

## STAR CLUSTERS IN THE CLOUDS OF MAGELLAN<sup>1</sup>

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### ABSTRACT

Star clusters in the Magellanic Clouds differ from those in the Galaxy in a number of important respects:

1. Both old and young clusters in the Clouds have radii  $r_h$  that are typically 3–4 times larger than those of their Galactic counterparts.
2. Luminous clusters of all ages in the LMC and the SMC are, on average, significantly more flattened than Galactic clusters.
3. The clouds contain a class of populous star clusters, with masses that are typically an order of magnitude smaller than those of average globulars, but an order of magnitude larger than those of most Galactic open clusters.
4. Many young clusters in the Magellanic Clouds are embedded in rich unbound stellar coronae. Such halos are probably the remnants of the associations in which these clusters were born. Stellar coronae around clusters can survive longer in the Clouds than in the Galaxy because tidal forces are much lower in the LMC and SMC than they are in the Galaxy.
5. The Large Cloud is surrounded by at least seven real globular clusters with ages greater than 10 Gyr (six of which contain RR Lyrae stars), whereas the Small Cloud has only one such companion. These clusters have luminosities and mass-to-light ratios similar to those of Galactic globulars. All six of the Large Cloud globular clusters for which color-magnitude diagrams are available have blue horizontal branches. This may indicate that these objects all have very large ages. Available data do not yet entirely exclude the possibility that these globular clusters belong to a spheroidal halo.
6. The specific globular cluster frequency is found to be  $S = 0.4 \pm 0.15$  for the LMC, and  $S = 0.3 \pm 0.3$  for the SMC.
7. In both the Large Cloud and the Small Cloud old clusters are found to be more widely distributed than are younger clusters. Known old clusters (and nova) exhibit no concentration to the Bar of the LMC.
8. Both the metal enrichment history and the ages of star clusters indicate that star formation in the SMC got off to a slow start. The large residual gas mass in the Small Cloud also indicates that the Small Cloud never went through an intense prolonged starburst phase. No Large Cloud clusters are presently known with ages between about 3 and 10 Gyr. The end of this hiatus may have coincided with a major burst of star formation in the LMC.
9. The fact that the two largest bursts of star and cluster formation in the LMC appear to have no counterparts in the SMC indicates that the bursts of star formation in the Large Cloud were *not* triggered by close encounters between the Clouds.

*Subject headings:* clusters: globular — galaxies: Magellanic Clouds — galaxies: stellar content — stars: evolution — stars: formation

### 1. INTRODUCTION

Most young stars are formed in stable (negative energy) clusters or in expanding (positive energy) associations (Ambartsumian 1949; Blaauw 1952). It is not yet known which physical factors favor the formation of star clusters. The Large Magellanic Clouds (LMC) and Small Magellanic Clouds (SMC) are both rich in star clusters, whereas the dwarf irregular IC 1613 contains associations but no star clusters (Baade 1963, p. 230; van den Bergh 1979). The discovery that the specific frequency of globular clusters in elliptical galaxies differs from galaxy to galaxy (Harris & van den Bergh 1981) suggests that cluster formation is affected by the environment in which such objects form. It is not yet known which factors govern galaxy-to-galaxy variations in the tendency to form clusters.

The Magellanic Clouds provide *prima facie* evidence for the conclusion that the mass spectrum of cluster formation differs in different galaxies. In the Milky Way system there exists a clear-cut dichotomy between massive globular clusters and much less massive open star clusters. However, in the Magellanic Clouds there also exists a class of intermediate-mass clusters that are rare or absent in the Galaxy. These objects will be referred to as “populous clusters.” It seems inappropriate to call such objects “blue globular clusters” because (1) some of them are red, (2) their masses are an order of magnitude lower than those of typical globular, and (3) their ages are approximately 10 Gyr or less.

When viewed through a telescope of moderate aperture, it is strikingly apparent that the globular clusters in the Magellanic Clouds have a lower surface brightness than do typical Galactic globulars. This conclusion is strongly confirmed by (still rather scanty) determinations of the structural parameters of Cloud clusters. Available data show that Cloud globular clusters typically have radii  $r_h$ , containing half of the cluster light in

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projection, which are 3 or 4 times larger than those of Galactic globulars of similar luminosity. Galactic open star clusters are also generally more compact than their counterparts in the Clouds of Magellan. The reason, or reasons, for these differences are not known. Clusters as compact as those in the Galaxy would easily have survived the weak tidal fields in the Clouds. The fact that they do not exist now therefore shows that significant numbers of clusters, as compact as those in the Galaxy, never formed in the Clouds. A similarity between the M31 (Crampton et al. 1985), Galactic (van den Bergh & Morbey 1984), NGC 5128 (Hesser et al. 1984) and Large Cloud (Hodge 1962; Mateo 1987) cluster systems is that clusters near the center of the LMC, the Galaxy, Centaurus A, and M31 are more compact than those located at greater distances. A possible interpretation of these observations is that dense clusters with small values of  $r_h$  form preferentially in regions in which the Jeans radius is small.

## 2. BASIC DATA ON CLOUD CLUSTERS

A catalog of 69 Small Cloud clusters is given by Kron (1956), and 116 SMC clusters are listed by Lindsay (1956, 1958). Clusters from the Kron and Lindsay catalogs are denoted by the letters K and L, respectively. Identification charts for the Lindsay clusters are given by Lindsay & McFarland (1971). Individual clusters are also identified in the Hodge & Wright (1976) atlas of the Small Magellanic Cloud. Hodge (1960) has cataloged a total of 35 red clusters associated with the LMC. It should be emphasized that this list contains both true globular clusters and populous old clusters. More recently Hodge (1986) has cataloged 213 new clusters in the SMC. He estimates the total SMC cluster population to be approximately 2000.

Shapley & Lindsay (1963) list and describe 897 star clusters in the LMC, and Lyngå & Westerlund (1963) tabulate 483 clusters located at distances greater than  $3^\circ$  from the center of the Large Cloud. Hodge & Sexton (1966) and Hodge (1988b) have cataloged 457 and 255 additional LMC clusters, respectively. Lyngå & Westerlund (1963) find that the LMC cluster system has an axial ratio  $b/a \approx 0.7$ . This conclusion is confirmed by the more recent results of Irwin (1991). A catalog of clusters in the outer region of the LMC is given by Olszewski et al. (1988). These authors find that the LMC cluster distribution has a major axis  $a = 15^\circ$ , corresponding to 13 kpc. An automated search for clusters near the Bar of the Large Cloud has recently been described by Bhatia & MacGillivray (1989). Clusters in the inner part of the LMC are identified in the atlas of Hodge & Wright (1967). Integrated photographic photometry for 50 Small Cloud clusters is given by de Vaucouleurs (1959). Aperture photometry on the *UBV* system for most of the brightest star clusters in the LMC and the SMC has been published by van den Bergh & Hagen (1968), and a compilation of all *UBV* data on Cloud clusters is given in van den Bergh (1981). Frogel, Mould, & Blanco (1990) have published integrated *JHK* photometry of 14 SMC and 24 LMC clusters. These authors also give *JHK* data on individual bright C and M stars in many of these clusters. Washington system photometry of Cloud clusters has been pioneered by Geisler (1987). Finally, *IUE* observations of 31 LMC clusters have been reported by Cassatella, Barbero, & Geyer (1987). Meurer, Cacciari, & Freeman (1990) have shown that such extreme ultraviolet (EUV) colors can be used to estimate cluster ages, although the age resolution obtained in this way is not very good for the youngest (and bluest) clusters. A bibliography of color-magnitude diagram studies of star clusters in the LMC

and SMC is given by Sagar & Pandey (1989). These authors also list age and  $[\text{Fe}/\text{H}]$  determinations for individual clusters.

A catalog of 122 associations in the LMC has been published by Lucke & Hodge (1970) and Hodge & Lucke (1970). Bok & Bok (1962) have observed the integrated *UBV* colors and magnitudes of the brightest of these associations. Photometry of individual stars in 96 LMC associations is given in Lucke (1974). Photometry for the Lucke & Hodge associations in the vacuum ultraviolet has been published by Smith, Cornett, & Hill (1987). An X-ray survey of OB associations in the LMC is given by Wang & Helfand (1991).

McKibben Nail & Shapley (1953) have identified five superassociations, which they refer to as "constellations," in the LMC. A more complete mapping of superassociations in the Large Cloud is shown in van den Bergh (1981). The SMC contains only one constellation, which comprises the clusters NGC 456, NGC 460, and NGC 465 in the "Wing" of the Small Cloud (Shapley 1956). Six small associations have also been found between the LMC and SMC (Irwin 1991). Radial velocities for stars in some of these associations are given by Irwin, Demers, & Kunkel (1990).

An excellent review, containing much information on clusters and associations in the Magellanic Clouds, has recently been published by Westerlund (1990).

## 3. THE INTEGRATED-LIGHT LUMINOSITY FUNCTION OF STAR CLUSTERS IN THE MAGELLANIC CLOUDS

In the Galaxy there is a clear-cut dichotomy (van den Bergh & Lafontaine 1984) between the luminosity function of the integrated magnitudes of open clusters, which is of the form  $N(M_V) \propto 10^{0.2M_V}$ , and that of globular clusters, which exhibits a Gaussian luminosity function with a dispersion  $\sigma \approx 1.3$  mag. The existence of populous clusters (Hodge 1984; Walker 1991) in the Magellanic Clouds suggests that such a dichotomy does not exist in the Clouds of Magellan. It should, however, be noted that some genuine old globulars (see Table 1), that contain RR Lyrae stars (Hodge 1984; Walker 1991), or which appear to have ages greater than 10 Gyr (see Table 2), are associated with the Magellanic Clouds. The mean absolute magnitude  $\langle M_V \rangle$  of the objects in Table 1 is  $-7.1$ , which (fortuitously) is identical to the value  $\langle M_V \rangle = -7.1 \pm 0.2$  which van den Bergh (1985) finds for the true globulars in M31 and the Galaxy. The fact that these magnitudes are identical indicates that *the genuine globulars in the Magellanic Clouds are objects of the same type as those in giant spirals*. This conclusion is, however, weakened somewhat by the fact that the sample of very old clusters might still be somewhat incomplete at faint absolute magnitudes. Perhaps the best faint very old

TABLE 1  
GLOBULAR CLUSTERS CONTAINING RR LYRAE  
STARS IN THE MAGELLANIC CLOUDS

| NGC       | LMC/SMC | V     | B - V | $M_V^a$ |
|-----------|---------|-------|-------|---------|
| 121.....  | SMC     | 11.24 | 0.78  | -7.7    |
| 1466..... | LMC     | 11.59 | 0.66  | -6.9    |
| 1786..... | LMC     | 10.88 | 0.74  | -7.6    |
| 1835..... | LMC     | 10.13 | 0.73  | -8.4    |
| 1841..... | LMC     | 14.08 | 0.90  | -4.4    |
| 2210..... | LMC     | 10.94 | 0.71  | -7.6    |
| 2257..... | LMC     | ...   | 0.69  | ...     |

<sup>a</sup> Values of  $(m - M_V) = 18.5$  and  $18.9$  adopted for the LMC and SMC, respectively.

TABLE 2  
CLOUD GLOBULAR CLUSTER COLOR-MAGNITUDE DIAGRAMS

| Cluster                     | $\langle V \rangle_{RR}$ | Reference            | [Fe/H]         | Horizontal Branch |
|-----------------------------|--------------------------|----------------------|----------------|-------------------|
| NGC 121 .....               | 19.58                    | Walker & Mack 1988a  | $-1.4 \pm 0.1$ | Red               |
| NGC 1466 .....              | 18.85 <sup>a</sup>       | Wesselink 1971       | -2.2           | Blue              |
| NGC 1786 .....              | 19.27                    | Walker & Mack 1988b  | -2.3           | Blue <sup>b</sup> |
| NGC 1835 .....              | 19.07 <sup>a</sup>       | Graham & Ruiz 1974   | ...            | Blue <sup>c</sup> |
| NGC 1841 .....              | 19.25                    | Andersen et al. 1987 | -2.1           | Blue              |
| NGC 2210 .....              | 19.12                    | Walker 1985          | -1.9           | Blue              |
| NGC 2257 .....              | 19.03                    | Walker 1989a         | $-1.8 \pm 0.1$ | Blue              |
| Hodge 11 <sup>d</sup> ..... | [18.89] <sup>e</sup>     | Andersen et al. 1984 | -2.2:          | Blue              |

<sup>a</sup>  $\langle B \rangle - \langle V \rangle = 0.31$  assumed.

<sup>b</sup> Walker 1990.

<sup>c</sup> Integrated cluster colors in the vacuum ultraviolet (Barbero et al. 1990) suggest that this cluster has a blue horizontal branch.

<sup>d</sup> Hodge 11 = SL 868.

<sup>e</sup> Based on fitting to the M92 color-magnitude diagram.

cluster candidates (Mateo 1990) are NGC 1916, NGC 2005, and NGC 2019. Finally, the Reticulum system (Gratton & Ortolani 1987), which contains 22 RR Lyrae stars (Demers and Kunkel 1976) having  $\langle V \rangle = 19.01$  (Walker 1991), may also be a faint distant companion to the LMC.

Available data on the clusters in the Clouds of Magellan may be interpreted in two different ways. Either the Clouds contain three distinct types of clusters—i.e., globular clusters, populous clusters, and open clusters—of which globular clusters and open clusters are exact counterparts to similar objects in our own Galaxy, or, alternatively, *globular clusters are physically similar objects in the Galaxy and in the LMC, but the luminosity function (mass spectrum) of open clusters extends to higher luminosities and masses in the Clouds than it does in the Galaxy*. The reason for this difference remains a mystery.

Unfortunately there do not yet exist any modern photoelectric surveys of complete cluster samples in either the LMC or the SMC. It is therefore not yet possible to make detailed comparisons between the luminosity functions of clusters in the LMC, the SMC, and the Galaxy. From eye estimates of the brightnesses of LMC clusters on a plate obtained with a 20 cm f/1 Schmidt camera Elson & Fall (1985b) conclude that the luminosity function of Large Cloud clusters is qualitatively similar to that for open clusters in the Galaxy.

Kennicutt & Chu (1988) have argued that the populous blue clusters in the Magellanic Clouds probably formed in super-H II regions, such as the 30 Doradus complex. That the Milky Way system presently does not produce such luminous H II regions is probably due to the fact that the Galaxy does not contain objects as massive and luminous as the populous blue clusters in the Magellanic Clouds. The fact that typical globular clusters in the Galaxy and the LMC have masses that are an order of magnitude greater than those of most blue populous clusters suggests that they may have formed in H II regions that were even more luminous than those presently observed in irregular galaxies such as the LMC. According to calculations by Chiosi, Bertelli, & Bressan (1988), a globular cluster, which presently had  $M_V = -7.1$ , would have had  $M_V = -10.9$  when its age was  $1 \times 10^8$  yr. The exact amount by which a cluster fades will, of course, depend on the adopted slope of the mass spectrum of cluster stars.

#### 4. 30 DORADUS

*The 30 Doradus complex is probably similar to, but somewhat less massive than, the regions that produced true globular clus-*

*ters some ~15 Gyr ago. NGC 2070, which is the central cluster of the 30 Doradus complex, has an age of  $\sim 2 \times 10^6$  yr and contains ~15 Wolf-Rayet (mostly late WN) stars in addition to ~60 stars hotter than O5 (Moffat et al. 1987; Melnick 1985). A good discussion of the 30 Doradus region and its central cluster is given in the review by Walborn (1984). Hyland (1991) finds a clear separation of the young blue stars and older red supergiants in the 30 Doradus region. This indicates that more than one generation of star formation has taken place in this area.*

Walborn (1973) and Rosa, Melnick, & Grosbol (1984) have shown that NGC 2070 exhibits many similarities to the very compact Galactic cluster NGC 3603, which is also situated at the center of a very luminous H II region. The integrated magnitude of NGC 3603 ( $M_V \simeq -9.2$ ) is, however, somewhat lower than that of NGC 2070 ( $M_V \simeq -10.1$ ). The conclusion that the cores of NGC 2070 (= R136a) and NGC 3603 are very similar objects has recently been greatly strengthened by the speckle observations of Weigelt & Baier (1985) and Hofmann & Weigelt (1986).

In recent years the nature of R136a = HD 38268, which is the central object in the 30 Doradus Nebula, has been the subject of heated controversy. Savage et al. (1983) and Panagia, Tanzi, & Tarengi (1983) have, for example, argued that the radiation from the object must be dominated by a single supermassive star with a mass of  $\sim 2 \times 10^3 M_\odot$ , or by a small group of supermassive stars. More recently Weigelt & Baier (1985) and Neri & Grewing (1988) have, however, used speckle observations to show that R136a actually consists of a supercompact cluster that contains at least eight stars located within a diameter of 1", rather than of a single superluminous object. X-ray observations of probable supernova shells in the 30 Doradus Nebula are given by Chu & Kennicutt (1991).

#### 5. DIAMETERS OF CLUSTERS

The tidal limits of star clusters are set by the cluster environment, while their core radii evolve rather rapidly. This suggests that  $r_h$ , the radius which contains half of the cluster light/stars in projection, might be a relatively stable, and hence meaningful, parameter to characterize a cluster. *N*-body calculations (e.g., Spitzer & Thuan 1972; Lightman & Shapiro 1978) show that  $r_h$  generally changes very little over periods as long as 10 cluster relaxation times. It should, however, be noted that these calculations do not take into account the effects of evolutionary mass loss by individual stars. Unfortunately not very much

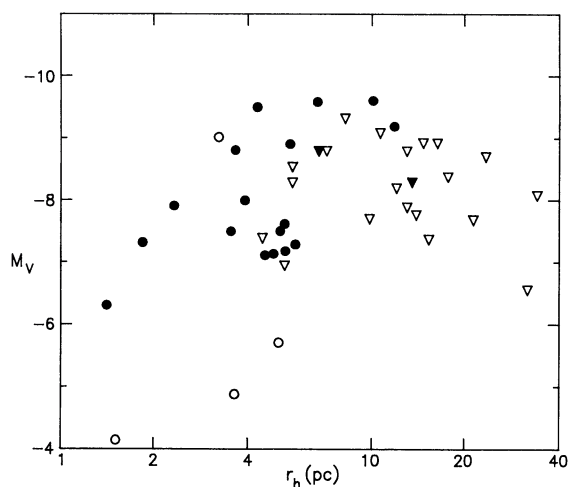


FIG. 1.—Absolute magnitude  $M_V$  vs. half-light radius  $r_h$  for Galactic globulars (filled circles), Galactic open clusters (open circles), Cloud globulars (inverted filled triangles), and Cloud open clusters (inverted open triangles). Cloud clusters are seen to have radii that are  $\sim 3$  times larger than those of Galactic clusters.

information on cluster  $r_h$  measurements is available in the literature. Aguilar, Hut, & Ostriker (1988) have recently published  $r_h$  values for most Galactic globular clusters,  $r_h$  determinations for a small number of rich Galactic open clusters are given in van den Bergh & Sher (1960), and  $r_h$  values for some clusters in the Magellanic Clouds can be derived from aperture photometry published by Gordon & Kron (1983). Ten additional  $r_h$  values are given in Elson, Fall, & Freeman (1987).

Figure 1 shows a plot of  $M_V$  versus  $r_h$  for Cloud clusters, Galactic open clusters, and every fifth Galactic globular in the table of Aguilar, Hut, & Ostriker (1988). The figure shows that *Cloud clusters have radii that are  $\sim 3$  times larger than those of typical Galactic star clusters*. A similar conclusion had previously been reached by Bhatia & MacGillivray (1989). Since the overall density of the Clouds is lower than that of the Galaxy, the most plausible explanation for this observation may be that *clusters with small radii are preferentially formed in regions of high density*. This is consistent with the pattern that is observed for the globular clusters in the Galaxy, in NGC 5128 (Hesser et al. 1984), and in M31 (Crampton et al. 1985), in which objects with the largest radii occur at the largest galactocentric radii. Furthermore, Burki & Maeder (1976) find that Galactic open clusters have diameters that increase with Galactocentric distance. The tentative conclusion that cluster radius correlates with density in the cluster-forming regions is consistent with the observation (Kron & Mayall 1960) that the globular cluster NGC 1049, in the low-density Fornax dwarf, is even larger than that of NGC 121 in the SMC.

Lupton et al. (1989) suggest that relatively young clusters, of which NGC 1866 in the LMC is an example, are not yet tidally limited and that such clusters might be embedded in unbound halos. Elson, Fall, & Freeman (1987) find that up to 50% of the mass of some clusters may be in such halos, which are so large that they must be unbound. Clusters like  $h$  and  $\chi$  Persei, which form in associations, might continue to be surrounded by stellar coronae over time scales comparable to the characteristic dissolution times of associations. These time scales may be as long as  $\sim 10^8$  yr in the LMC, in which differential rotation does not contribute as strongly to the dissolution of associ-

ations as it does in the Galaxy. If Elson, Fall, & Freeman (1987) are correct in concluding that up to 50% of the mass of some Cloud clusters resides in unbound halos, then the interpretation of the  $r_h$  values for such clusters becomes somewhat problematical.

Some clusters in the LMC are observed to be members of what appear to be binary pairs (Bhatia & Hatzidimitriou 1988; Kontizas, Kontizas, & Xiradaki 1989; Hatzidimitriou & Bhatia 1990). Such objects were, like  $h$  and  $\chi$  Persei, probably formed in a single association and do not necessarily constitute bound binary systems. Bhatia & MacGillivray (1988) argue that the elongated young LMC NGC 2214 is, in fact, a binary cluster in an advanced state of merging. Elson (1990) and Sugimoto & Makino (1989) have suggested that the ellipticity of some Cloud clusters might be due to merger of preexisting clumps.

Meylan & Djorgovski (1987) have searched for collapsed cores in 33 clusters of various ages in the Magellanic Clouds. No collapsed objects were found in the SMC. In the LMC, NGC 2019 has a collapsed core and NGC 1774 and NGC 1951 are strong candidates for having such cores. Similar studies have been undertaken by Mateo (1987), who finds that the old red clusters NGC 2005 and NGC 2019 are probably dynamically evolved objects that have undergone core collapse. Mateo (1987) and Hodge (1962) also find a strong correlation between the core radii of clusters and their distance from the rotation center of the Large Cloud.

Data on the core radii of LMC clusters are collected in Elson, Freeman, & Lauer (1989) and Elson (1990). These authors conclude that the core radii of LMC clusters increase while they age from  $10^6$  to  $10^9$  yr, and suggest that this increase is due to mass loss from evolving stars. The rate of such evolutionary mass loss will, of course, depend critically on the shape of the mass spectrum of star formation.

## 6. FLATTENING OF CLUSTERS

Perhaps the most striking difference (van den Bergh & Morbey 1984) between luminous star clusters in the Galaxy and in the Magellanic Clouds is that many Cloud clusters are highly flattened, whereas Galactic globular clusters (White & Shawl 1987) are predominantly spherical. There are no Galactic counterparts to such highly flattened objects as NGC 121 in the SMC and NGC 1978 in the LMC. According to Kontizas et al. (1990), clusters in the SMC are, in the mean, even more flattened than those in the LMC. The reason for this difference in the mean ellipticity of clusters in different stellar systems is not known. In the Galaxy (e.g., Harding 1965; Pryor et al. 1986) the slight flattening of some globular clusters appears to be due mainly to rotation. The difference between the mean flattening of Galactic and Cloud clusters therefore suggests that there may be a systematic difference between the angular momentum with which clusters are formed in the Galaxy and in the Magellanic Clouds. Alternatively, Galactic clusters may have been “spun down” more by expansion than was the case for clusters in the Magellanic Clouds. (If so, Galactic clusters would, however, be expected to be *larger* than those in the Clouds—which is contrary to observation.) The reason for such a hypothetical *difference* in expansion (which might result from stellar mass loss) is not obvious. Very young clusters, such as NGC 3603 and NGC 2070 (30 Dor) (cf. Moffat, Shara, & Seggewiss 1986), have unusually small core radii. This observation possibly provides some support for the hypothesis (Verschueren & David 1989; Elson 1990) that clusters expand

during the earliest phase of their evolution, when the effects of rapid mass loss are most severe. Cluster core radii published by Elson, Freeman, & Lauer (1989) indicate that such mass-loss-driven expansion may affect cluster structure up to ages of a few times  $10^8$  yr. Calculations by Chernoff & Weinberg (1990) indicate that mass loss is an important factor in cluster evolution during the first  $5 \times 10^9$  yr of their existence. Violent relaxation (Elson, Fall, & Freeman 1987) might also influence the early evolution of clusters.

Previous papers on flattening of clusters in the Galaxy and in the Magellanic Clouds are by Frenk & Fall (1982), Fall & Frenk (1984), Geisler & Hodge (1980), Geyer & Richtler (1981), Geyer, Hopp, & Nelles (1983), van den Bergh (1983a, b), Kontizas et al. (1985), Zepka & Dottori (1987), Bhatia & MacGillivray (1989), and Kontizas et al. (1989).

A detailed statistical study by van den Bergh & Morbey (1984) shows that (1) *both old and young clusters in the LMC are, on average, more highly flattened than Galactic globulars*, and (2) luminous clusters in the LMC are more flattened than faint ones. Using a "bootstrap" statistical technique, these authors show that the apparent correlation between age and flattening of LMC clusters is no longer statistically significant after the dependence of cluster ellipticity on luminosity is removed.

In § 5 it was found that clusters in the Magellanic Clouds are systematically larger (and have lower surface brightnesses) than their Galactic counterparts. Furthermore, Cloud clusters are more flattened *at any age* (van den Bergh & Morbey 1984) than those in the Galaxy. Possibly these two phenomena are causally related, because low-density clusters might be more easily distorted than compact centrally condensed ones. To test this hypothesis, we have, in Figure 2, plotted  $r_h$ , the radius containing half of the light of Galactic globular clusters in projection (Aguilar, Hut, & Ostriker 1988), versus cluster ellipticity (White & Shawl 1987). (The cluster M19 = NGC 6273 was excluded because its apparent flattening appears to be due to patchy foreground absorption; van den Bergh 1982.) The figure shows no obvious correlation between the axial ratios  $b/a$  and the radii  $r_h$  of these clusters. This conclusion is confirmed by a Kolmogorov-Smirnov test, which shows no significant difference between the frequency distributions of  $r_h$  values for  $b/a \leq 0.90$  and for  $b/a > 0.90$ . Inspection of Figure 2 does, however, suggest that clusters with  $r_h > 10$  pc might be slightly more prone to high flattening than are those with  $r_h < 10$  pc. Four out of 20 (20%) of the clusters with  $b/a \leq 0.90$  are seen to have  $r_h > 10$  pc, compared with four out of 51 (8%) for those

with  $b/a > 0.90$ . An alternative explanation is that some relatively highly flattened Galactic globulars with  $r_h > 10$  pc, such as NGC 5053 and NGC 7492, originated in the Magellanic Clouds and were torn from either the LMC or the SMC by tidal forces. Such objects might, of course, also have been formed in dwarf galaxies that were subsequently drawn into the Galactic halo by tidal friction.

## 7. COLOR-MAGNITUDE DIAGRAMS

References to the most recent color-magnitude diagrams of globular clusters in the Magellanic Clouds are listed in Table 2. Inspection of such color-magnitude diagrams shows no obvious systematic differences between Cloud globulars and Galactic globular clusters of similar age and chemical composition. In the LMC there is a wide age gap between the true globular clusters and old red populous clusters. The Small Magellanic Cloud does, however, contain some old populous clusters, such as L1 (Olszewski, Schommer, & Aaronson 1987) and K3 (Rich, Mould, & Da Costa 1984), with ages slightly smaller than those of true globulars (Gascoigne 1966), that are of a type which is not known to occur in the Galaxy or in the LMC.

Hagen & van den Bergh (1974) have pointed out that the stars in old SMC open clusters lie on evolutionary tracks that differ systematically from those of stars in Galactic open clusters of similar age. Giant stars in SMC open clusters are, presumably as a result of their lower metallicity, seen to be systematically bluer than their Galactic counterparts. Open clusters in the LMC have metallicities and giant branch colors that are intermediate between those of clusters in the Galaxy and in the SMC.

Studies of the populous clusters in the Magellanic Clouds are of particular value (Renzini 1991) because they allow one to study stars in rapid evolutionary phases, which are unlikely to be observed in sparser Galactic open clusters. Furthermore, the integrated colors of populous clusters in the Magellanic Clouds are less likely to be affected by a single supergiant or bright giant than is the case for less populous Galactic open clusters. Cloud clusters are therefore particularly suitable for comparisons between observed and predicted (Chiosi 1989) integrated cluster colors. Finally, star clusters in the Magellanic Clouds are of interest because most of them populate a region of the age-metallicity plane (see § 10) that is not populated by Galactic clusters near the Sun.

Among populous young clusters, NGC 1866 (Brocato et al. 1989) is of particular interest because it contains a large number of Cepheid variables (Storm et al. 1988; Welch et al. 1990). This cluster therefore sheds some light on the evolutionary tracks which bring stars into the Cepheid instability strip. It is also noteworthy (Chiosi et al. 1989) that evolutionary tracks with convective overshoot ( $T = 2 \times 10^8$  yr) fit the NGC 1866 observations better than do those without convective overshoot ( $T = 7 \times 10^7$  yr).

Mateo, Olszewski, & Madore (1990) have discovered three Cepheids in the young LMC cluster NGC 2157. Two of these variables appear to be overtone pulsators. These objects yield the same mass discrepancy for their pulsational masses that has long been known for Galactic Cepheids in clusters. Mateo, Olszewski, & Madore suggest that this Cepheid mass discrepancy might be resolved by using modified evolutionary tracks involving convective overshoot. A search for Cepheids in eight LMC clusters is described by Mateo, Olszewski, & Madore (1991).

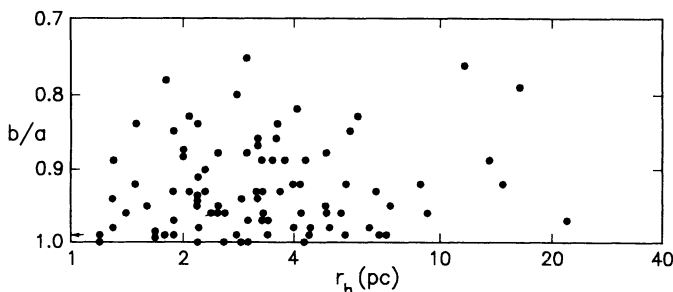


FIG. 2.—Axial ratio  $b/a$  of Galactic globular clusters vs. the radius  $r_h$  containing half of the cluster light in projection. The figure shows no statistically significant difference between the distributions of  $r_h$  values for  $b/a \leq 0.90$  and for  $b/a > 0.90$ . Note, however, that two out of four highly flattened clusters with  $b/a < 0.80$  have  $r_h$  values larger than 10 pc.

The populous young cluster NGC 346 in the SMC (Niemela, Marraco, & Cabanne 1986; Walborn & Blades 1986; Massey, Parker, & Garmany 1989) contains at least 33 O-type stars (including one object of type O3 III) with masses of up to  $85 M_{\odot}$ , i.e., the upper mass limit for star formation in the SMC is not appreciably lower than it is in the Galaxy. The mass spectrum  $F(\log M) \propto M^{\alpha}$  of stars in NGC 346 has a slope  $\alpha = -1.9$ , a value quite similar to that of the initial mass function (IMF) in the solar neighborhood. Blaha & Humphreys (1989) also find that the luminosity function of O- and B-type stars in the Magellanic Clouds is similar to that observed within 3 kpc of the Sun. For two LMC associations Massey et al. (1989) found a slope of the IMF that is similar to that in the solar neighborhood. A quite different conclusion is, however, reached by Mateo (1988b), who obtains a steep slope  $\langle \alpha \rangle \simeq -2.5$  from CCD photometry of luminous stars in six Magellanic Cloud clusters, compared with  $\alpha \simeq -1.5$  in the solar neighborhood. Finally Elson, Fall, & Freeman (1989) conclude that six clusters studied by them have a *flatter* mass spectrum than that of the IMF in the solar neighborhood. Clearly it would be very worthwhile to extend such work to more clusters to see whether the slope of the initial mass function differs from cluster to cluster.

#### 8. CLUSTER AGES

Problems related to the ages of clusters in the Magellanic Clouds have been reviewed by Hodge (1983), by Mould & Da Costa (1988), and by Da Costa (1991). Walker (1989b) has searched for RR Lyrae stars in eight old SMC clusters with ages ranging from 3 to 12 Gyr. Only in NGC 121, which is the oldest of these clusters, are RR Lyrae variables found to be present. No cluster-type variables were found in the cluster L1, which has a age of  $(10 \pm 2)$  Gyr (Olszewski, Schommer, & Aaronson 1987). This suggests that RR Lyrae stars are tracers of a stellar population with an age greater than 10 Gyr. The fact that L1 contains one carbon star (Mould & Aaronson 1979) indicates that carbon stars are diagnostic for a cluster population with an age of approximately 10 Gyr or less. A possibly slightly higher age limit for carbon stars is obtained from the observation (Stryker, Da Costa, & Mould 1985) that NGC 121, which has an age of 12 Gyr, contains a marginal carbon star.

The existence of an upper age limit for carbon stars is consistent with theory (Bessell, Wood, & Lloyd Evans 1983), which shows that dredge-up during helium flashes cannot produce carbon stars from stars with main-sequence masses of approximately  $0.9 M_{\odot}$  or less if  $[\text{Fe}/\text{H}] \approx -1$ , or approximately  $1.3 M_{\odot}$  or less if  $[\text{Fe}/\text{H}] \approx 0$ . Persson et al. (1983) show that carbon stars do not appear to be present in Cloud clusters with ages  $\leq 1$  Gyr. Frogel, Mould, & Blanco (1990) only find carbon stars in clusters with Searle, Wilkinson, & Baguolo (1980) age classes in the range III–IV to VI–VII. Frogel et al. also note that the carbon stars in the oldest clusters are fainter than those in younger clusters. Carbon stars are observed in the class VII cluster NGC 339 in the SMC; however, no carbon stars are known in LMC clusters in this age class. Neither are asymptotic giant branch (AGB) carbon stars observed in Galactic globular clusters. Either stars on the AGBs of the most ancient clusters in the Galaxy and the LMC are too old to produce carbon stars, or their chemical abundance mixture makes it impossible for them to begin the cycle of thermal pulses which ultimately results in carbon dredge-up (Iben & Renzini 1983).

Plots of the integrated colors and magnitudes of clusters in the Magellanic Clouds are shown in van den Bergh (1981). These data show a clear dichotomy, first noted by Gascoigne & Kron (1952), between young blue clusters and old red clusters. It should, perhaps, be emphasized that the causes of this dichotomy are complex and involve both the fading and the color evolution of individual clusters. Alongi (1991) finds that a true age gap contributes to the observed bimodality of the integrated colors of LMC clusters. Mould & Aaronson (1979) have stressed the fact that *a few red Cloud clusters have ages similar to Galactic globular clusters, but that most others are of intermediate age*. In both the LMC and the SMC young blue clusters outnumber old red ones. The opposite effect is seen in the Andromeda Nebula (van den Bergh 1984), in which old red clusters greatly outnumber young blue ones. This shows that most cluster formation in M31 took place long ago, whereas star clusters are still being formed vigorously in both the Large and the Small Cloud. A thorough discussion of the color evolution of LMC clusters is given by Chiosi, Bertelli, & Bressan (1988).

Hodge (1988a) has derived the age distribution of clusters in the Large Cloud from observations of bright stars in 473 clusters located in 12 LMC fields. He finds that clusters form at a nonuniform rate, which depends on position within the Cloud. This conclusion is confirmed by Mateo (1988a, b), who has made a study of the color-magnitude diagrams of 31 clusters with  $V \lesssim 14$  in the outskirts of the LMC. Mateo finds evidence for a burst of cluster formation in the LMC between 2 and 4 Gyr ago.

The average cluster formation rate in the LMC is presently  $\sim 270$  per  $10^8$  yr. Hodge finds that the median age of clusters is  $1.1 \pm 0.2$  Gyr, in the LMC and 0.9 Gyr in the SMC (Hodge 1987). These values may be compared with a median age of only 0.2 Gyr for open clusters in the Galaxy (Wielen 1971). Typical dissolution time scales for clusters in the Magellanic Clouds are therefore 3–5 times greater than those for open clusters in the Galaxy. Reasons for this difference are probably both longer evaporation times for large-diameter Cloud clusters, and lower disruption rates resulting from weaker tidal fields in the LMC and the SMC.

From color-magnitude diagrams for 57 clusters in the Large Cloud, Elson & Fall (1988) confirm the age distribution of clusters found by Hodge (1988a). It is particularly noteworthy that their LMC cluster age distribution shows no clear-cut evidence for bursts in the cluster formation rate. It should, however, be emphasized that these cluster data are sparse, and do not give good time resolution, for ages greater than 1 Gyr.

Sagar & Pandey (1989) give a listing of all published age determinations for clusters in the LMC and the SMC, complete to 1988 October. Most of the cluster age calculations quoted by Sagar & Pandey do *not* invoke convective overshooting. The binned age distribution for 96 clusters in the Large Cloud and 38 clusters in the Small Cloud is given in Table 3. In cases in which Sagar & Pandey list multiple age determinations, the most recent value was adopted. The Sagar & Pandey (1989) catalog is most complete for clusters of high luminosity, and is probably biased against clusters embedded in rich star fields. Because the number of clusters for which ages are available is still small, considerable caution should be exercised in interpreting their observed age distribution.

Figure 3 shows that the age distribution of clusters in the Large Cloud appears to exhibit considerable structure. The figure suggests that the LMC was relatively quiescent between

TABLE 3  
FREQUENCY OF CLUSTER AGES IN THE  
MAGNELLANIC CLOUDS

| $\log T$ (yr)     | $n(\text{LMC})$ | $n(\text{SMC})$ |
|-------------------|-----------------|-----------------|
| 6.00–6.33 .....   | 0               | 0               |
| 6.34–6.66 .....   | 3               | 1               |
| 6.67–6.99 .....   | 7               | 0               |
| 7.00–7.33 .....   | 8               | 5               |
| 7.34–7.66 .....   | 9               | 2               |
| 7.67–7.99 .....   | 16              | 4               |
| 8.00–8.33 .....   | 6               | 7               |
| 8.34–8.66 .....   | 2               | 8               |
| 8.67–8.99 .....   | 15              | 3               |
| 9.00–9.33 .....   | 16              | 2               |
| 9.34–9.66 .....   | 8               | 3               |
| 9.67–9.99 .....   | 0               | 1               |
| 10.00–10.33 ..... | 6               | 2               |
| Total .....       | 96              | 38              |

0.1 and 0.5 Gyr ago, and between 3 and 10 Gyr ago. In the Large Cloud there are only six clusters with ages in the range 0.1–0.5 Gyr, compared with 14 clusters with ages in the range 0.5–1.0 Gyr. This difference is unexpected, since clusters in the latter age groups are more likely to have dimmed or disintegrated with the passage of time. The reality of the age gap for clusters with ages of a few times  $10^8$  yr is supported by the observed distribution of vacuum UV colors of LMC clusters by Barbero et al. (1990) and the cluster ages derived from them (Meurer, Cacciari, & Freeman 1990).

In the LMC a particularly large age gap, which contains no clusters at all, extends from ages of approximately 3 Gyr to 10 Gyr (Jensen, Mould, & Reid 1988). The low-mass cluster ESO 121–SC03 (Mateo, Hodge, & Schommer 1986), which is situated at a distance of 9°9' from the rotation center of the Large Cloud, may, however, have an age near the upper end of this

time interval. The LMC is not known to contain counterparts to such populous SMC clusters as K3 (8 Gyr) and L113 (4.5 Gyr). It would be important to obtain color-magnitude diagrams for certain objects, such as NGC 1916, NGC 2005, and NGC 2910 (Mateo 1990), to see whether these objects do, or do not, fall in the age gap noted above. A special search (based on integrated cluster colors on the Washington system) by Da Costa (1991) did not turn up any LMC clusters with ages in the interval 3–10 Gyr.

Mateo (1990) has emphasized the fact that there exist a large number of clusters (e.g., NGC 1783, NGC 2121, NGC 2155, and NGC 2203) that are now 2–3 Gyr old and that will still be impressive objects 3–10 Gyr from now. The fact that clusters with ages 3–10 Gyr have been found in the SMC also militates against the assumption that the absence of such objects in the Large Cloud might be due to selection effects.

No obvious bursts of cluster formation or long periods of quiescence, are visible (see Fig. 3) in the age distribution of Small Cloud clusters that is derived from the compilation of Sagar & Pandey (1989). The fact that the Small Magellanic Cloud does not appear to exhibit a burst of star formation at the same time as the major burst that took in the Large Cloud  $\sim 3$  Gyr ago shows that *this burst was probably not triggered by an interaction between the LMC and the SMC* (Mateo, Bertelli, & Chiosi 1990).

Since selection effects are probably similar in the LMC and SMC, it appears meaningful to compare the age distributions of clusters in the Large and Small Clouds. A two-tailed Kolmogorov-Smirnov test shows that the observed age distributions of clusters in these two galaxies do not differ at a respectable level of statistical significance. A similar conclusion is reached from a comparison of the distributions of values of the cluster age parameter  $s$  (Elson & Fall 1985a) in the LMC and the SMC. This indicates that data on the ages of clusters in the Magellanic Clouds are still not numerous (or accurate) enough to provide unambiguous information on differences between the evolutionary history of these objects.

It is, however, of interest that *the end of the hiatus in cluster formation between 10 and 3 Gyr*, which has been noted by Jensen, Mould, & Reid (1988), *possibly coincides with the onset of a major burst of star formation in the LMC*. From a study of a star field situated 4° from the Bar of the LMC, Butcher (1977) concluded that the bulk of star formation in this region started between 3 and 5 Gyr ago. In a nearby field Frogel & Blanco (1983) draw a similar conclusion from the luminosities of field asymptotic branch stars. Finally, Stryker, Butcher, & Jewell (1981) find that the oldest stars in a field surrounding NGC 2257 are much younger than those in the globular cluster NGC 2257 itself. Stars in a barred galaxy will move in complex quasi-chaotic orbits. Old stars of a given age are therefore expected to be widely distributed over the face of the LMC. Sampling of many individual star fields is therefore not necessary to gain insight into the global star-forming history of the Large Cloud.

It is of interest to note that the star-forming history of the LMC, with an initial burst of star formation that involved the formation of presumably old globular clusters with blue horizontal branches, and a second later burst of star and cluster formation, resembles that in the Carina dwarf system. In Carina (Mould & Aaronson 1983; Mighell 1990) an initial burst of star formation that produced RR Lyrae stars was apparently followed by a second, much larger, burst of star formation that occurred  $7.5 \pm 1.5$  Gyr ago.

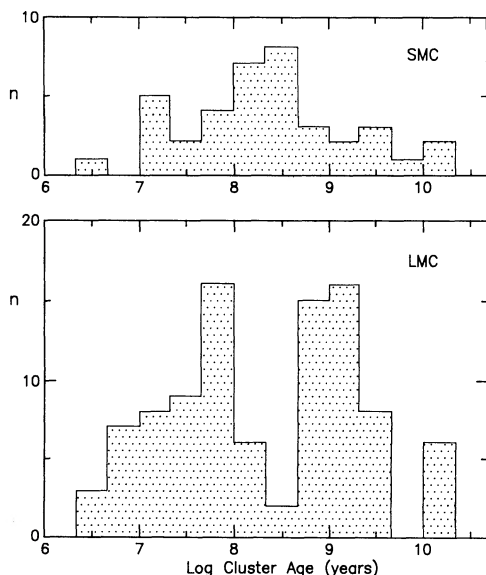


FIG. 3.—Frequency distribution of cluster ages in the LMC and the SMC. Note possible quiescent periods in the Large Cloud from 0.1 to 0.5 Gyr ago and from 3 to 10 Gyr ago.

## 9. DYNAMICS OF CLOUD CLUSTERS

Meylan et al. (1989) have used multimass dynamical models to fit the radial profile, and the central velocity dispersion of  $\sigma = 10.1 \text{ km s}^{-1}$ , to obtain a mass for the LMC globular cluster NGC 1835. They find a cluster mass in the range  $0.8 \times 10^6 M_\odot$  to  $1.0 \times 10^6 M_\odot$  and a mass-to-light ratio  $2.8 < M/L_V < 3.6$ . The latter value is similar to  $2.1 \leq M/L_V \leq 3.6$  that is found for the six best-studied Galactic globular clusters. This result suggests that the globular clusters associated with the LMC are similar in both  $M$  and  $M/L$  to their Galactic counterparts. The  $M/L_V$  value obtained above is an order of magnitude higher than the tidal limit masses previously estimated by Elson & Freeman (1985),  $M/L_V = 0.18$ , and by Chun (1978),  $M/L_V = 0.15$ . This suggests that the tidal masses which Elson & Freeman (1985) and Chun (1978) obtained for the globular cluster NGC 2210 and NGC 2257 are probably also too low.

The blue populous cluster NGC 330 in the SMC has been studied by Feast & Black (1980). From 81 spectra of 25 cluster stars these authors found a velocity dispersion  $\sigma < 1.8 \text{ km s}^{-1}$ . The corresponding cluster mass is  $M < 4 \times 10^4 M_\odot$ , yielding a mass-to-light ratio (in solar units)  $M/L < 0.1$ . For the populous cluster NGC 1866 in the LMC, Fischer et al. (1991) obtain  $M = (8.1 \pm 1.6) \times 10^4 M_\odot$  and  $M/L = 0.2$ . This observation shows that *even the brightest young populous clusters have masses that are smaller than those of most Galactic globular clusters*. Data presented by Mateo, Welch, & Fischer (1991) show that, as expected,  $M/L$  for LMC clusters increases with increasing cluster age.

## 10. ABUNDANCES IN CLOUD CLUSTERS

Pioneering studies of the age-metallicity relation for clusters in the Magellanic Clouds are by Searle, Wilkinson, & Bagnuolo (1980) and Cohen (1982). Possible differences between the age-metallicity relations for clusters in the LMC and the SMC are discussed by Da Costa (1991). A homogeneous set of metallicity estimates of Cloud clusters, based on measurements of the strength of the G band and of the H and K lines of Ca II, has been published by Smith, Searle, & Manduca (1988). For six SMC clusters their data may be represented by the relation

$$[\text{Fe}/\text{H}] = -0.75 - 0.044T, \quad (1)$$

in which  $T$  is the cluster age in Gyr. For 20 LMC clusters their observations are adequately represented by the linear relation

$$[\text{Fe}/\text{H}] = -0.30 - 0.12T. \quad (2)$$

Note that this behavior is quite different from that in the Galaxy (Twarog 1980), in which the rate of metallicity enrichment was very high initially but slowed down later. The age-metallicity relation in a northern region of the LMC is discussed by Mateo (1988a). Since the LMC is a barred irregular, there should be considerable gas streaming in the Large Cloud. As a result of stirring of interstellar gas in the LMC the age-metallicity relation is not expected to differ much from region to region. A quite different situation is encountered in the Galaxy, in which enrichment of the heavy elements is presumed to have proceeded most rapidly in the dense nuclear bulge.

The very low metallicity that Spite et al. (1986), Spite (1991), and Richtler & Seggewiss (1988) find for the young Small Cloud cluster NGC 330 is puzzling and inconsistent with equation (2). Bessell (1991) points out that adoption of a higher

cluster reddening would result in a higher metallicity estimate for NGC 330. Some support such a higher reddening value is provided by Walton et al. (1991), who find a reddening  $E_{B-V} = 0.11$  for a planetary nebula in the field of NGC 330.

## 11. KINEMATICS AND DISTRIBUTION OF CLUSTERS

The most distant LMC clusters lie well beyond the region containing the bulk of the LMC hydrogen clouds (Olszewski 1988). The distribution of the seven true globular clusters associated with the Large Cloud is shown in Figure 4. The Reticulum cluster (Gratton & Ortolani 1987), which contains 22 RR Lyrae stars (Demers & Kunkel 1976), might also be an outlying globular associated with the LMC. Perhaps the best-known distant intermediate-age cluster is E2 (Schommer, Olszewski, & Aaronson 1986), with an age of 1.5 Gyr, which is located  $8^\circ$  from the center of the LMC. The existence of such clusters shows that either (1) the gas-filled volume of the Large Cloud has shrunk with time or (2), more plausibly, that such objects are presently near the apogalactic points in their orbits. Among the clusters most distant from the center of the LMC are the globulars NGC 1466, NGC 1841, and NGC 2257. Note, however, that Webbink (1985) lists both NGC 1466 and NGC 1841 as Galactic globular clusters! Located at a projected distance of  $14.8$  (13 kpc) from the center of the LMC, NGC 1841 can only be bound weakly to the Large Cloud, unless the LMC has a massive dark halo. Cowley & Hartwick (1981) have argued that NGC 1466 cannot be a member of the LMC because of the  $105 \text{ km s}^{-1}$  radial velocity difference between these two objects. A much smaller velocity difference of  $58 \text{ km s}^{-1}$  is, however, found by Freeman, Illingworth, & Oemler (1983).

From the data compiled by Webbink (1985) there are seen to be  $n = 10$  Galactic globular clusters with galactocentric distances in the range  $30 < R(\text{kpc}) < 70$ . (This number includes NGC 1466 and NGC 1841). For a spherically symmetric

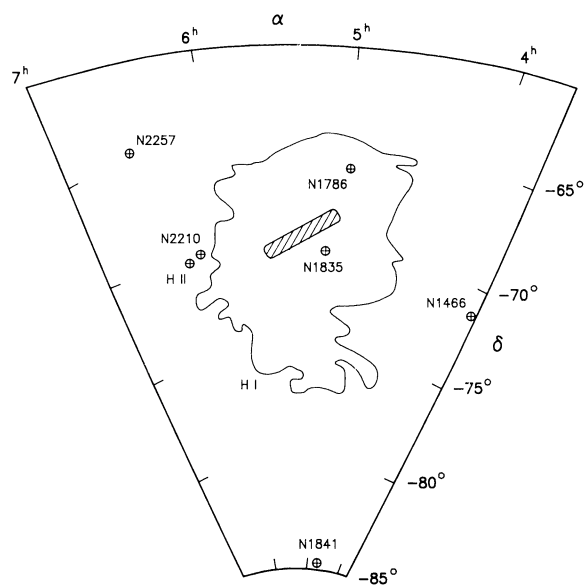


FIG. 4.—Distribution of LMC globular clusters. Note that five of the seven Large Cloud globulars lie beyond the outermost H I contour of McGee and Milton (1966). The location of the LMC Bar is indicated by shading. The Reticulum cluster at  $\alpha(1950) = 4^{\text{h}}35^{\text{m}}4$ ,  $\delta(1950) = -58^{\circ}56'$  lies just outside the figure boundary.

Galactic globular cluster system the *a priori* probability that one of these clusters will be located within  $15^\circ$  of the LMC is  $p = 0.017n$ . If  $n = 10$ , then  $p = 0.17$ , whereas  $n = 8$  and  $p = 0.14$  if NGC 1466 and NGC 1841 are not members of the Galactic halo. The fact that NGC 1841 has a radial velocity similar to that of the LMC, and that its color-magnitude diagram resembles that of the other LMC globulars, suggests that the probability of it not being associated with the Large Cloud is probably even less than the value  $p = 0.14$ – $0.17$  derived above.

If the LMC and SMC have seven and one globular clusters, respectively, then the Large Cloud has a specific cluster frequency, defined as the number of globulars per  $M_V = -15$  of parent galaxy luminosity (Harris & van den Bergh 1981),  $S = 0.4 \pm 0.15$ , and the Small Cloud has  $S = 0.3 \pm 0.3$ . Note that these values might be slightly too low if some faint clusters with ages greater than 10 Gyr have remained unrecognized in the Clouds.

It would clearly be very important to obtain accurate radial velocities for all seven certain LMC globular clusters and for the Reticulum system. Strom & Carney (1991) and Seitzer (1991) have already published new velocities for NGC 1841 and the Reticulum system, and for NGC 1835 and NGC 2257, respectively. Such observations might show whether the oldest population component of the LMC, which has  $[\text{Fe}/\text{H}] \simeq -2$ , constitutes a true halo population. Observations of long-period variables with  $100 < P(\text{days}) < 225$  in the LMC suggest that these objects, which are expected to have  $[\text{Fe}/\text{H}] \simeq -1$ , belong to a thick disk population with axial ratios  $a/b \simeq 0.3$  (Hughes 1991).

Figure 5a shows the distribution of old ( $U-B > 0.0$ ,  $B-V > 0.5$ ; van den Bergh 1981) clusters associated with the Large Cloud. These clusters are seen to have quite a wide distribution and to exhibit no concentration to the Bar of the Large Cloud. The centroid of the old clusters is located north of the Bar, i.e., close to the dynamical center of the Large Cloud (de Vaucouleurs & Freeman 1972; Rohlfs et al. 1984). In regard to their wide distribution, centroid, and lack of concentration to the Bar, typical old clusters resemble LMC novae (van den Bergh 1988), which are believed to belong to an old disk population. Clearly it would be very important to search for old clusters in the crowded Bar of the Large Cloud, to see whether the apparent absence of such objects is real or whether it is due to observational selection effects.

Figure 5b shows that young ( $U-B < 0.0$ ,  $B-V < 0.5$ ) clusters in the LMC are less widely distributed than old clusters, even though they have approximately the same centroid. Young clusters appear to show some concentration to the Bar of the LMC, as do Cepheids of intermediate age (Payne-Gaposchkin 1972). Not surprisingly, young clusters exhibit a clumpy distribution over the face of the Large Cloud. Comparison of Figures 4 and 5b shows, somewhat surprisingly, that few clusters are located in the huge lobe of H I gas that extends up to  $7^\circ$  to the south of the LMC Bar.

Figure 6a shows that old clusters associated with the SMC avoid the Bar region, whereas young SMC clusters are strongly concentrated toward the Bar of the Small Cloud. As was the case in the LMC, "old" clusters were defined to be objects with  $B-V > 0.5$  and  $U-B > 0.0$ , while clusters with  $B-V < 0.5$  and  $U-B < 0.0$  are considered to be "young." The results plotted in Figure 6a suggest that the Bar of the SMC is also a relatively young feature; such a conclusion is consistent with its relatively blue integrated color (Elsässer 1958).

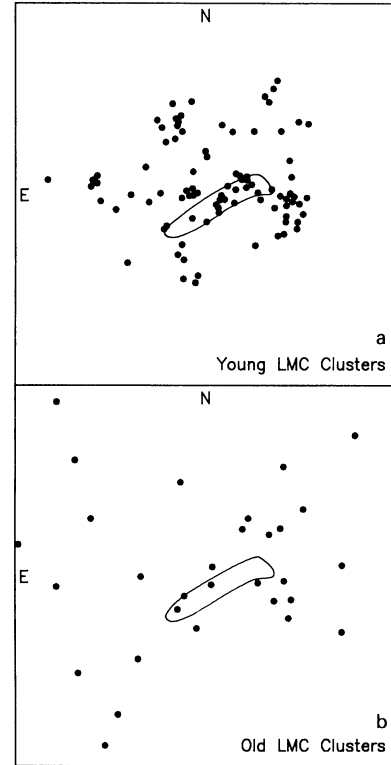


FIG. 5.—Comparison between the distributions of old ( $B-V > 0.5$ ,  $U-B > 0.0$ ) and young ( $B-V < 0.5$ ,  $U-B < 0.0$ ) clusters in the Large Magellanic Cloud. The figure shows that old clusters are more widely distributed than young ones. Young clusters exhibit some concentration to the Bar of the LMC, whereas old clusters do not.

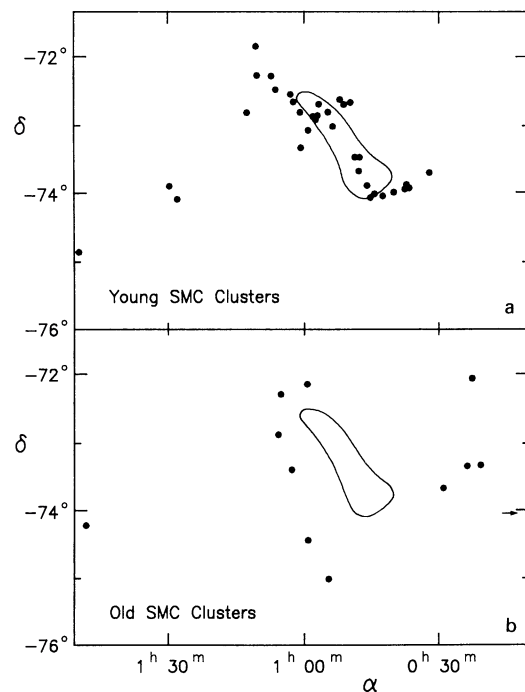


FIG. 6.—Comparison between the distributions of old and young clusters in the Small Magellanic Cloud. The figure shows that only young clusters are associated with the Bar of the SMC.

Freeman, Illingworth, & Oemler (1983) find that LMC clusters with ages of approximately 1 Gyr or less have motions similar to that of the gas in their vicinity and share the rotation solutions that have been derived from H I velocity maps and from velocities of individual H II regions. For these clusters a line-of-sight velocity dispersion of  $\sim 15 \text{ km s}^{-1}$  is superposed on a rotation curve with an amplitude of  $37 \text{ km s}^{-1}$ . The line of nodes for the rotation of the young cluster system has a position angle of  $1^\circ \pm 5^\circ$ . This value is indistinguishable from the major-axis orientation of  $7^\circ \pm 10^\circ$  for the LMC cluster system determined by Lyngå & Westerlund (1963). Freeman, Illingworth, & Oemler (1983) also find that intermediate-age clusters, with ages of a few Gyr, belong to a flattened disklike system with an intrinsic line-of-sight velocity of only  $17 \text{ km s}^{-1}$ . It would be very worthwhile to obtain additional velocities of clusters with ages in the range 1–4 Gyr to see whether the deviant line of nodes with position angle  $41^\circ \pm 5^\circ$ , which Freeman, Illingworth, & Oemler find for these clusters, can be confirmed. In this connection it is of interest to note that Meatheringham (1991) finds that LMC planetary nebulae form a flattened disk with almost the same spatial distribution and rotation solution as the H I.

## 12. PROBLEMS AND DESIDERATA

1. It would be very important to get high-quality color-magnitude diagrams for the red populous clusters in the Magellanic Clouds. By fitting such observations to modern evolutionary tracks, it should be possible to trace the history of star and cluster formation in the Clouds. It would be particularly interesting if the puzzling hiatus in LMC cluster formation between 3 and 10 Gyr ago could be confirmed.

2. Precise color-magnitude diagrams of large stellar samples in populous Cloud clusters could tell us about evolutionary phases during which stars evolve rapidly. Furthermore, such color-magnitude diagrams can give information on the evolution of stars located in parts of the metallicity-age plane that cannot be sampled in the solar vicinity. A possibly related question is why all true globular clusters associated with the LMC, for which color-magnitude diagrams are available, have blue horizontal branches. (The only exception is the Reticulum system, in which the maximum, horizontal-branch population falls in the RR Lyrae gap.) A color-magnitude diagram is still needed for the globular cluster NGC 1835. *Space Telescope* might also be able to study such compact old clusters as NGC 1916, NGC 2005, and NGC 2019 in the Bar of the LMC.

3. High-quality information on the structural parameters of clusters having differing ages might provide insight into the nature and origin of the relation between cluster radius and galactocentric distance of Cloud clusters. It would be particularly important to know why the Magellanic Clouds do not appear to have formed any clusters as compact as those observed in the Galaxy.

4. Better observations of the flattening of Cloud clusters, of differing ages and masses, might provide a clue to the puzzling difference between the ellipticities of luminous clusters in the Galaxy, the LMC, and the SMC.

5. It is important to know why the Magellanic Clouds contain intermediate-mass populous clusters, whereas the Galaxy exhibits a clear-cut dichotomy between massive globulars and much less massive open clusters. There is clearly a need for integrated light luminosity functions derived from complete samples of LMC and SMC clusters.

6. More work needs to be done on the mass spectrum of star formation in the Magellanic Clouds to see whether it differs systematically from that near the Sun. It would also be interesting to know whether the initial stellar mass function differs significantly from cluster to cluster.

7. We do not yet know why star formation in the SMC got off to such a slow start, or why so much gas remains in the Small Cloud ( $\mathcal{M}_g/\mathcal{M}_T \approx 0.3$ ). In particular, it is not clear why the present star and cluster formation rate in the SMC is relatively low, even though the Small Cloud has a higher average gas density per square parsec than any other Local Group galaxy (cf. van den Bergh and Pierce 1991).

8. It would be very important to obtain more accurate radial velocities for the globular clusters associated with the LMC. Such observations might provide useful constraints on the mass of dark matter associated with the Large Cloud. Ultimately radial velocities of RR Lyrae variables and blue horizontal-branch stars in the outer halo of the LMC could provide more stringent limits on the mass of dark matter in the halo of the Large Cloud.

## 13. SUMMARY AND CONCLUSIONS

Both old and young clusters in the Magellanic Clouds have radii that are  $\sim 3$  times larger than those of comparable Galactic star clusters. It is speculated that this difference might be due to the fact that Cloud clusters formed in a lower density environment than clusters in the Galaxy. Young clusters in the LMC and SMC seem to remain embedded in the remnants of associations for extended periods because tidal forces in the Clouds are weaker than they are in the Milky Way system. It is not yet understood why Cloud clusters of all ages are, on average, much more flattened than their Galactic counterparts.

The Clouds contain genuine globular clusters, defined as objects which contain RR Lyrae stars or which have color-magnitude diagrams that show their ages to be greater than 10 Gyr. The *a priori* probability that both NGC 1466 and NGC 1841 are Galactic globulars, which appear projected near the LMC by chance, is found to be only  $(0.17)^2$ . The specific globular cluster frequency is  $S = 0.4 \pm 0.15$  ( $n = 7$ ) in the LMC, and  $S = 0.3 \pm 0.3$  ( $n = 1$ ) in the SMC. The mean luminosity  $\langle M_V \rangle$  of globular clusters is very similar in the Magellanic Clouds, the Galaxy, and M31. Galactic and LMC globulars also appear to have very similar  $\mathcal{M}/L$  ratios. The color-magnitude diagrams of LMC globulars are also indistinguishable from those of old metal-poor Galactic globular clusters. These observations show that Large Cloud globulars are physically indistinguishable from old Galactic globular clusters and were therefore, presumably, formed under rather similar physical conditions.

Age determinations of LMC clusters suggest, but do not yet prove, that the cluster formation rate in the Large Cloud was low between the end of the era of globular cluster formation and 3–5 Gyr ago. There are indications that active star formation in the LMC also started  $\sim 4$  Gyr ago. Radial velocity observations show that the red clusters with ages less than 4 Gyr form a flattened subsystem. The absence of clusters similar to K3 in the Large Cloud is consistent with the speculation that the LMC, but not the SMC, was rather inactive  $\sim 10$  Gyr ago.

No old clusters are known to be associated with the Bar of the LMC, or with the Bar (main body) of the SMC. It would be important to know whether the lack of old clusters in the Bar

of the LMC is real or whether it is due to observational selection effects.

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