FIELD STUDIES, LUMINOSITY FUNCTIONS, AND STAR FORMATION HISTORY IN THE MAGELLANIC CLOUDS

L.L. Stryker
Dominion Astrophysical Observatory
Herzberg Institute of Astrophysics
Victoria, B.C. Canada, V8X 4M6

I. INTRODUCTION

One of the most fundamental questions we might ask about galaxies is, Do all galaxies have the same age? A less general question, and one which we can surely succeed in answering is, Are the Magellanic Clouds (MCs) the same age as the Galaxy? We must also make clear what is meant by the same age if, in fact, star forming activities in these systems have proceeded along different timescales. The age of a system can be masked if the strongest star-forming epoch was not coincident with the initial epoch. Deep colour-magnitude diagrams (CMDs) and luminosity functions (LFs) have had to wait until the advent of large southern telescopes, sensitive emulsions and detectors, and accurate methods of measuring crowded images.

Our knowledge of the stellar population structure in the Clouds as of 1970 was mainly based on observations to $V<18$ by Arp, Bok and collaborators, Hodge, Tifft, Westerlund, and Woolley (Westerlund 1970; and the ESO volume, Muller 1971). Most of these studies were made relatively close to the inner regions of the Clouds, or near associations or clusters. Many showed that clusters and their nearby fields had closely related populations. Even so, CMDs really become interesting at $V \sim 19$, where one can begin to learn something about the horizontal branch and giant clump.

Harvard workers, Shapley, Bok, and Hodge, produced star counts and LFs down to $V=17.5$ ($M_V=-1.5$) in a number of areas in the Clouds. Their investigations indicated that both Clouds had LFs that were similar to the van Rhijn Solar Neighbourhood function but with a possible excess of bright supergiants in the LMC (Hodge 1961).

Very little was known of the halo-type populations in either Cloud other than the globular cluster CMDs of Gascoigne (1966) and that of Tifft's (1963) field near NGC 121. Equally unstudied was the LMC Bar. It had been suggested (Tifft 1971) that "the older stellar components of the MCs are significantly younger, on the average, than the old star component of the Galaxy", and that the oldest population appeared only sparsely in the Clouds.

S. van den Bergh and K. S. de Boer (eds.), Structure and Evolution of the Magellanic Clouds, 79–87.

This paper will attempt a) to outline the advances made since 1970 in faint field CMDs and main-sequence LFs, and b) to derive a general notion from these studies of how star formation (SF) may have proceeded in the Clouds.

II. FIELD STUDIES

II.1. The Large Magellanic Cloud.

The first published field CMDs typically showed strong, blue main sequences and varying proportions of red giants. In the last decade many deeper studies have appeared (c.f. Table I). The discussion here will emphasize studies of the Bar and outlying areas.

Tifft and Snell (1971=TS) studied the Bar West (BW) $1\overset{\circ}{.}5$ NW of Bar centre, down to $V\sim17.5$. Many of their conclusions have been superceded by a study to $V\sim21$ by Hardy et al. (1983), who found the main giant clump at V=19.2, B-V=0.8, with an asymptotic giant branch (AGB) tip at V=16, B-V=2.2 -- suggesting a strong intermediate-age population (contrary to TS). No blue horizontal branch was found. From their CMD, LF, and from evolutionary models of clump red giants, they concluded that: 1. SF continues in the bar; 2. old Pop. II is not a significant contributor; 3. most SF started between 1 to 3.10^9 years ago (and has since been continuous); and 4. the Bar population is considerably younger and more metal - poor than that in the Solar Neighbourhood.

Frogel and Blanco (1983=FB) produced an infrared CMD of M giants in the same BW region. They found two well-separated AGBs, indicating two discrete epochs of SF, the main one having taken place "a few 10^9 years ago". This latter result is in agreement with conclusions found in other regions (Butcher 1977; Stryker and Butcher 1981; Hardy et al. 1983), and strengthens the idea that a global increase in the star-formation rate (SFR) occurred in the LMC during that epoch. The secondary episode of SF was ~10x less-efficient than the first and took place $\sim10^8$ years ago. Between episodes, the SFR was much lower, suggesting non-continuous SF, contrary to the suggestion of Hardy et al. (1983). Integrated colours for Area 5 (=BW) in Hardy's (1978) study of colours in and around the Bar, suggest that BW is typical of the entire Bar. However, ~11-12' S of the Bar, colours become significantly redder.

These studies indicate that the Bar has been a place of quite active SF, at least up to $\sim10^8$ years ago. Since the dust lane signature is lacking and the LMC is neither regular nor massive, there is no evidence thus far that the presence of a bar in any way drives SF.

From a study near the old globular cluster, NGC 2257, Stryker et al. (1981), and Stryker (1983), find that even in the outer (~9 kpc) regions SF must have taken place in relatively recent times. The field CMD is that of a more metal-rich population, showing a strong red horizontal branch. Also there is no old, extremely metal poor (in the galactic globular cluster sense) component in the field, other than the RR Lyrae stars (Nemec et al. 1984), which themselves may show a range in metallicity.

These field studies show a mixture of young and old stars in all areas of the LMC. V_B, the apparent magnitude of the brightest blue evolved stars (B-V <0.4) in each field CMD, can be used to get a rough notion of ages (Hodge 1983). Figure 1 shows V_B plotted versus radial distance from the LMC centre. (We ignore the Shapley Constellations to concentrate on the older, background population.) Approximate relative ages, from Hodge (1983, fig. 1), appear on the right ordinate. Fig. 1 shows a radial drop-off in "youngest stars".

TABLE I

Recent Field Studies in the Magellanic Clouds

RA 1975.	Dec	Dir	Near cluster	CMD Ref.[a]	V_B	M_V	Age
LMC							
05 09.5	-68 57	1°4 NW	N1850	(1,2,3)	14.5,16	-4.1,-2.6	5.10^7
05 19.7	-70 59	1.5 S	---	(4)	18	-0.6	$2\text{-}3.10^8$
05 48.5	-71 30	2.9 SE	N2121	(5)	18.5	-0.1	
05 28.4	-66 15	3.3 NE	N1978	(6)	17,18,19	-1.6,0.4	$1\text{-}4.10^8$
05 21.8	-73 31	4.0 S	---	(7)	20	1.4	$< 10^9$
05 13.0	-65 30	4.1 N	N1866	(8)	18.5	-0.1	
04 59.0	-66 00	4.2 NW	N1783	(9,10)	19.5	0.9	6.10^8
06 14.0	-69 20	4.4 E	H11	(11)	19.5-20	1.2	$< 10^9$
05 14.3	-63 59	5.6 N	N1868	(12)	19	0.4	4.10^8
06 10.0	-73 50	5.7 SE	N2209	(13)	19.3	0.7	5.10^8
06 30.0	-64 10	8.5 NE	N2257	(9,14,15)	20.5	1.9	$\sim 10^9$
SMC							
01 07.6	-72 42	1.2 E	N419	(16)	17.5-18	-1.5	$1\text{-}2.10^8$
00 27.0	-72 52	1.8 W	K3	(17)	20.2	1.0	$8\text{-}9.10^8$
01 09.0	-71 42	1.8 NE	---	(18)	18.5	-0.7	2.10^8
01 22.0	-72 02	2.4 NE	---	(18)	20	0.8	$6\text{-}7.18^8$
00 25.7	-71 41	2.4 NW	N121	(19)	~ 22	2.8	$\sim 10.10^9$
01 06.0	-75 30	2.7 S	N339	(20)	~20.8	1.6	1.10^9
00 09.8	-73 36	3.5 SW	---	(21)	20	0.8	$6\text{-}7.10^8$
01 49.0	-73 51	4.2 E	L113	(22)	~22.2	3	$\sim 10.10^9$

[a] Refer to the Reference list, which includes these codes.

Evidently, from Fig. 1 and the studies mentioned above, the Bar has had several episodes of SF right up to several 10^7 years ago. The farthest fields, however, show no star-forming activity after $1\text{-}2.10^9$ years ago (though tidal forces may have dispersed the stars away from their original connections with gas and molecular clouds). For the fields listed in Table I, the ratio of blue to red stars (for stars with V <20) is roughly constant to ~4.5-5° from the Bar, beyond which it falls steadily. In many CMDs, a typical Pop. I giant "clump" (age $<5.10^9$ years) is seen, in contrast to, say, a Pop. II red horizontal branch (age $>10.10^9$ years). In no field region studied thus far has a convincing blue horizontal branch been seen.

https://doi.org/10.1017/S0074180900039978 Published online by Cambridge University Press

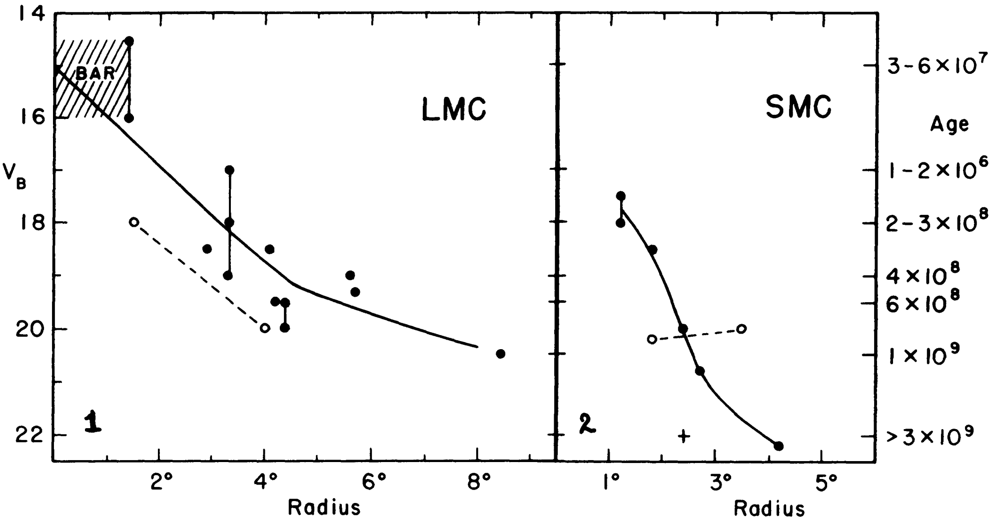

Fig. 1,2. V_B vs. radial distance. LMC: (●) for fields in BW, E, and N; (o) for fields S. SMC: (●) for fields E, N, and S; (o) for fields W. (+) is for the field near NGC 121.

II.2. The Small Magellanic Cloud.

Following the fine review of the population structure of the SMC by Brück (1982), we outline the regions by increasing age (decreasing SF activity).

Bar, Arms, and Wing. current or recent SF 10^6-10^7 yrs ago, no intermediate-age clusters, planetary nebulae in Bar. SF began in Bar $\sim10^9$ yrs ago (Pop. I), Arms and Wing show evidence of recent SF bursts (extreme Pop. I).

Outer Arm, Outer Wing, and Bridge: SF $1-6.10^7$ yrs ago, nothing since. No populous clusters in Wing.

Disc: Pop. I objects in dense regions, older objects spread over entire area. SF 5.10^7 to 10^8 yrs ago.

Halo: Objects much younger than galactic halo members, large density of RR Lyrae stars (similar to that in the galactic disc), large intermediate-age component $\sim3.10^9$ yrs old.

The Edinburgh Group have made extensive star counts (Brück 1978, 1980) and field CMDs to $V\sim21.2$ (see Table I). Brück and Marsoglu (1978) find, in fields in the outer arm and halo near NGC 458, evidence of layers of SF superposed on a population $>10^9$ years old. Hawkins and Brück (1982), near K3, confirm a 3.10^9 year old component without ruling out an older constituent. Their latest work (Hawkins and Brück 1984) is much farther out (3.°5 SW) and similar results are obtained.

Hardy and Durand (1983) studied fields in the inner wing near NGC 419 and found a probable subgiant branch, indicating a median age of SF older in the SMC than in the LMC. Stryker and Nemec (1983), working down to V ~22.5, find the majority of stars in a field S of NGC 339, to be older than the nearby intermediate-age cluster NGC 643. Stryker et al. (1983), find the field near the old cluster NGC 121, to be ~10.10^9 years old, and Mould et al. (1983) find the same result for their field 4° E of the Bar, near L113. Thus, from analyses to date, the background sheet of stars in the SMC appears to be of a similar age as the galactic disc. Fig. 2 shows the radial distribution of V_B for the SMC. Note that the SMC displays an essentially older stellar population than appears in the LMC, even after allowance for differences in metallicity.

III. MAIN SEQUENCE LUMINOSITY FUNCTIONS

According to Salpeter (1955), the observed Solar Neighbourhood LF depends on: 1. the relative probability for the creation of stars of mass M at time t (i.e., the initial mass function, IMF(M)); 2. the rate of creation of stars as a function of time since the formation of the Galaxy (i.e., the SF rate, SFR(t)); and 3. the evolution of stars of different masses after they leave the main sequence. Assumptions were that mass-loss is important only in the later stages of evolution; the IMF is time-independent; and the SFR is constant over the last 5.10^9 years (the lifetime of the Pop. I Solar Neighbourhood). Salpeter found a "knee" or change in slope in the local LF at M_V~+4, consistent with an age of the disc, ~10.10^9 years. Since it is believed that other galaxies condensed and formed at about the same time, their LFs should also exhibit either a discontinuation (elliptical galaxies) or a change in slope (spirals and irregulars) at M_V~+4. What is found from the faint LFs in the Magellanic Clouds?

Many problems are encountered in actually deriving a main sequence LF in the Clouds: getting data to sufficiently faint magnitudes where things begin to get interesting (V >21.5); doing accurate photometry in crowded fields; making corrections for the loss of faint stars, due partly to obscuration by brighter stars, to achieve a complete starcount; eliminating non-main sequence stars and foreground/ background contaminators. Added to these problems are the uncertainties in the distance modulus (~$0^m_.2$), the chemical composition, the original shape of the IMF, and the SF history or rate.

The first derivation of a main sequence LF was discussed by Butcher (1977) for a field ~4° N of the Bar. Later, Stryker (1981) and Stryker and Butcher (1981) discussed a second region $4^\circ_.5$ NW of the Bar. These authors deconvolved partially merged images, and studied the error distributions and completeness with the use of artificial images. Their major finding was that in the LMC the change of LF slope occurs at M_V=+3, a full magnitude brighter than in the Solar Neighbourhood. The difference in chemical composition between the Galaxy and LMC contributes only ~$0^m_.1$, assuming similar helium content. The interpretation of this magnitude difference has been that a major epoch of SF occurred in the LMC at ~$2-5.10^9$ years ago, instead of 10.10^9, as expected. Also, when the younger "age" is assigned the LMC, the correction to the initial LF reproduces the Salpeter initial LF.

Concern remained because these results were obtained from photometry done at the very limits of photographic plates and because of the possibility that the LMC mass function may be deficient at the low mass end (thus causing a brighter knee to be observed in the LF).

In an attempt to understand better the LMC LF and its interpretation, Stryker and VandenBerg (1983=SV) are constructing LF models for chemical compositions [Fe/H]= 0, -0.5, and -1, and IMF slopes of 0 and 1.35. Their preliminary models use the set of isochrones generated by VandenBerg (1983), for masses from $3M_\odot$ to $0.5M_\odot$ (lifetimes from $0.25 - 10.10^9$ years). Evolutionary tracks are found to be sensitive to the metallicity adopted (as demonstrated by the convective "hooks" along the main-sequence). SV are also testing several different SFRs, such as sporadic bursts, constant rate, and continuous SF in equal intervals of log time (power law). The IMF used is the usual simple power law $dn/dm \propto m^{-(1+x)}$. A SF burst occurs with IMF slope x and burst strength specified. Stars are counted until hydrogen-shell burning begins.

Models for [Fe/H] = -1, x = 0 and 1.35 have been compared to observations in three SF cases: 1. sporadic star bursts, 2. constant SF (Δt), and 3. constant SF ($\Delta \log t$). For Case 1, SV find a reasonably good fit with bursts (in 10^9 years, followed by burst strength) at 5(1), 4(1), 2(0.5), 0.25(0.25), 0.05(0.05). Exchanging 10(0.25) for 4(1) fits equally well. Figs. 3-4 show Case 2 models; Figs. 5-6, Case 3 models. Regardless of IMF slope or type of SF chosen, all models require a strong intermediate-age component.

SV conclude that a significant amount of SF 10.10^9 years ago cannot be ruled out, but its strength must have been less than that $\lesssim 5.10^9$ years ago, the age of the majority of stars. Large factors of a $6,8,10.10^9$ year old population move the knee towards $M_V=+4$. It is realized that field CMDs show local variations, but the data used (Stryker and Butcher 1981) are nearly identical to those of Butcher (1977). Also, IMFs in the Galaxy and LMC are probably similar. Case 3 agrees with Rocca-Volmerange (1983) who, from UV colours of Irregular galaxies, finds an active present SFR, a low mean past SFR, and similar IMFs.

The strength of the 10.10^9 year old population can be best ascertained by Space Telescope observations, since it shows up at $M_V \gtrsim +4$. The slope of the IMF and any low-mass deficiency can be determined as well with observations $+4 < M_V < +6$. Ground-based CCD observations can aid considerably in defining the LF with observations in many fields to V=24.

IV. FUTURE WORK

Is the LMC halo spherical or flat? What are the chemical compositions of halo stars, RR Lyrae stars, and intermediate-age giants? Are the oldest clusters as old as the galactic globulars? More deep CMDs and LFs to V=24 are needed in many more areas of both Clouds. The

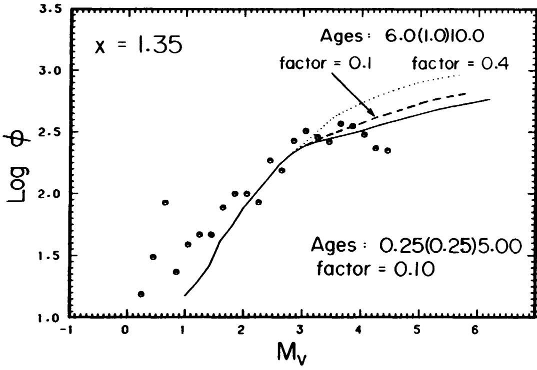

Fig. 3. Model LF with constant SFR, x = 1.35, ages 0.25-5.10^9 in time-steps of 0.25.10^9 (equal factors). Dashed line shows ages 6-10.10^9 added, (1/4 weight); dotted line, same (full weight).

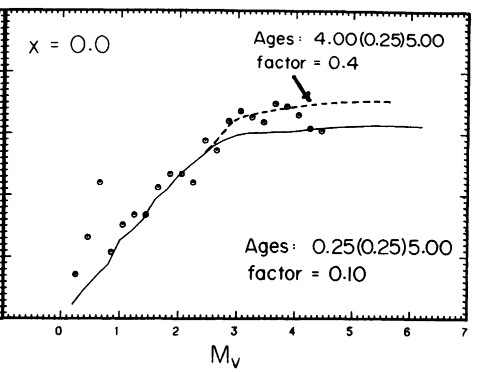

Fig. 4. Same as Fig 3. but with x = 0. Dashed line is result after addition of strong intermediate-age component.

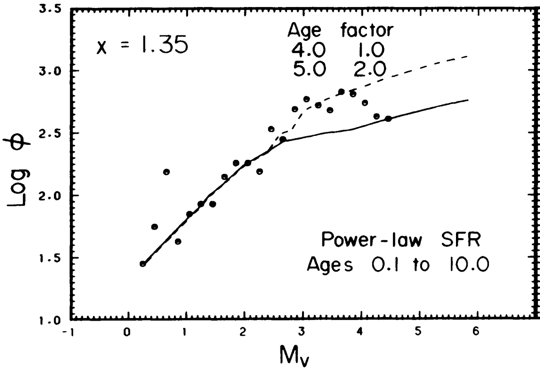

Fig. 5. Model LF, power law SFR ages 0.1-10.10^9, x = 1.35. Dashed line shows addition of very strong intermediate-age component.

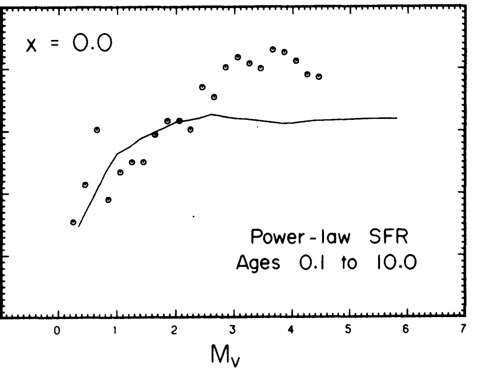

Fig. 6. Same, as Fig. 5 but with x = 0.

Space Telescope will not only be able to reach M_V~+7, but will reduce considerably the problem of crowded images. We should then be able to define the LF shape past M_V~+4, learn more about the oldest population component in the Clouds, and be able to find out whether the Clouds are deficient in low-mass stars compared to the Solar Neighbourhood. In addition, more studies of galactic halo and disc fields would be useful for comparison.

The author wishes to thank M. Brück, J. Frogel, E. Hardy, J. Mould, E. Olszewski, and B. Rocca-Volmerange for sending information pertinent to this paper, and J. Hesser, S. van den Bergh, and H. Harris for comments on early versions. The Deutsche Forschungsgemeinshaft (DFG) and the IAU provided support for travel to this symposium.

REFERENCES

Brück, M.T.: 1978, Astron. Astrophys. 68, 181.
Brück, M.T.: 1980, Astron. Astrophys. 87, 92.
Brück, M.T.: 1982, in Compendium in Astronomy, eds. E. G. Mariolopoulos et al. (Dordrecht: Reidel), p. 297.
Brück, M.T., & Marsoglu, A.: 1978, Astron. Astrophys. 68, 193. (18)
Butcher, H.R.: 1977, Astrophys. J. 216, 372. (8)
Flower, P., Geisler, D., Hodge, P., & Olszewski, E.: 1980, Astrophys. J. 235, 769. (12)
Flower, P., Geisler, D., Hodge, P., Olszewski, E., & Schommer, R.: 1983, Astrophys. J., (in press). (5)
Frogel, J.A., & Blanco, V.C.: 1983, Astrophys. J. Letters, (in press). (FB) (3)
Gascoigne, S.C.B.: 1966, Monthly Notices Roy. Astron. Soc. 134, 59.
Hardy, E.: 1978, Pub. Astron. Soc. Pacific 90, 132.
Hardy, E., & Durand, D.: 1983, (preprint). (16)
Hardy, E., Melnick, J., & Rheault, C.: 1980, in IAU Symp. 85, ed. J.E. Hesser (Dordrecht: Reidel), p. 343. (13)
Hardy, E., Buonnano, R., Corsi, C., Janes, K., & Schommer, R.: 1983, Astrophys. J., (in press). (2)
Hawkins, M.R.S., & Brück, M.T.: 1982, MNRAS 198, 935. (17)
Hawkins, M.R.S., & Brück, M.T.: 1984, this volume, p. 101. (21)
Hodge, P.: 1961, Astrophys. J. Suppl. 6, 235.
Hodge, P.: 1983, Astrophys. J. 264, 470.
Lindgren, H., Ardeberg, A., Linde, P., & Lyngå, G.:1980, in Proc. of ESO Workshop on 2-Dim. Photometry, eds P. Crane & K. Kjar, p.155 (4)
Mould, J.R., Da Costa, G.S., & Crawford, M.D.: 1983, (preprint) (22)
Muller, A.B.: 1971, ed "The Magellanic Clouds", (Dordrecht:Reidel).
Nemec, J.M., Liller, M.H., & Hesser, J.E.: 1984, this volume, p. 39.
Olszewski, E.: 1982, Ph.D. Thesis, University of Washington. (6)
Rocca-Volmerange, B.: 1983, "First Stellar Generations", Frascati Workshop, Mem. della Soc. Ast. Italiana, (in press).
Salpeter, E.: 1955, Astrophys. J. 121, 161.
Stryker, L.L.: 1981, Ph.D. Thesis, Yale University. (9)
Stryker, L.L.: 1984, Astrophys. J., (in press). (15)
Stryker, L.L.: 1983, (in preparation). (7)
Stryker, L.L., & Butcher, H.R.: 1981, in IAU Coll. 68, eds. A.G.D. Philip & D.S. Hayes (Schenectady: Davis), p. 255. (10)
Stryker, L.L., & Nemec, J.M.: 1983, (in preparation). (20)
Stryker, L.L., & VandenBerg, D.A.: 1983, (in preparation). (SV)
Stryker, L.L., Butcher, H.R., & Jewell, J.L.: 1981, in IAU Coll. 68, eds. A.G.D. Philip & D.S. Hayes (Schenectady:Davis), p.267 (14)
Stryker, L.L., Da Costa, G.S., & Mould, J.R.: 1983, (in prep.) (19)
Stryker, L.L., Nemec, J.M., Hesser, J.E., & McClure, R.D.: 1984, this volume, p. 43. (11)
Tifft, W.: 1964, IAU/URSI Symp. 20, eds F.J. Kerr & A.W. Rodgers (Canberra: Austral. Acad. Sci.) p. 349.
Tifft, W., & Snell, C.: 1971, MNRAS 151, 365. (TS) (1)
VandenBerg, D.A.: 1983, Astrophys. J. Suppl. 51, 29.
de Vaucouleurs, G., & Freeman, K.: 1972, in Vistas Astron. 14, 163.
Westerlund, B.E.: 1970, in Vistas Astron. 12, 335.

DISCUSSION

Flower: Your composite color-magnitude diagram of 10 fields in outlying regions appears to be very similar to the color-magnitude diagrams of NGC2121 and NGC1978; i.e. the brightest main sequence stars in your fields are near $V \simeq 20.3$ (vs $V = 20.0$ for NGC2121 and $V = 20.3$ for NGC1978) and the clump of red giants (or red horizontal branch stars) is at $V \simeq 19.2$ (vs $V = 19.0$ for NGC2121 and $V = 19.3$ for NGC1978). The relatively bright main sequence and red giants in these clusters suggest cluster ages less than about 1 Gyr. Thus your fields appear to be rather young.
Stryker: I would be surprised if these 10 outlying fields really did look like NGC1978 or NGC2121. The fields show a well-defined red horizontal branch, not an intermediate-age clump. My point is that there are several ages present in the fields, the youngest at about 1 to 2 Gyrs old; the oldest about 10 Gyrs. The oldest population is stronger. The other point was that although the near cluster (NGC2251) is more than about 14 Gyrs old and very metal-poor, the field seems <u>not</u> to have a significant portion of similar stars.
Lequeux: I am prepared to accept your conclusion from the luminosity function that intense star formation has started only about 4 Gyrs ago in the LMC; by the way, this is not inconsistent with what can be derived from global properties. However this conclusion rests entirely on the assumption that there <u>are and have been</u> stars with $M \lesssim 1\ M_\odot$ formed in the LMC. Unfortunately nothing in the theory or observations can prove this statement, and it may well be that the lack of stars with $M_V \gtrsim +3$ in the luminosity function is not an age effect but the result of a break or cut-off in the IMF at low masses.