.77	3870	37:	0.052	1, 8
	ROA320	7.82	3.8	0.94	0.21	...	0.17	0.30	-3.1	3750:	...	...	
NGC 5897	V5	9.76	3.33	0.84	0.16	...	0.07	0.015	-3.27	4090	54.5:	0.075	1
NGC 5927	V3	6.95	∼7	1.04	0.32	0.51	0.65	0.21	-4.52	3210	312	0.074	LPV, 7
	V5	8.15	5.4	1.05	0.20	...	0.12	0.165	-3.40	3510	...	...	
	V6	8.42	5.3	1.01	0.17	...	0.07	0.16	-3.16	3530	...	...	
	V8	8.17	5.8	1.02	0.22	...	0.11	0.20	-3.36	3445	70	0.046	7
	V9	8.09	6.2	1.08	0.20	...	0.09	0.14	-3.41	3380	85	0.051	7
NGC 6121	V4	5.79	3.3	0.68	0.16	0.28	0.05	-0.03	-3.45	4120	60	0.063	Pec, 5
(M4)	V13	6.24	3.6	0.85	0.15	0.19	0.055	0.09	-2.86	3935	40	0.055	1
NGC 6171 (M107)	V25	7.64	4.08	0.98	0.16	...	0.07	0.17	-3.42	3785	...	...	
NGC 6352	L36	6.91	6.2	1.03	0.29	0.49	0.46	0.185	-3.73	3380	...	...	10
	V4	7.27	5.1	1.06	0.22	...	0.09	0.15	-3.42	3550	...	...	
NGC 6553	V4	6.05	6.45	1.06	0.32	0.41	0.46	0.20	-4.62	3340	270:	0.067	LPV, 1
	V5	6.18	7.4	1.02	0.27	0.36	0.33	0.21	-4.46	3110	>100:	...	LPV?, 1

TABLE 1—*Continued*

Cluster	Star	K_o	$(V-K)_o$	$(J-K)_o$	$(H-K)_o$	$(K-L)_o$	H_2O	CO	M_{bol}	T_e	P	Q	Notes
NGC 6637	V3	8.42	4.19	0.95	0.14	...	0.08	0.155	-3.78	3750	...	...	Pec
(M69)	V4	7.95	4.80	1.14	0.37	...	0.56	0.145	-4.05	3600	196	0.091	LPV, 1
	V6	8.18	5.55	1.03	0.19	...	0.13	0.20	-3.80	3485	...	...	
	V7	8.58	4.43	1.03	0.19	...	0.08	0.19	-3.54	3680	...	...	
NGC 6656	V5	6.63	3.2	0.71	0.12	0.14	0.06	0.025	-3.47	4175	93.1	0.10	6
(M22)	V8	6.83	2.9	0.64	0.13	0.24	0.145	0.025	-3.39	4360	61	0.079	Pec, 6
	V9	6.65	3.5	0.78	0.12	0.14	0.045	0.10	-3.34	3960	87.7	0.089	6
	V30	6.69	3.21	0.78	0.12	0.08	0.105	0.04	-3.38	4165	...	...	
NGC 7006	V19	12.21	3.14	0.82	0.14	...	...	0.035	-3.38	4200	92.2	0.11	Pec, 1
	V54	13.22	2.48	0.66	0.10	...	...	...	-2.66	4660	...	...	Pec

NOTES TO TABLE 1

1. Period from Hogg 1973.
2. Period from Fox 1982. For the longer period of 165^d (Hogg 1973; Fox 1982) the Q value is 0.080.
3. Period from Fox 1982.
4. No period is available for this star, but for Q to be greater than 0.07, P must be greater than 63^d.
5. Hogg 1973 lists the period for this star as $50-70^d$.
6. Periods for M22 variables from Wehlau and Hogg 1977, who note that the periods may not be constant.
7. Period from Lloyd Evans and Menzies 1977.
8. T_e's for these cool ω Cen variables were changed from the values given in GC 3 to those inferred from the $V-K$ calibration given by Ridgway *et al.* 1980 as discussed in this paper and in GC 5.
9. Period from Wehlau *et al.* 1982.
10. Possible field star.

[a] Included in this table are all red cluster variables with infrared data from the series of papers on globular clusters by my colleagues and myself, specifically GC 3, GC 5, GC 7, and GC 8. Members of the class of variables that lie to the blue of the giant branch are denoted by a "Pec" in the Notes column.

[b] The Q values were calculated for $M = 0.7\ M_\odot$ for each star.

[c] Bolometric magnitudes and effective temperatures are from GC 8 with the following exceptions: 47 Tuc from GC 5; ω Cen from GC 3; NGC 7006 from GC 7.

point at which evolution up the first giant branch ceases (GC 9). Thus, as was argued in GC 5, the LPVs are most likely asymptotic giant branch (AGB) stars. From Figure 1 one can also conclude that no other type of cluster variable has an M_{bol} in the LPV range, i.e., ≤ -4.0, and hence AGB status can be assigned unambiguously only to the LPVs. Again as discussed in GC 5, variability alone does not compel assignment of a star with an M_{bol} fainter than the top of a cluster giant branch to the AGB.

Consider the three brightest non-LPV variables in Figure 1. One of them is L36 in NGC 6532. Lloyd Evans and Menzies (1977) consider this star a possible cluster member, although it lies quite far from the center. Its colors (see particularly Fig. 2) and large H_2O index are consistent with its being an LPV, but Lloyd Evans and Menzies (1977) claim that its range in V is only 0.5 mag. The other two bright non-LPVs are V3 and V6 in NGC 6637 (M69). Their colors give no indication that they are misclassified LPVs. In Appendix A of GC 9 the possibility that the distance modulus to this cluster has been overestimated is pointed out. If this is true, then these two M69 variables would no longer stand apart from the rest of the non-LPVs.

The appearance of Figure 1 indicates that a minimum luminosity is required for the onset of variability in globular cluster giants and that this minimum is not a strong function of metallicity.[3] Also, in the metal-rich clusters essentially *all* stars in the vicinity of the giant branch tip have been identified as variables (e.g., GC 5, GC 8), whereas in clusters like M4 and M22 only a fraction of the brightest giants seems to be variable (White's 1981 work, though, suggests that the fraction may be considerably higher than previously thought). Because of the homologous shapes of the cluster giant branches (GC 9), a minimum luminosity corresponds to a maximum temperature for variability—the value of the maximum being a *decreasing* function of metallicity as is evident from Figure 1. Furthermore, most of the variables in the metal-rich clusters are significantly cooler than the coolest stars in the metal-poor clusters.

A question which has not been completely addressed in the literature is why LPVs occur only in metal-rich clusters (Feast 1973). In part, the answer must lie in the fact that these clusters have the coolest giant branches. But the real significance of this question has to do with the luminosities of the LPVs. If the luminosity of a star on the AGB is largely independent of its pulsational characteristics and if the distance moduli of the clusters

[3] With three or four exceptions, all of the red giant variables in the cluster sample have been observed. It is possible, though, that fainter giant variables exist but have not been discovered because of incomplete searches or small V amplitude (see, for example, the recent work of White (1981).

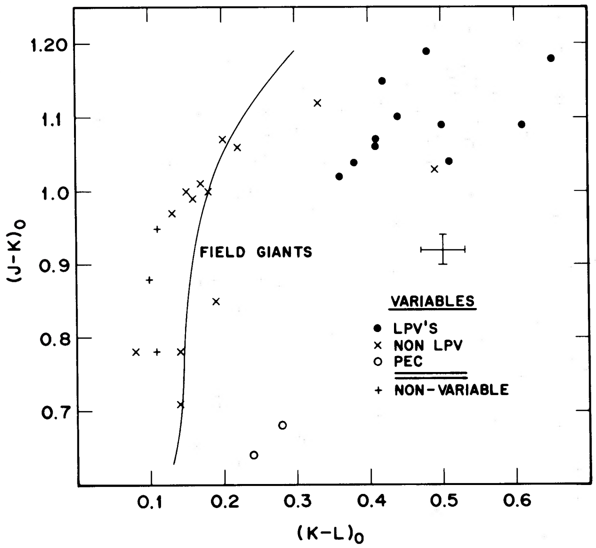

FIG. 2.—All stars with $K-L$ colors from GC 8 and GC 1–7 are plotted here. The field giant line is based on the $J-K$ colors from Frogel *et al.* (1978) and the $K-L$ colors of Johnson (1966) and Lee (1970). Although the L filters employed by us, by Lee, and by Johnson are similar, it is quite likely that some transformation should be applied to transform the $K-L$ colors of the two systems. Our colors are defined by the standard stars in Elias *et al.* 1982. Colors of the coolest giant stars therein are in fact consistent with the mean line drawn in this figure. For the four 47 Tuc LPVs, colors observed at both maximum and minimum light (Table 7 of GC 5) are plotted. The non–LPV star near the center of the LPV distribution is L36 in NGC 6532. The "Pec" variables are two of the variables which lie significantly to the blue of the giant branches of the clusters of which they are members. Typical $\pm 1\ \sigma$ error bars are shown.

are not grossly in error, then the key question is: Why do only metal-rich clusters have luminous AGB stars?

The brightest average luminosity for the 47 Tuc LPVs corresponds to an $M_{\rm bol}$ of -4.25. Robertson and Feast (1981) indicate that variables in NGC 5927 are as bright as -4.7. Let us say then that in a metal-rich cluster an AGB star can achieve an $M_{\rm bol}$ of -4.4, while in the metal-poor clusters—e.g., M3—there is no AGB star brighter than the tip of the first red giant branch at $M_{\rm bol} - 3.4$. Can this difference be understood from the effect of metallicity on a star's evolutionary rate?

An analytic formula attributed to Rood (eq. [2.5] of Renzini 1977) gives the total mass of a star at the beginning of its life as a red giant as a function of age and chemical composition. For an age of 15×10^9 years, a helium abundance $Y = 0.25$, and Z values of 0.004 and 0.0006 (which correspond to a typical metal-rich and metal-poor cluster, respectively), the values of $M_{\rm RG}$ are 0.83 and 0.77 $M_\odot$, respectively—a difference of 0.06 $M_\odot$. The question, then, is whether this mass "excess" in a metal-rich globular cluster giant is sufficient to fuel ascent on the AGB to an $M_{\rm bol} \sim -4.4$. (A similar problem has been investigated by Frogel and Whitford 1982 in a somewhat different context.)

Models of low-mass AGB stars show that for $M_{\rm bol} < -3.0$, these stars should be thermally pulsing due to periodic "flashes" in the helium-burning shell (e.g., Gingold 1974; Iben 1982). The core masses can be then calculated from a core mass-luminosity relationship such as that given in equation (2) of Iben and Truran (1978). For $M_{\rm bol} = -4.4$ and -3.4, the core masses so calculated are 0.55 and 0.48 $M_\odot$, respectively—a difference in mass essentially the same as the difference calculated in the previous paragraph between the two stars at the start of their careers as red giants. A reasonable assumption to make at this point is that a globular cluster LPV at -4.4 and a metal-poor AGB star at -3.4 are at or close to the end of their lives as giants and have burnt up essentially all of their hydrogen-rich envelopes. Thus, their core masses must be quite close to their total masses. An unreasonable but instructive assumption to make is that the AGB star which became an LPV lost no mass in evolving from $M_{\rm bol} = -3.4$ to -4.4. It is possible to conclude, then, that the difference in maximum AGB luminosity achieved by stars from metal-rich and metal-poor clusters can be understood from the metallicity difference alone *if and only if* both stars have lost essentially the same amount of mass—about 0.3 $M_\odot$—in evolving from the base of the first giant branch to the top of the AGB.

Very little quantitative information is known about mass loss from red giants in globular clusters. Peterson (1982) claims that the presence of mass loss, as inferred from Hα emission lines observed in these stars, depends *not* on metallicity, but merely on whether or not a cluster giant lies in the proper domain of the H-R diagram. On the other hand, it is possible to argue from theory that mass loss should have a Z dependence (see reviews by Renzini 1977 and Iben and Renzini 1983). In actual practice a mass loss rate for cluster red giants is usually calculated from a formula such as that of Reimers (1975). In any case, it is highly unlikely that no additional mass is lost by a star as it evolves up the AGB from $M_{\rm bol} - 3.4$ to -4.4 (see discussion in the next section). This excess mass loss will now be estimated.

The mass loss rate of a star as it evolves up the AGB may be estimated from equation (17) of Iben and Truran (1978) which is of the Reimers form but rewritten somewhat:

$$\frac{dM}{dt} = -3.97 \times 10^{-13} \alpha L^{3/2} T_e^{-2} M^{-1} \quad M_\odot\ {\rm yr}^{-1} .$$

Mass, temperature, and luminosity are in solar units. The scaling parameter, α, probably lies between 0.25 and 0.5 (Iben and Truran, and references therein). For an $M = 0.7\ M_\odot$ and mean values of L and T_e determined from Figure 1, $\Delta M = 0.35\alpha\ M_\odot$ in 10^6 years. Equation (4.3) of Renzini (1977) is used to estimate a time of 1×10^6 years for an AGB star to evolve from the level of the core helium flash to the domain of the LPVs in Figure 1. The temperature scale employed here appears to be near the high end of those that are currently in favor—a blackbody scale results in temperatures which are 10% or more cooler. Thus, if α is taken to be $\frac{1}{3}$, the metal-rich cluster giants which become LPVs must lose at least 0.1 $M_\odot$ more than the metal-poor cluster giants whose AGB evolution appears to be terminated at a luminosity level no greater than that corresponding to helium core flash on the first giant branch. Add to this the difference in mass calculated from the core mass-luminosity relation to give a minimum total mass difference between the two AGB stars of 0.17 $M_\odot$—three times greater than that predicted from the theoretical relation between total red giant mass and composition at constant age.

There are a number of interesting possibilities which could account for the differences between the different mass estimates; among them are the following:

1. The AGB core mass-luminosity relation (or the evolution rate-luminosity relation) is not applicable to the LPVs.

2. The relative distance moduli of the clusters are grossly incorrect.

3. The mass loss rates of globular cluster giants are inversely proportional to metal abundance.

4. The dependence of red giant initial mass on Z is much steeper than predicted by current models (a dependence steeper than Z^4 would be needed).

5. The metal-rich globulars are younger than the metal-poor ones—if the former were 10×10^9 instead of 15×10^9 years old as assumed above, the red giant mass would be increased by 0.10 $M_\odot$ for a net difference between the metal-rich and metal-poor giants of 0.15 $M_\odot$, close to the 0.17 $M_\odot$ calculated above.

Point 1 finds little favor with theoreticians (Iben and Renzini, private communications), and point 2 seems rather unlikely at present. Undoubtedly, the mass loss rate for giants and its dependence on the physical parameters of a star is quite uncertain. However, it would be difficult to argue physically in favor of point 3.

Point 4 seems to lead to problems with the rest of the H-R diagram for clusters. Point 5 is quite controversial. Demarque (1980) has argued that metal-rich clusters *are* younger than metal-poor ones by several times 10^9 years. VandenBerg (1981), on the basis of new model calculations, has argued that there is *no* age dependence. Sandage (1982) finds no evidence for a spread in cluster ages. Carney (1981) argues that observational and theoretical uncertainties are such that no definitive statement can be made about the dependence of cluster age on metallicity.

An interesting observations which could be interpreted to support point 5 concerns ω Cen. It certainly seems to have a number of giants which are as metal rich as those in M71 or 47 Tuc, and these giants have bolometric luminosities as bright as the brightest non–AGB stars in the latter two clusters (GC 3). But in spite of its large stellar population, it has no LPVs. In fact, with the possible exception of V6, none of its stars have bolometric luminosities greater than the first giant branch tip of metal-rich globulars such as 47 Tuc. Recall, however, that ω Cen's horizontal branch is an almost pure blue one with none of the red stars that one would expect to be the descendents of metal-rich giants. Does this mean, then, that ω Cen is significantly older than other metal-rich clusters? In that case, by the argument in point 5, no luminous AGB stars should be seen.

IV. EMPIRICAL EVIDENCE FOR MASS LOSS IN THE LPVS

With only two exceptions (L36 in NGC 6532 discussed above and V8 in 47 Tuc), none of the non–LPV variables have $(K-L)_0$ colors as red as the LPVs at the same $(J-K)_0$ (Fig. 2). The effect of H_2O absorption on *JHK* colors has been discussed in GC 5 and GC 8. Although the LPVs have significantly more H_2O absorption that non–LPVs at the same $(J-K)_0$, (the difference can amount to more than 0.6 mag in the H_2O index), the effect of H_2O on the K filter is given by $0.2 \times H_2O$ (GC 5), so this effect can account for not more than half of the $(K-L)_0$ shift. A likely explanation is that thermal emission from circumstellar dust is affecting the $K-L$ colors of the LPVs.[4] Observations at 10 μm are consistent with the presence of a modest amount of circumstellar emission in some of the cluster LPVs (Frogel and Elias, unpublished). This implies that for these LPVs effective temperatures cannot be obtained from *JHKL* colors in a straightforward fashion (cf. Robertson and Feast 1981). A very similar separation in $K-L$ at constant $J-K$ is seen for the relevant groups of stars in Baade's Window (Frogel, Whitford, and Blanco, in preparation).

Given the relative positions of the LPV and non–LPV variables in Figure 1, it is reasonable to expect that the mass loss rates in the former group should be considerably higher than in the latter. Consider the mass loss rates given in the previous section. If values for the non–LPV group of 3700 K and -3.3 are taken as representative from Figure 1, while values of -4.3 and 3200 K are taken for the LPVs, then *the LPVs will have a dM/dt which is 4.5 times greater than the non–LPVs.* Also it seems reasonable to expect that the much larger amplitude of the pulsation activity in the LPVs will provide an additional energy source to drive mass loss.

V. PULSATION CONSTANTS

The necessary data and their sources for this discussion are given in Table 1. A Q value for each star was calculated according to the formula (e.g., Glass and Feast 1982):

$$\log Q = \log P + 0.5 \log M/M_\odot + 0.3M_{\rm bol} + 3 \log T_e - 12.71 \,.$$

A value of $M/M_\odot = 0.7$ was used for each star. These Q values are compared with the results of calculation by Fox and Wood (1982) in Figure 3. Variables with

[4] Can the difference in $K-L$ between the variables and non-variables be due to temperature? As an example, take the extreme case and suppose the change in $K-L$ from 0.3 to 0.6 is due entirely to temperature. For blackbody emission, this corresponds to a change from 3500 K to 2400 K. The corresponding change in $J-K$ should be from 0.8 to 1.6, inconsistent with Fig. 2.

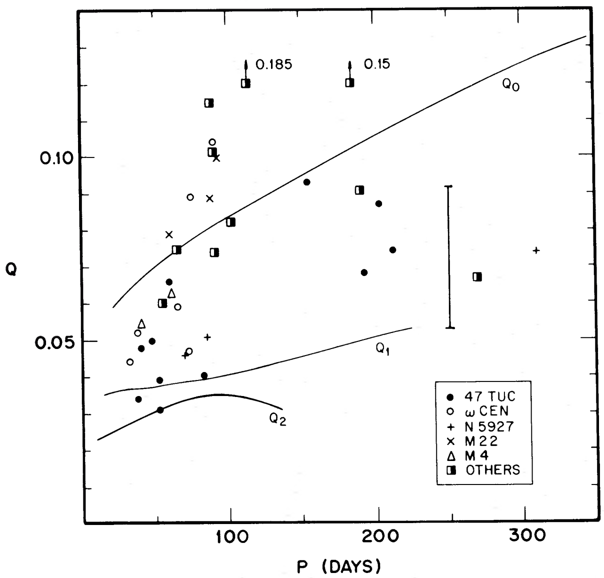

FIG. 3.—Theoretical and observed values of the pulsation constant Q, as a function of period. Q_0, Q_1, and Q_2 are the fundamental, first, and second harmonic values from Table 5 of Fox and Wood (1982). These are for a star with $M/M_\odot = 0.65$, and $(X, Z) = (0.699, 0.001)$. The observed values are from Table 1 here, calculated as described in the text. A stellar mass of 0.7 $M_\odot$ was assumed. The error bar illustrates the effect of a $\pm 10\%$ change in temperature for a star with initial parameters of $T = 3300$ K and $Q = 0.07$.

periods less than 150 days have temperatures greater than 3500 K, and hence should have the smallest uncertainties. Fox (1982), with similar data, has performed the same analysis for variables in 47 Tuc. The present 47 Tuc results for the shorter period variables are in reasonable agreement with his—namely, pulsation in some harmonic mode seems to be favored over the fundamental mode. For the LPVs, differences between these results and his arise primarily from differences in the temperature scale. Two of the other LPVs observed—V3 in NGC 5927 and V4 in NGC 6553—are close to the Q_1 line while V4 in NGC 6637 has a Q value close to that expected for a fundamental pulsator. This mode for LPVs is favored by Willson (1981). In view of the considerable uncertainty regarding the temperature scale for the LPVs, at present a strong case cannot be made for a particular mode of pulsation.

Wood (1981) claimed that variables in M4 are pulsating in the first harmonic mode, while those in M22 and ω Cen are pulsating in the fundamental mode. His statement about M22 is consistent with the data in Figure 3, but the M4 variables are marginally closer to the Q_0 line rather than the Q_1 line, while the ω Cen variables exhibit a significant range in Q.

Figure 3 shows that more than a half of the short-period cluster variables appear to be pulsating in the fundamental mode. They lie close enough to or above the Q_0 line that errors in T_e sufficient to change the Q value to the Q_1 line would have to be greater than 200–300 K—which seems unlikely for these relatively hot stars. Only the small-amplitude variables from the two most metal-rich clusters—47 Tuc and NGC 5927—are consistent with pulsation in an overtone mode. Periods and photometric data need to be obtained for a larger sample of variables if one wishes to pursue these matters further.

VI. THE PECULIAR VARIABLES

Finally, consider the variables denoted "Pec" in Table 1. All of these stars lie significantly to the blue of the mean giant branches of their respective clusters in both $(V-K)_0$ and $(J-K)_0$, thus ruling out the possibility that the displacement arises from lack of simultaneity of the V and K measurements. NGC 4833–V9 was not previously known to be a member of this class of variables; it is identified here as such for the first time. The blueness of the two NGC 7006 variables, particularly that of V54, is much more evident from the infrared photometry (Fig. 2 of GC 7) than from the optical (Sandage and Wildey 1967).

Eggen (1972, 1977), Lloyd Evans (1974, 1982), and GC 5 speculated that these stars are AGB stars in a transitory evolutionary state. Wehlau and Hogg (1977) quote a private communication from E. A. Mallia to the effect that V8 and V9 in M22 (the former star being one of the extreme examples of this class of variables) have barium star characteristics which would indicate that they are AGB stars since *s*-process elements are not expected to be synthesized on a star's first ascent of the giant-branch. Models calculated by Gingold (1974) show that AGB stars do in fact execute blue loops during their evolution. The four most extreme (as judged by their location on infrared *C-M* diagrams) members of this class of variables for which CO indices have also been measured—V19 (R10) in 47 Tuc, V9 in NGC 4833, V4 in M4, and V8 in M22—*all* have weak CO absorption relative to other stars in their clusters, both variable and nonvariable, with similar $(V-K)_0$ and $(J-K)_0$ colors.[5] If these variables really are in an advanced evolutionary state, then it seems possible that extensive mixing has seriously depleted carbon from the outer layers (cf. optical work by Zinn 1973 and review by Kraft 1979 concerning C depletion in AGB stars). Note in Figure 2 that the two variables of this type with $K-L$ data (M22–V8 and M4–V4) both seem to be somewhat red in this color. These two stars also have $K-[10\ \mu m]$ colors of $\sim +0.9$ (Frogel and Elias, unpublished), indicative of a modest circumstellar dust envelope. Additional work, both photometric and spectroscopic, on these stars would be worthwhile.

I want to thank Eric Persson and Judith Cohen for obtaining some of the observations upon which this paper is based. The paper was begun while I was on sabbatical leave at Caltech and completed at the

[5] An unpublished spectral scan with a resolution of 100 by Persson and Cohen of V4 in M4 through the 2.2 μm window shows that, at least for this star, CO absorption is in fact nearly absent, so that its low CO index is not due to a red continuum.

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