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RADII, STRUCTURE, AND ORBITS OF GLOBULAR CLUSTERS[1]

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ABSTRACT

Galactic globular clusters, that do not have collapsed cores, are found to exhibit a well defined correlation between luminosity and central concentration of light. Available observations tentatively suggest that globulars in the Large Cloud, and perhaps in M31 obey similar relationships. Galactic globular clusters on nearly circular orbits are seen to be systematically larger than other globulars (>99% confidence). Clusters on retrograde orbits are systematically smaller than other globulars. Globular clusters in the outer halo of the Galaxy and in the halo of the Magellanic Clouds have very large radii. The observation that globulars in the Fornax dwarf are smaller than those in the outer halo of the Galaxy, and that carbon stars are rare in the halo, suggests that the bulk of outer halo of the Galaxy may not have formed by the disintegration of dwarf spheroidal galaxies. Implications of the present results for ideas on the formation of (baryonic) galactic halos are briefly discussed.

1. INTRODUCTION

Most galaxies are embedded in systems of globular clusters (Harris 1991). The low metallicity, high velocity dispersion, and extended spatial distribution of globular cluster systems, all indicate that globulars constitute one of the most ancient galactic population components. Observations of such old clusters should therefore provide insights into the earliest phases of galactic evolution. Important clues about galaxy formation are also provided by the luminosities (masses), compositions, and orbits of individual clusters, and by the distribution of luminosities, compositions and orbital parameters within each cluster system. Additional constraints on ideas regarding the early evolution of galaxies, and the formation of globular clusters, are provided by (a) radial gradients in the diameters of globulars that occur in a number of cluster systems, (b) the dependence of specific cluster frequency on parent galaxy type, (c) the relation between mean cluster metallicity and parent galaxy luminosity, (d) differences between the elipticity distributions of globulars associated with different galaxies, and (e) the small dispersion in [Fe/H] of individual stars in most globular clusters. In this respect globular clusters differ from dwarf spheroidals, which generally exhibit a large metallicity spread.

2. CLUSTER RADII

The core radii r_c of globular clusters can evolve rapidly, as is shown by the fact that a significant fraction of globulars have had time to develop collapsed cores (Djorgovski & King 1986). However, N-body calculations (Spitzer & Thuan 1972; Hénon 1973; Lightman & Shapiro 1978; Murphy *et al.* 1990) show that the half-light radii r_h of clusters will, in general, only change by small amounts during periods as long as ten cluster relaxation times. For many globulars r_h therefore provides information on physical conditions that prevailed at the time of cluster formation. Murray & Lin (1993) have recently reemphasized the fact "that both cluster masses $\mathscr{M}$, and their radii r_h have remained largely unchanged due to post-formation evolution of the clusters." Furthermore these authors point out that the presently observed values of [Fe/H] in globulars must be similar to those existing in the protocluster from which each globular formed.

2.1 Galactocentric Distance and Cluster Radius

Within individual cluster systems the half-light radii r_h of globular clusters grow with increasing galactocentric distance $R_{\rm gc}$. This effect has now been observed in the Galaxy (van den Bergh *et al.* 1991), in the Large Magellanic Cloud (Hodge 1962; Mateo 1987), and in NGC 5128 (Hesser *et al.* 1984). Figure 1 shows a plot, based on a recent compilation of data by Djorgovski (1993), of log r_h vs log $R_{\rm gc}$ for metal-poor (halo) Galactic globular clusters with $[{\rm Fe/H}]<-1.0$. This figure shows that the radii r_h of halo globulars increase with increasing galactocentric distance $R_{\rm gc}$. Furthermore, the moderately metal deficient $-1.0<[{\rm Fe/H}]<-2.0$ clusters, and the very metal poor ones with $[{\rm Fe/H}]<-2.0$, are both seen to scatter about similar relations between log $R_{\rm gc}$ and log r_h. To guide the eye Figs. 1, 2, 4–7 all show the relation

$$\log r_h({\rm pc}) \approx 0.65 \log R_{\rm gc}({\rm kpc}). \quad (1)$$

The correlation coefficients between log $R_{\rm gc}$ and log r_h are found to be 0.85 ± 0.09, 0.60 ± 0.07, and 0.42 ± 0.15 for the clusters with $[{\rm Fe/H}]<-2.0$, $-2.0\leq[{\rm Fe/H}]\leq -1.0$ and $[{\rm Fe/H}]>-1.0$, respectively. (The low correlation coefficient for the most metal-rich clusters is, partly, due to the fact that such objects only occur over a restricted range in $R_{\rm gc}$.) It has recently been emphasized by Surdin (1994) that the lack of large clusters at small values of $R_{\rm gc}$ is, at least in part, due to the destruction of fragile extended clusters by Galactic tidal forces. However, *the absence of compact clusters in the*

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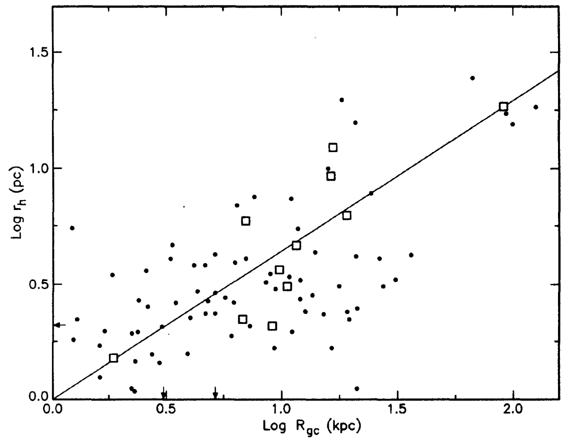

FIG. 1. Cluster radius vs Galactocentric distance for globular clusters with $-2.0<[\mathrm{Fe/H}]<-1.0$ (dots) and $[\mathrm{Fe/H}]<-2.0$ (squares). The fiducial line is the relation $\log r_h(\mathrm{pc})=0.65 \log R_{\mathrm{gc}}(\mathrm{kpc})$. Clusters in both metallicity ranges appear to scatter about the same r_h vs R_{gc} relation.

Galactic halo must be due to the fact that such systems never formed. A similar plot of $\log r_h$ vs $\log R_{\mathrm{gc}}$ for metal-rich ($[\mathrm{Fe/H}]>-0.8$) disk globular clusters is shown in Fig. 2. Perhaps unexpectedly, disk and halo clusters both appear to scatter about similar relations between r_h and R_{gc}. The nuclear globular clusters HP 1 (Mallen-Ornelas & Djorgovski 1993) and Terzan 1 are seen to fall considerably above the fiducial line defined by Eq. (1). Possibly, these two clusters have become puffed-up by bulge shocks (Aquilar *et al.* 1988). Alternatively, the estimates of the radii of these two clusters, which are located in very rich starfields, may have been overestimated, or their (uncertain) distances may be in error.

The observation that the fraction of clusters with collapsed cores is greatest at small values of R_{gc} is, no doubt, a consequence of the fact that compact clusters in the central region of the Galaxy have shorter relaxation times ($t_{\mathrm{rh}} \propto r_h^{3/2}$) than do larger globulars at greater Galactocentric distances.

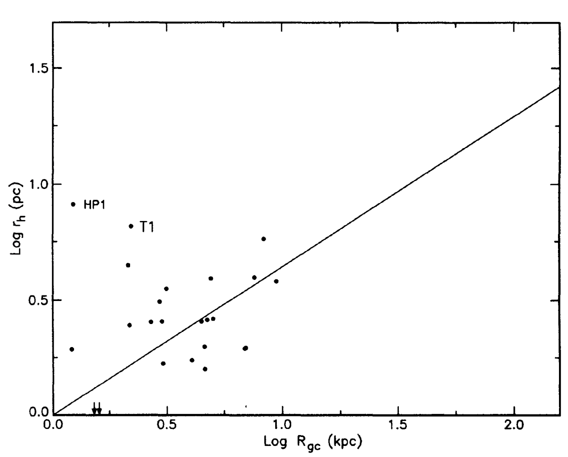

FIG. 2. Cluster radius vs Galactocentric distance for disk globular clusters with $[\mathrm{Fe/H}]>-0.8$. These disk clusters are seen to scatter about the same r_h vs R_{gc} relation as halo globulars.

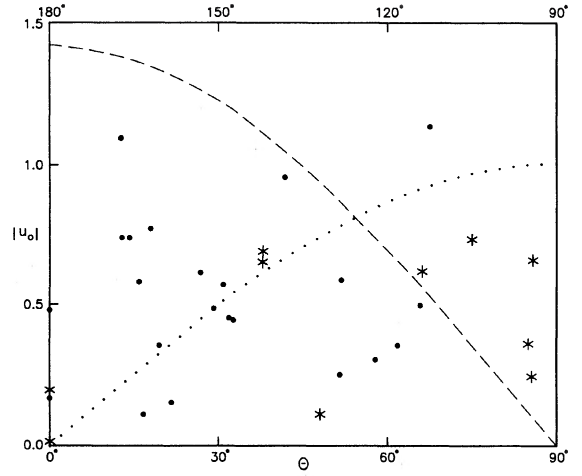

FIG. 3. *Ordinate:* cluster radial velocity (after removal of the component due to the Sun's galactic rotation), divided by the circular velocity at the cluster. *Abscissa:* angle θ between the Sun and the Galactic center, as viewed from the cluster. The dotted curve ($u_o=\sin\theta$) is the limit for circular orbits, and the dashed curve ($u_o=\sqrt{2}\cos\theta$) is the limit for linear orbits. Dots are small clusters that fall at least 0.20 above the line given by Eq. (1), whereas asterisks are large clusters that fall at least 0.20 below this line. The figure shows that the positions of most large clusters (asterisks) are compatible with near circular orbits, whereas the positions of most small clusters (dots) in the figure are compatible with linear orbits.

Perhaps surprisingly (van den Bergh *et al.* 1991), the radii r_h of clusters do *not* appear to correlate with their luminosities M_v.

2.2 *Radii of Clusters on Circular Orbits*

Perek (1954), von Hoerner (1955), and Kinman (1959) have shown that globular clusters with linear orbits, and clusters on circular orbits, occupy different regions in a $|u_o|$ vs θ plot (see Fig. 3). It should, of course, be emphasized that inferences about orbit shape, based on only a single velocity component, are uncertain and in many cases only statistical in nature (Zinn 1984; Rees & Cudworth 1991). The data plotted in Fig. 3 suggest that the majority of compact clusters (dots) probably lie on highly elongated orbits, whereas most of the extended clusters (asterisks) are on nearly circular orbits. Six halo clusters that lie on circular (or nearly circular) orbits are NGC 4372, NGC 5139, NGC 5904, NGC 6144, NGC 6362, and NGC 6723 (van den Bergh 1993a). Figure 4 shows that all of these objects fall above the line given by Eq. (1), i.e., such objects are of above-average size. A Kolmogorov–Smirnov test shows that there is less than 1% probability that the clusters on nearly circular orbits were drawn from the same parent population as the other halo globulars. *The observation that clusters on nearly circular orbits are of above-average size might be due to the fact that such clusters do not plunge into the dense bulge of the Galaxy,* where their outer regions could be stripped off tidally.

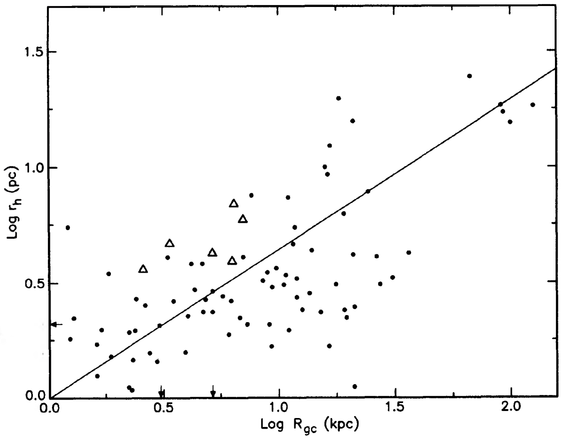

FIG. 4. Metal-poor clusters on circular orbits (triangles), are seen to have above-average radii.

2.3 *Clusters with Retrograde Orbits*

Figure 5 shows a plot of r_h vs R_{gc} for metal-poor ([Fe/H] <-1.0) halo clusters. The date on r_h and R_{gc} were both drawn from the recent compilation by Djorgovski (1993). The figure shows that the 11 globulars suspected to be on retrograde orbits (van den Bergh 1993a) appear to have below-average sizes. A Kolmogorov–Smirnov test shows that there is only a 3% probability that the 11 halo clusters, which according to van den Bergh (1993a,b) probably have retrograde orbits (asterisks), and the 78 other metal-poor clusters (dots) were drawn from the same parent population of distances from the fiducial line defined by Eq. (1). *The below-average radii of clusters in retrograde orbits might have been produced by ram-pressure stripping of gas from protoclusters,* as these objects moved through the (mostly prograde) gas in the protoGalactic corona. On this hypothesis one might expect clusters on retrograde orbits to be fainter (Stetson 1994) than clusters on direct orbits. For the present small data sample this is *not* observed to be the case. 11 clusters on retrograde orbits (van den Bergh 1993a,b) have $\langle M_v \rangle = -7.40 \pm 0.25$, compared to $\langle M_v \rangle = -6.95 \pm 0.63$ for 12 clusters on prograde orbits.

The majority of globular clusters on retrograde orbits either formed very early, when motions in the protoGalaxy were still highly chaotic, or they originated in ancestral galaxy fragments that were subsequently captured into retrograde orbits by the protogalactic core. It is therefore surprising that globular clusters in retrograde orbits do *not* have extremely low metallicities (Rodgers & Paltoglou 1984). For 11 globulars, which on the basis of their radial velocities are likely to be on retrograde orbits (van den Bergh 1993a), $\langle$[Fe/H]$\rangle = -1.59 \pm 0.07$. The three clusters with the most extreme retrograde orbits are NGC 3201, NGC 6934, and NGC 7006. These three clusters have very similar [Fe/H] values of -1.56, -1.54, and -1.59, respectively. Among the globulars to which van den Bergh (1993a,b) assigns retrograde orbits only NCG 7099 is an extremely metal-poor object with [Fe/H]<-2.0. For 12 halo ([Fe/H]<-1.0) globulars, to which van den Bergh (1993a) assigned prograde motions, [Fe/H]$=-1.65 \pm 0.11$. Perhaps unexpectedly, this value does not differ significantly from the value $\langle$[Fe/H]$\rangle = -1.59 \pm 0.07$ that is found for halo clusters that are probably on retrograde orbits. Possibly, the observation that clusters in retrograde orbits are not extremely metal-poor is due to the fact that they were formed deep in the Galaxy, i.e., near perigalacticon. (This might also account for their below-average r_h values.) Alternatively, such clusters might have been formed in a relatively metal-rich companion to the protoGalaxy, that was subsequently captured from a retrograde orbit. According to van den Bergh (1975), the mean metallicity of a cluster system is highest if its parent galaxy is luminous (massive). Because the mean metallicity of globulars on retrograde orbits ($\langle$[Fe/H]$\rangle = -1.59$) is higher than that of the 13 true globulars (Suntzeff 1992) in the LMC, for which $\langle$[Fe/H]$\rangle = -1.86$, the putative captured ancestral galaxy would probably have to have been quite massive.

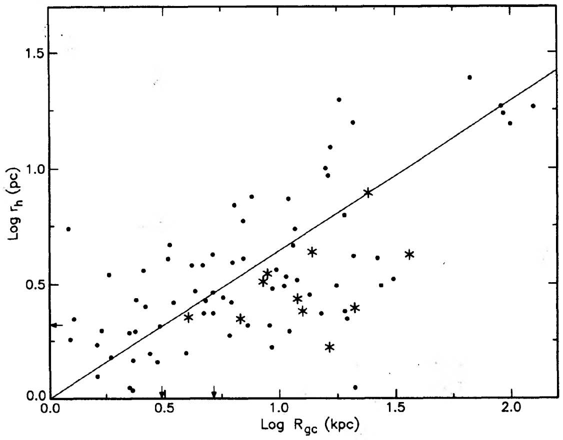

FIG. 5. Clusters on retrograde orbits (asterisks) appear to have below-average radii and fall below the mean relation between r_h and R_{gc} defined by Eq. (1).

2.4 *Cluster Radii and Population Assignments*

Following in the footsteps of Searle & Zinn (1978), van den Bergh (1993a) showed that Galactic globular clusters can be assigned to three "populations" on the basis of their location in a plot of [Fe/H] vs $(B-R)/(B+V+R)$, in which B, V, and R are the number of blue, variable, and red stars on the cluster horizontal branch. Clusters of types α and β appear to belong to younger and older halo populations, respectively, whereas globular clusters of the γ population are associated with a more centrally concentrated disk. Figure 6 shows the distribution of clusters of the α population in a plot of $\log r_h$ vs $\log R_{gc}$. These objects are seen to lie predominantly, but not exclusively, below the line defined by Eq. (1). In other words *clusters of the α population tend to have radii that are smaller than those of other globulars at similar Galactocentric distances.* Figure 6 also demonstrates that all clusters belonging to the α population have $R_{gc} > R_\odot$. Figure 7 shows that older halo clusters of the β population

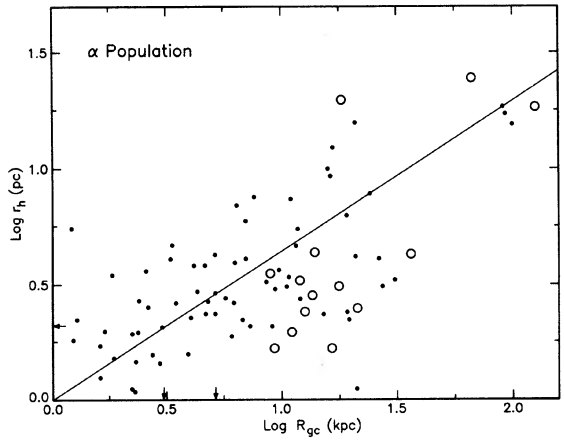

FIG. 6. Young halo globular clusters belonging to the α population of van den Bergh (1993a,b) are shown as open circles. These clusters are all seen to lie beyond R_{gc}=8.5 kpc. Furthermore, 12 out of 14 of these objects fall below the line defined by Eq. (1), i.e., they are smaller than other clusters at the same Galactocentric distance. Of the objects that fall below this line half are in retrograde orbits.

fall both above and below the feducial line defined by Eq. (1). Note, however, that most clusters belong to the β population have $R_{gc}<R_\odot$.

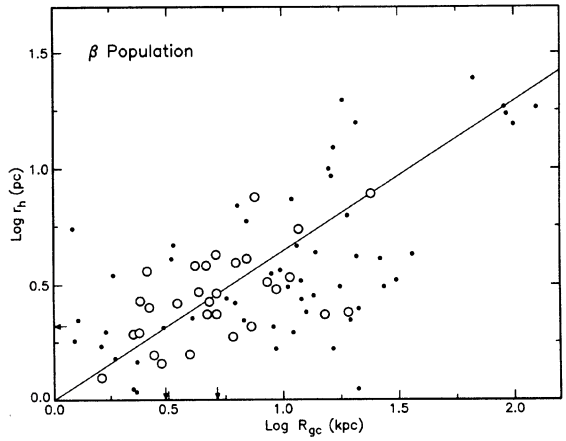

FIG. 7. Old halo globular clusters belonging to the β population of van den Bergh (1993a,b) are shown as open circles. Objects of this population, which mainly occur in the inner halo with R_{gc}<12 kpc, do not appear to deviate systematically from the relation defined by Eq. (1).

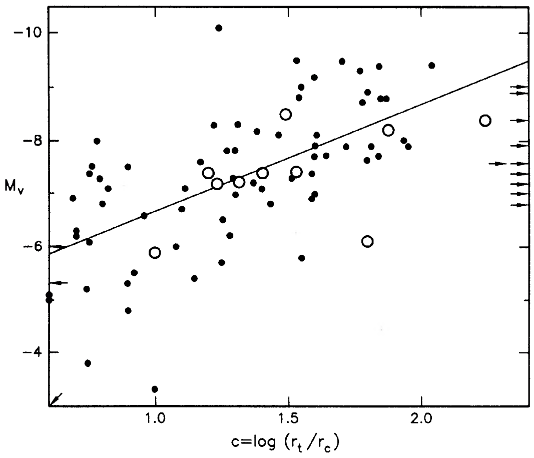

FIG. 8. Relation between cluster luminosity M_v and central concentration $c=\log(r_t/r_c)$. Clusters with collapsed cores, shown as arrows, do not follow this relation. Globulars on retrograde orbits (open circles) are seen to fall close to, or slightly below, the mean relation given by Eq. (2).

3. CLUSTER LUMINOSITY AND CONCENTRATION CLASS

It was first pointed out by Shapley & Sawyer (1927) that the central concentration of light in globular clusters correlates with luminosity. For clusters that do not have collapsed cores the reality of this correlation was subsequently confirmed by Djorgovski (1990) and van den Bergh (1994). Figure 8 shows this relation between cluster luminosity M_v and central concentration $c=\log(r_t/r_c)$ using the data recently compiled by Djorgovski (1993). This relation is adequately represented by the equation

$$M_v \simeq -4.7-2\log(r_t/r_c). \tag{2}$$

The observed dispersion of individual clusters about this relation is, in part, due to the fact that disk and bulge shocks can either increase or decrease the central concentration, depending on a cluster's initial concentration and on the shock parameters (Aguilar 1993). In Fig. 8 the distribution of clusters that probably lie on retrograde orbits (van den Bergh 1993a) does not seem to deviate systematically from that of other globulars.

Ground-based observations of a few bright globulars in M31 (Bendinelli *et al.* 1990) show that these objects have central concentration parameters in the range $1.5 \lesssim c \lesssim 2$, which is similar to that of the Galactic globulars of similar luminosity that are plotted in Fig. 8. The radial luminosity profiles of clusters Nos. 2–5 in the Fornax system (Rodgers & Roberts 1994a,b) also yield values of $c=\log(r_t/r_c)$ that are consistent with the M_v values expected from Eq. (2). In Sec. 5 it will be shown that clusters in the Large Cloud also appear to conform to the relation given by Eq. (2). It would be important, and very exciting, to use the *Hubble Space Telescope* to obtain accurate structural information on additional globular clusters in M31, and for clusters in other more distant galaxies.

4. GLOBULAR CLUSTERS IN FORNAX

The Fornax dwarf spheroidal galaxy contains five globular clusters. The metallicities of all of these objects are low, which is consistent with the hypothesis (van den Bergh 1975) that the mean metallicity of globular cluster systems decreases with decreasing parent galaxy luminosity. Some data on the magnitudes, colors and radii of the globular clusters associated with the Fornax system are collected in Table 1. The clusters in Table 1 have $\langle M_v \rangle = -7.2$, which is close to the value $\langle M_v \rangle = -7.41$ for Galactic globulars (Abraham & van den Bergh 1994).

The half-light radii of clusters listed in the table were derived from data given by Rodgers & Roberts (1994a,b).

TABLE 1. Globular clusters in Fornax.

Cluster No.	r_c [a]	r_h [b]	r_h(pc)[c]	V[d]	$B-V$[e]
1[f]	5″9	-	-	15.6	-
2	5.5	9″1	5.4	13.5	0.68
3(NGC 1049)	3.4	4.0	2.4	12.6	0.64
4	3.9	4.6	2.7	13.6	0.75
5	3.7	4.0	2.4	13.4	0.61

[a] Visual core radii from Rodgers & Roberts (1994a).
[b] Visual half-light radius.
[c] For an assumed distance of 123 kpc.
[d] From Webbink (1985).
[e] From van den Bergh (1969).
[f] r_h cannot be measured because of superposed star.

These half-light radii for Fornax clusters fall in the range 2.4–5.4 pc. Such values are similar to those of typical globular clusters in the inner galactic halo. Perhaps surprisingly, the Fornax clusters are found to be significantly smaller than globulars in the outer halo of the Galaxy, which typically have $r_h \gtrsim 10$ pc. This result indicates that globular clusters in the outer halo of the Galaxy were not formed in dwarf spheroidal galaxies that were subsequently disrupted by Galactic tidal forces. This suggests that dwarf spheroidals were not the predominant building blocks (Zinn 1993) for the Galactic halo. A similar conclusion is perhaps also suggested by the fact that giant carbon stars are common in dwarf spheroidals, but relatively rare in the Galactic halo. From a survey of faint high-latitude carbon stars Green *et al.* (1994) estimate a surface density of ~0.02 carbon stars per square degree. The corresponding total population of halo giant carbon stars is $\sim 1 \times 10^3$. According to Azzopardi & Lequeux (1992) the Fornax dwarf spheroidal galaxy, which has $M_v = -13.7$, contains a total of 77 carbon stars. All of the carbon stars in the Galactic halo could therefore have been derived from disintegrated dwarf spheroidals with a total luminosity of only $M_v \sim -16.5$. Some support for such an origin for halo carbon stars is provided by Green *et al.* (1994), who find that the distribution of Galactic halo carbon stars has a larger effective Galactocentric radius than that of the Galactic globular cluster system. The value $M_v \sim -16.5$ derived above is somewhat smaller than the integrated magnitude $M_v = -17.4$ that Suntzeff *et al.* (1992) estimate for all Galactic population II stars. Alternatively, it might be argued that red giant carbon stars in dwarf spheroidals are intermediate-age objects, and that the paucity of such carbon stars in the halo is due to the fact that most dwarf spheroidals were captured by the Galaxy *before* they had a chance to form second generation stars.

Rodgers & Roberts (1994a) note that Fornax clusters Nos. 1 and 2 may have interacted to produce the observed truncation of cluster No. 2, and perhaps also the partial disruption of cluster No. 1. Similar effects might also be expected to have occurred in globulars formed together in small ancestral fragments, that had a low internal velocity dispersion.

TABLE 2. Clusters in the LMC.

Name	type[a]	M_v[b]	r_h(″)	r_h(pc)[c]	$\log(r_t/\ r_c)$[d]	R(LMC)[d]
NGC 1718	Pop.I	−6.9	35.9[e]	8.7[e]	1.68	3:43
NGC 1754	⊕	−7.2	10.5	2.5	1.03	2.56
NGC 1786	⊕	−8.0	12.3	3.0	1.68	2:50
NGC 1835	⊕	−9.1	14.1	3.4	1.68	1.61
NGC 1841	⊕	−7.6	60.6[f]	12.0	1.08	14.9
NGC 1852	Pop.I	−7.0	26.9	6.5	1.03	1.81
NGC 1978	Pop.I	−8.5	29.2	7.1	1.26	3.11
NGC 2005	⊕	−7.4	11.5	2.8	—	0.95
NGC 2019	⊕	−7.9	10.4	2.5	—	1.33
NGC 2155	⊕	−6.4	20.4	4.9	1.03	5.23
NGC 2210	⊕	−8.2	18.0[g]	4.4[g]	1.45	4.50
NGC 2257	⊕	−7.1	46.2[g]	11.2[g]	1.10	8.48
H 11	⊕	−7.3	29.6[e]	7.2	1.00	4.71
H 14	Pop.I	−5.3	17.6	4.3	1.03	4.44
Reticulum	⊕	−6.2	79.1[f]	17.3[f]	1.00	11.4

[a] According to Suntzeff 1992).
[b] $(m-M)_v = 18.6$ assumed.
[c] Distance of 50 kpc assumed.
[d] From Mateo (1987).
[e] r_c and r_t from Mateo (1987), r_h from Eq. (3).
[f] From Suntzeff *et al.* (1992) and Eq. (3).
[g] Data from Elson & Freeman (1985).

5. CLUSTERS IN THE LMC

Half-light radii of a dozen clusters associated with the Large Cloud were read from plots of their radial surface brightnesses published by Elson & Freeman (1985) and Mateo (1987). For a few of these clusters r_h is rendered somewhat uncertain because Mateo's brightness profiles do not extend out far enough to determine the total cluster luminosity with complete confidence. A few additional values of r_h for LMC clusters were estimated from published core radii r_c and tidal radii r_t. For Galactic globular clusters, that do not have collapsed cores, it is found that

$$\log r_h = +0.41 \log r_c r_t + 0.03. \tag{3}$$

[The relation $r_h = 0.7 \sqrt{r_c r_t}$ used by Fall & Rees (1977) overestimates r_h for ~90% of the best-observed clusters that do not have collapsed cores.]

All available data on the radii of Cloud clusters are summarized in Table 2. Also included in this table are data for NGC 1841 and the Reticulum system, which are probably very distant companions to the Magellanic Clouds (Suntzeff *et al.* 1992). From Eq. (3) and the values of r_c and r_t in Table 4 of Suntzeff *et al.* (1992) one obtains $r_h = 12.0$ pc and $r_h = 17.3$ pc for NGC 1841 and the Reticulum system, respectively. It is interesting to note that *these two clusters in the halo of the Magellanic Clouds have radii that are comparable to those of globulars that populate the outer reaches of the Galactic halo.* The other LMC globulars have radii that are quite comparable to those of most Galactic globular clusters with $R_{gc} \lesssim 10$ kpc.

The data from Table 2 are plotted in Figs. 9 and 10. Figure 9 strengthens and confirms the conclusion by Hodge (1962) and Mateo (1987) that the radii of LMC clusters grow with increasing galactocentric distance. There may also be some indication that populous old open clusters are, at a given value of R(LMC), slightly larger than globular clusters. However, more observations are needed to strengthen or disprove this tentative conclusion. The fiducial line drawn in Fig. 9 is the relation

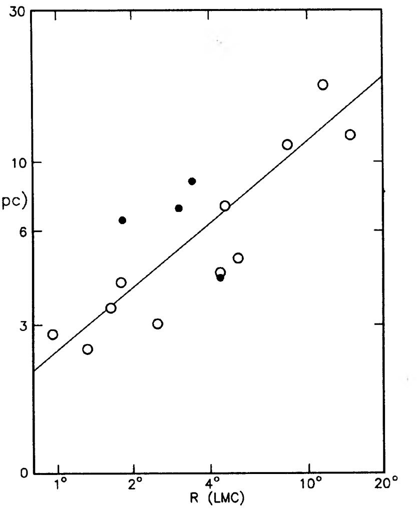

FIG. 9. Half-light radii of clusters in pc vs distance from center of LMC in degrees. The figure shows that cluster radius increases with increasing galactocentric distance. At a given distance from the center of the Large Cloud populous old clusters of Population I (filled circles) may, on average, be slightly larger than globular clusters (open circles). The line in the figure is given by Eq. (4).

$$\log r_h = \frac{2}{3} \log R(\mathrm{LMC}) + 0.4, \tag{4}$$

in which r_h is in pc and the *projected* distance R(LMC) is in degrees. Finally it is noted that globular clusters account for ~2% of the luminosity of Population II stars in both the LMC and the Galaxy (Suntzeff *et al.* 1992).

6. CAPTURE OF GLOBULAR CLUSTERS

The clusters Palomar 12 and Ruprecht 106 appear to have ages that are 3 and 4–5 Gyr, respectively, younger than those of typical Galactic halo globular clusters. Lin & Richer (1992) have argued that Rup 106 might have been tidally captured from the Magellanic Clouds. These authors also find that a similar, although somewhat weaker, argument for tidal capture can be made for Pal 12. A difficulty with the hypothesis that Pal 12 was captured from the Large Cloud is that it has $[\mathrm{Fe/H}]=-1.14$, which falls outside the $-2.17 < [\mathrm{Fe/H}] < -1.37$ range observed for true globular clusters (Suntzeff 1992) in the LMC. With an age of $\gtrsim 10$ Gyr, Pal 12 is also too old (and too metal-poor) to be associated with LMC populous clusters, which all have ages $\lesssim 5$ Gyr (Da Costa 1991). However, the possibility that it is related to the maverick cluster ESO 121=SC03, which has $[\mathrm{Fe/H}] \simeq -1$ and an age of ~10 Gyr, cannot yet be excluded. Alternatively, Pal 12 might have been stripped from the SMC in which clusters with ages in the range 4–12 Gyr are observed to have $[\mathrm{Fe/H}] \sim -1.3$ (Da Costa 1991). This value is close to $[\mathrm{Fe/H}]=-1.14$ obtained for Pal 12. The low ($[\mathrm{Fe/H}]=-1.69$) metallicity (Da Costa *et al.* 1992) of Rup 106 would be compatible with an origin in the LMC.

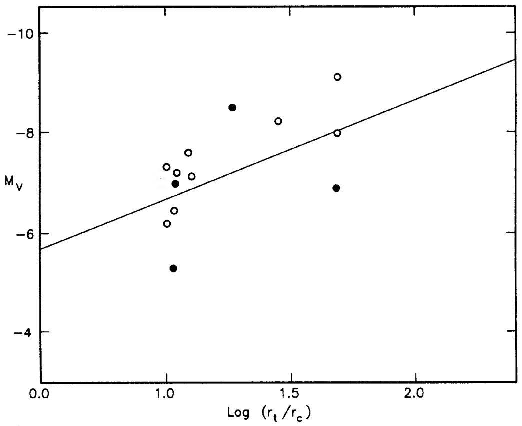

FIG. 10. Relation between luminosity and central concentration for globular clusters (open circles) and populous old clusters (filled circles) in the Large Cloud. The data, which were taken from Table 2, suggest that LMC clusters may obey the same M_v vs $\log(r_t/r_c)$ relation [Eq. (2)] as do Galactic globulars.

NGC 2257, which is located $8^{\circ}\!.5$ from the center of the Large Cloud, has a core radius of 6.1 pc. This is similar to the values $r_c=5.8$ and $r_c=6.2$ which Djorgovski (1993) finds for Rup 106 and Pal 12, respectively. In other words, these two young globular clusters are so large that they are only expected to have occurred in the inner halo of the Large Cloud, which is compatible with the tidal stripping hypothesis.

The clusters Terzian 7 and Arp 2 (Buonanno *et al.* 1994) have ages derived from their main sequence turnoffs that are 2–4 Gyr younger than those of the majority of Galactic globular clusters. Buonanno *et al.* therefore suggest that these objects may have been captured by the Milky Way galaxy. This suggestion appears unattractive for Terzian 7, which has $[\mathrm{Fe/H}] \sim -0.5$, because it is much more metal-rich than other LMC and SMC clusters of similar age. The large core radius ($r_c=13$ pc) and low metallicity of ($[\mathrm{Fe/H}]=-1.85$) of Arp 2 are, however, compatible with tidal capture from the outer halo of the Magellanic Clouds.

7. GLOBULAR CLUSTER LUMINOSITY FUNCTIONS AND MASS SPECTRA

Figure 11 shows the luminosity functions for small [$\log r_h(\mathrm{pc}) < 0.40$], intermediate-size [$0.40 \leq \log r_h(\mathrm{pc}) \leq 0.80$], and large [$\log r_h(\mathrm{pc}) > 0.80$] Galactic globular clusters. These luminosity functions are based on the compilation by Djorgovski (1993), which assumes $M_v(\mathrm{RR})=+0.6$. Inspection of Fig. 11 shows, and a Kolmogorov–Smirnov test confirms, that the luminosity functions of small and of intermediate-sized globular clusters do not differ significantly. The luminosity function of the largest clusters appears to be broader than that for small and intermediate-sized clusters. However, a Kolmogorov–Smirnov test shows that this apparent difference is *not* significant at the 95% confidence level.

Due to the presence of a few very faint clusters (some of which may be on the path to oblivion) the luminosity function of Galactic globulars appears slightly asymmetrical. The influence of such outliers can be minimized by expanding the

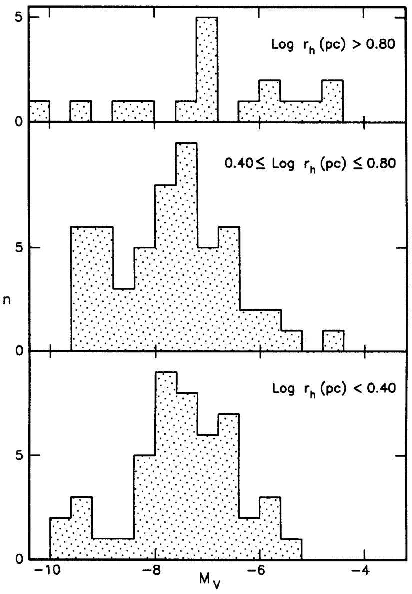

FIG. 11. Luminosity functions for small, intermediate-sized, and large Galactic globular clusters. The luminosity function for large clusters appears broader than that for smaller clusters. However, this difference is not significant at the 95% confidence level.

observed cluster luminosity function into Gauss–Hermite polynomials (Abraham & van den Bergh 1994). This method shows that the core of the Galactic globular cluster luminosity function is well described by a Gaussian with $\langle M_v \rangle = -7.41$ and σ $(M_v) = 1.24$ mag. The corresponding mass distribution is, of course, log-normal. Alternatively, Harris & Pudritz (1994) have recently argued that the mass distribution of globulars with $\mathcal{M} \gtrsim 10^5$ $\mathcal{M}_\odot$ may be represented by a power law with $N \propto \mathcal{M}^{-1.7}$. A fit of such a power law to the data for Galactic globulars (Djorgovski 1993) with $3 < R_{gc}$(kpc)<30 is shown in Fig. 12. The observed mass spectrum of Galactic globulars appears to deviate from a power law in the same sense as that of the globular clusters associated with giant elliptical galaxies in the Virgo cluster (Harris *et al.* 1991).

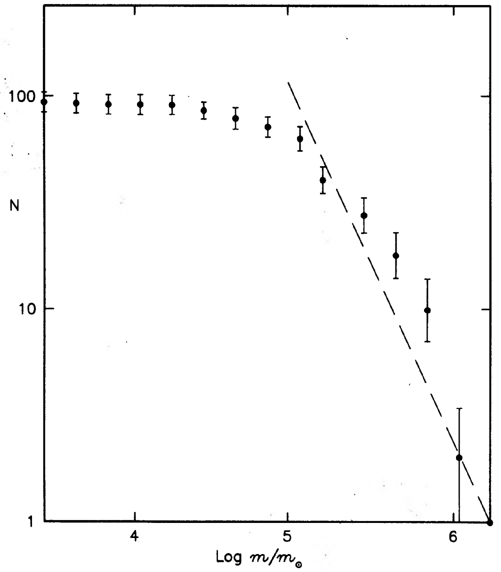

FIG. 12. Observed mass spectrum of Galactic globular clusters with $3 < R_{gc}$ (kpc)<30 for an assumed mass-to-light ratio $(\mathcal{M}/L)_v = 2.0$. Also shown is a fit to a power law with $N \propto \mathcal{M}^{-1.7}$ for $\mathcal{M} > 1 \times 10^5$ $\mathcal{M}_\odot$.

Harris & Pudritz (1994) note that the present mass spectrum of giant molecular clouds also has the form $N \propto \mathcal{M}^{-1.7}$. This coincidence may, or may not, have physical significance. It is, for example, not clear that the present mass spectrum of dusty metal-rich GMC's in the Galactic disk should be identical to that which prevailed long ago for metal-poor, dust free clouds in the Galactic halo. Furthermore, it is not obvious that the masses with which clusters form will be proportional to that of their (much more massive) ancestral clouds.

Perhaps the most remarkable feature of the globular cluster luminosity function is that it is independent of environment. Armandroff (1989) and Abraham & van den Bergh (1994) find that globular clusters belonging to the Galactic disk and halo subsystems have luminosity functions that are statistically indistinguishable. Furthermore, Harris *et al.* (1991) find that the peak of the cluster luminosity function of giant ellipticals in the Virgo cluster has an M_v value that is very similar to that of the globular clusters associated with the Fornax dwarf spheroidal galaxy (see Sec. 4). It should, however, be emphasized that the luminosity function (and mass spectrum) of all globular clusters differ dramatically from that of open clusters (van den Bergh 1993b).

8. ARE THERE GRADIENTS IN THE OUTER HALO?

Present ideas on the formation of the Galactic halo have been profoundly influenced by the discovery (Searle & Zinn 1978) that globular clusters in the halo region with $R_{gc} > R_\odot$ exhibit little or no radial abundance gradient. From this observation these authors concluded that the outer halo did not have pressure support. Searle & Zinn (1978) therefore speculated that the stars and globular clusters in the outer halo were formed in large independent gas clouds (or small ancestral galaxies) that were subsequently captured by the protoGalactic core. A quite different situation is, however, suggested by Fig. 1, which appears to suggest that the half-light radii r_h of Galactic globular clusters exhibit a pronounced radial gradient. This difference in size between clusters in the inner and outer halo of the Galaxy is dramatically illustrated by Fig. 13 (Plate 81), which shows a comparison between the typical inner halo cluster M3 and the outer halo cluster NGC 2419. In this figure both clusters are shown to the same *linear* scale.

A slightly different way of looking at the problem of possible gradients in the outer part of the Galactic halo is provided by Fig. 14. In this figure $\langle \mu_h(V) \rangle_0$, the mean surface brightness in V light (corrected for absorption) within the half-light radius r_h, is plotted as a function of Galactocentric distance R_{gc}. The figure can be interpreted in two quite distinct ways: either (a) there is a radial gradient in cluster surface brightness that extends from $R_{gc} \sim 10$ kpc to distances ~ 100 kpc, or alternatively, (b) the Galaxy is surrounded by a

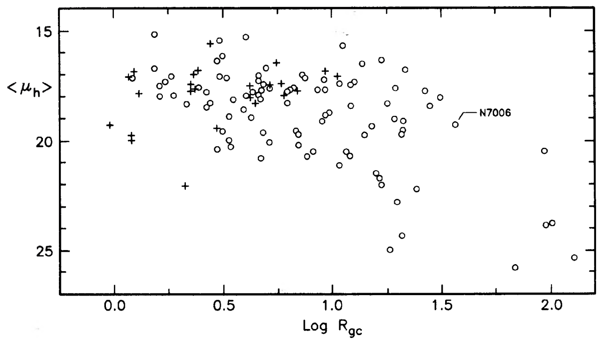

FIG. 14. Average surface brightness (corrected for absorption) $\langle\mu_h\rangle_0$ within the half-light radius vs Galactocentric distance R_{gc}. Clusters with collapsed cores are shown as crosses. The figure might be interpreted in two ways: either (a) Galactic globular clusters exhibit a gradient in their mean surface brightness, or (b) there is a separate population of large clusters with low surface brightnesses in the outer part of the galactic halo.

population of normal globular clusters with high surface brightnesses that range out to $R_{gc}\sim 30$ kpc, which is embedded within an additional component consisting of low surface brightness objects that extends over the range $15 \lesssim R_{gc}$ (kpc)$\lesssim 100$. Possibly, members of this low surface brightness population, that once existed at $R_{gc}<15$ kpc, have by now all been destroyed by galactic tidal forces. A problem with the second interpretation is, however, that it does not explain why there are no high surface brightness globulars beyond $R_{gc}=36$ kpc. It is noted in passing that the most distant compact globular cluster is the well known second-parameter object NGC 7006 (Sandage & Wildey 1967).

9. SUMMARY AND CONCLUSIONS

Within globular cluster systems the radii of clusters are (with considerable scatter) related to their galactocentric distances by the relation

$$r_h \propto R^\gamma, \tag{5}$$

in which $\gamma\sim 2/3$. The existence of such a *gradient* in cluster radii suggests that globular cluster systems may constitute a single dynamical and evolutionary unit. Tidal destruction of large clusters at small galactocentric distances might account for part of the observed gradient in globular cluster dimensions. However, the absence of small compact clusters in the halo appears to be an intrinsic phenomenon that is related to the cluster formation process.

It is curious that the globular cluster radii at $R>R_\odot$ appear to exhibit a radial gradient, while cluster metallicities do not (Searle & Zinn 1978). *This conundrum could, perhaps, be resolved by assuming that metal enrichment in the Galactic halo was predominantly a local phenomenon, whereas cluster radii might have been mainly determined by global properties of the halo of the protogalaxy.* An external source of UV and soft x-ray radiation (Kang *et al.* 1990, Murray & Lin 1992) originating in or near the Galactic nucleus is an example of an agent that might produce a global gradient in halo cluster properties.

Within the Galaxy Eq. (1) appears to be independent of metallicity. However, globular clusters in retrograde orbits tend to have below-average radii. It is suggested that the small size of globulars in retrograde orbits might have been produced by ram-pressure stripping of the outer regions of protoglobulars as they moved through gas in the protogalactic corona. However, their luminosities militate against this hypothesis. Globular clusters in nearly circular orbits are (at >99% confidence) found to have above-average radii. This phenomenon may be due to the fact that such clusters do not suffer as much tidal stripping as do clusters on elongated orbits that plunge deeply into the dense central region of the galaxy.

No significant correlation is found between r_h and M_v of globular clusters. The moderately high ($\langle[\mathrm{Fe/H}]\rangle=-1.59 \pm 0.07$) metallicity of clusters in retrograde orbits suggests that they were formed near perigalacticon. Alternatively they might have been captured into retrograde orbits from a relatively massive and metal-rich ancestral galaxy. The relatively large radii of the "young" globular clusters Palomar 12 and Ruprecht 106 are consistent with their having been stripped from the halo of the Magellanic Clouds. The rather high metallicity of Pal. 12 might favor an origin in the Small Cloud. The observation that all of the globular clusters associated with the Fornax dwarf spheroidal galaxy have relatively small values of r_h indicates that the large globular clusters in the outer halo of the Galaxy were probably *not* formed in proto dwarf spheroidal galaxies that subsequently disintegrated.

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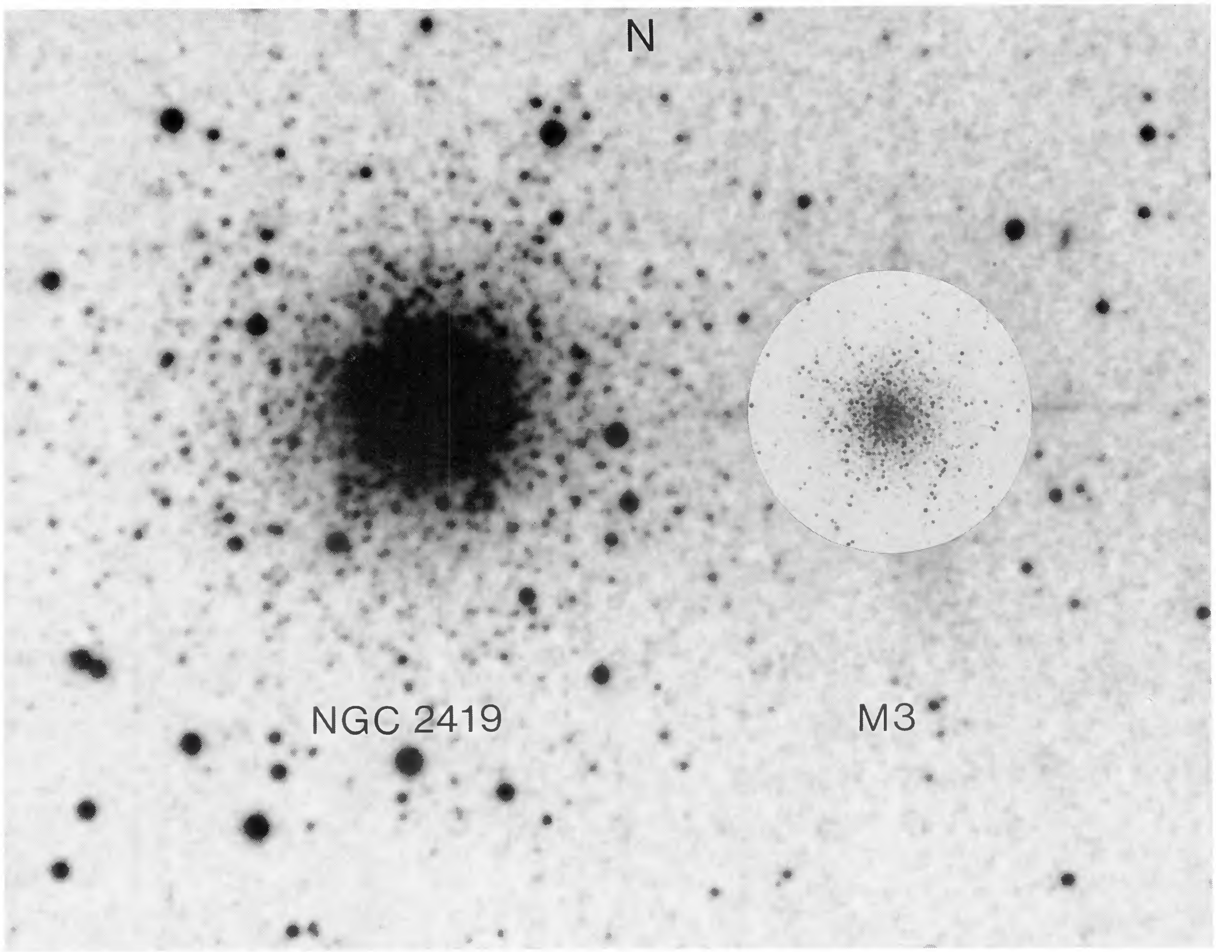

FIG. 13. Images of M3 and of the outer halo cluster NGC 2419 printed to the same linear scale. The figure shows that some clusters in the outer Galactic halo are much larger than globulars located in the inner halo. ©National Geographic Society—Palomar Sky Survey.

S. van den Bergh (see page 2151)