THE STELLAR POPULATIONS OF THE MAGELLANIC CLOUDS

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I. Introduction

In many ways, studies of the stellar populations in the Magellanic Clouds are more straightforward than in our own Galaxy because of our external vantage point of the Clouds. This allows us to study the global properties of their stellar populations, as well as the individual stars that comprise them. The resulting picture describing the stellar content of the Clouds is obviously complex, defying any attempt to present a complete description in a short review such as this. Thus, my goal is to provide a very broad overview of the global properties of the Magellanic Clouds, along with some slightly more detailed discussions on a few selected topics addressed by recent studies. Recent reviews of the global properties and stellar content of the Magellanic Clouds based on observations ranging from radio to x-ray wavelengths can be found in the Proceedings of IAU Symposium 148 (Haynes and Milne 1991) and in Westerlund (1990). More specialized reviews have been written recently by van den Bergh (1991), Freeman (1989), and Feast (1989), and by numerous authors in the proceedings of a recent European Colloquium on the Magellanic Clouds (de Boer, *et al.* 1989).

II. Global Properties

Some of the global properties of the Magellanic Clouds are summarized in Table 1, along with corresponding values for the Galaxy. It has long been appreciated – and is evident in Table 1 – that many of the global properties of the three galaxies vary smoothly along the sequence SMC ⇒ LMC ⇒ Galaxy (as represented by the solar neighborhood). For example, the mean present-day abundances of these galaxies increase along this sequence (Russell and Bessell 1989; Russell and Dopita 1989), while the gas-to-dust ratios decrease. Such trends make the Magellanic Clouds invaluable tools to study how the properties of stellar populations vary with global galaxian properties. As an illustration, Maeder (this volume) has shown that the changes in the relative numbers of C and N Wolf-Rayet stars and of the numbers of O stars in the three galaxies can be understood by the increased efficiency of stellar winds with increasing metallicity; similarly, the form of the chemical abundance enrichment histories of the three galaxies differ systematically (see §IV), perhaps related to their total masses or gas fractions.

A classic review of the global optical properties of the Magellanic Clouds can be found in de Vaucouleurs and Freeman (1972), while a more recent discussion of the large-scale photometric parameters of both galaxies was published by Bothun and Thompson (1988). Irwin (1991) discusses the structure of the Magellanic clouds based on deep star counts using Schmidt plates. While the LMC shows a generally regular outer structure, the SMC is clearly disturbed on the side facing the LMC, suggestive of a recent encounter between the two galaxies. The growing body of evidence of a significant line-of-sight depth in various parts of the SMC (nicely summarized by Hatzidimitriou and Hawkins 1989) supports this

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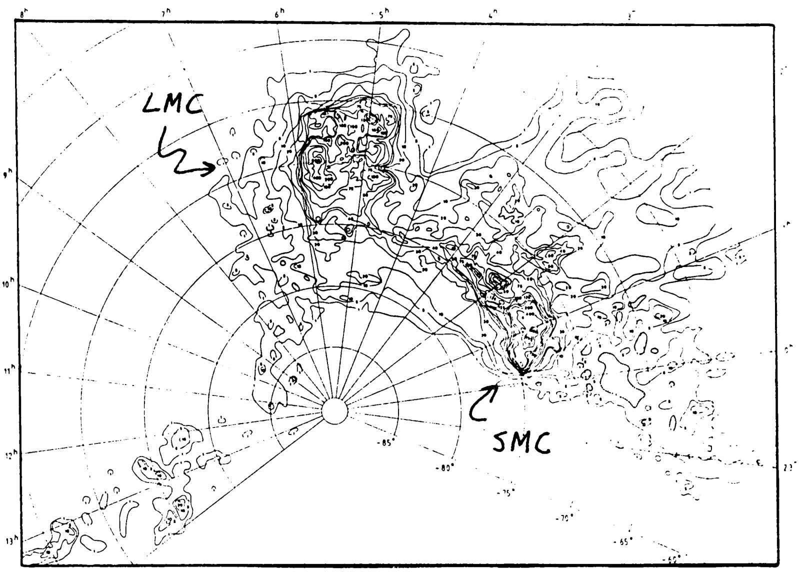

Figure 1 – An HI map of the Magellanic Clouds from Mathewson and Ford (1984). Note the complexity of the distribution of the gas over the entire Magellanic system.

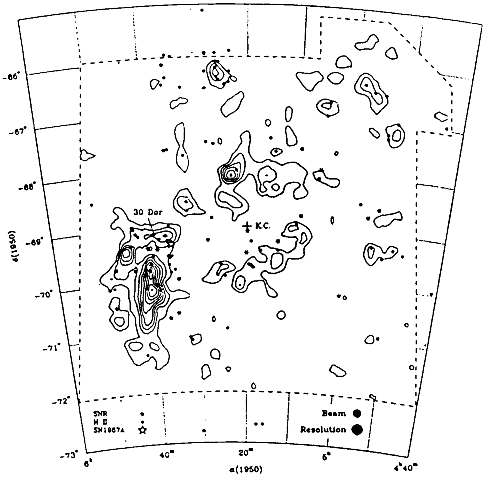

Figure 2 – The CO map of Cohen, *et al.* (1989). The gigantic CO cloud South of 30 Dor is a prominent feature.

Table 1

Global Properties of the Galaxy and Magellanic Clouds

	SMC	LMC	Galaxy
Distance (kpc)	58 ± 10	50 ± 5	...
$V_{0,tot}$	2.2	−0.1	...
$(B-V)_{0,tot}$	0.50	0.55	...
Luminosity ($L_\odot$)	4×10^8	2×10^9	2×10^{10}
Angular Size	14°	23° × 17°	...
Mass ($M_\odot$)	1×10^9	2×10^{10}	5×10^{11}
	($R < 3$ kpc)	($R < 6$ kpc)	($R < 50$ kpc)
Global M/L (Solar Units)	3	10	25
M_{HI} ($M_\odot$)	4×10^8	5×10^8	5×10^9
M_{HI}/M_{tot}	0.35	0.03	0.01
M_{molec} ($M_\odot$)	'low'	1.4×10^8	4×10^9
M_{molec}/M_{HI}	'low'	0.3	0.8
$[Fe/H]_0$	−0.7	−0.3	0.0

interpretation, as does the recent discovery of *young* stellar associations located between the Clouds (Irwin, *et al.* 1990; Grondin, *et al.* 1990). Radio astronomers have long appreciated that the Magellanic Clouds are the most prominent components of the single, much larger system shown (in part) in Figure 1 (from Mathewson and Ford 1984). How this complex structure has come about remains controversial. A review of the various possibilities is given by Wayte (1991) who favors the interpretation that the Magellanic Stream has been stripped via ram pressure from the Magellanic Clouds during their passage through the Galactic halo. In contrast, Murai and Fujimoto (1980) interpret the Stream as a tidal tail expelled from the Clouds during a recent near-collision of the two galaxies. Either way, it is clear that interactions – both with each other and with the Galaxy – have played important roles in the global evolution of the Clouds.

Recent studies have extended our view of the Magellanic Clouds to wavelengths other than the optical and radio. Notable among these is the CO survey by Cohen, *et al.* (1989) who mapped the inner 6° × 6° of the LMC during a multi-year survey from CTIO. The resulting map (Figure 2) reveals large CO clouds near a number of large star-forming regions, especially to the south of 30 Dor and near Shapley Constellation III north of the LMC Bar. A comparison of CO and H I maps in the vicinity of 30 Dor (Figures 1 and 2) with each other and with maps of the far-UV (Page and Carruthers 1981; Smith, *et al.* 1987) and Hα emission (Davies, *et al.* 1976) provides one of the clearest examples of how star formation propagates through massive gas complexes. It is not hard to guess that the next gigantic star formation region in the LMC will probably be located just south of the 30 Dor region where the largest CO cloud complex is observed.

III. The Populous Star Clusters of the Magellanic Clouds

The Magellanic Clouds possess rich populations of star clusters; just how rich can be seen from inspecting the map of the spatial distribution of the clusters in both Clouds (Irwin 1991). Many of these clusters are luminous objects that are morphologically similar to Galactic globular clusters. Some contain RR Lyr variables, possess blue horizontal branches, (*e.g.*, NGC 2257 and NGC 1841; Walker 1989, 1990) and have red integrated colors consistent with their identification as old stellar systems (van den Bergh 1981); in other words, these *are* globular clusters. However, most of the the bright Magellanic clusters are clearly very different. Their integrated spectra and colors imply that they contain stellar populations considerably younger than those found in true (*i.e.*, ancient) globular clusters (van den Bergh 1981). Detailed studies of the stellar content of these clusters have confirmed their relative youth compared to globular clusters (useful bibliographies of recent age determinations for Magellanic Cloud clusters can be found in Seggewiss and Richtler (1989) and Sagar and Pandey (1989)). Although the Clouds contain many of these luminous ($M_V \lesssim -8$) young clusters, there are few, if any, in the Galaxy. Are they simply globular clusters that have formed recently?

Table 2 lists the present-day integrated photometric properties and ages (based on analyses of color-magnitude diagrams) of five populous Magellanic Cloud clusters. Also listed are the predicted absolute visual magnitudes for these clusters for an age of 15 Gyr based ***only*** on the stellar evolutionary fading predicted by simple models for a Salpeter IMF slope (Elson, *et al.* 1987). Most of these clusters will have luminosities comparable to that of globular clusters in our Galaxy and M 31 ($\overline{M}_V = -7.1$, with an intrinsic dispersion of about 1 magnitude (van den Bergh 1985)). Alternatively, we can avoid using evolutionary models and compare clusters masses directly. As an example, consider NGC 1866. Lupton, *et al.* (1989) obtained velocities for 29 members of this cluster and derived an upper limit of $4 \times 10^5 M_\odot$ for its mass. Fischer, *et al.* (1991) analyzed more precise velocity measurements for 69 cluster members. Combined with a newly determined surface density profile spanning 3.5 decades of surface brightness, they derived a mass of $1.7 \pm 0.3 \times 10^5 M_\odot$ for NGC 1866. The mass of a typical Galactic globular cluster is about $1.2 \times 10^5 M_\odot$, assuming M/L = 2.

Although these comparisons suggest that *some* Magellanic Cloud clusters may be 'proto-globulars', it is important to recall that the overall luminosity function (LF) of clusters in the Clouds more closely resembles a power-law (similar to the LF of Galactic open clusters) than the Gaussian LF characteristic of globular clusters (Elson and Fall 1985). This suggests that *most* of the Magellanic Cloud clusters probably comprise a population similar to the Galactic open clusters. Nevertheless, assuming that some of the brightest blue clusters in the Clouds are in fact young globulars, their presence suggests that the Clouds today somehow resemble conditions in the early Galactic halo (Renzini 1991; but see Fujimoto and Noguchi 1990). Isolating these properties (low specific angular momentum? weak tidal fields?) may ultimately allow us to study how star formation proceeded during the early history of our Galaxy.

As emphasized by many authors (*e.g.*, Mould 1991, Renzini 1991), the star clusters of the Magellanic Clouds are invaluable laboratories for studies of the global properties of 'simple' stellar populations. Two examples can be cited from recent observational work. First, studies of the internal kinematics of a number of Magellanic Cloud clusters are now published or in progress, providing an opportunity to measure how mass-to-light ratios vary with age. Some results are shown in Figure 3 illustrating that the simple models mentioned

Table 2

Luminosities of Populous Cloud Clusters at Age = 15 Gyr

Cluster	Age (Myr)	M_V	M_V(15 Gyr)
NGC 2070 (LMC)	3	−10.9	−7.2
NGC 330 (SMC)	10	−9.9	−6.2
NGC 2100 (LMC)	10	−9.6	−5.9
NGC 1866 (LMC)	100	−9.5	−7.0
NGC 1978 (LMC)	2000	−8.5	−7.2

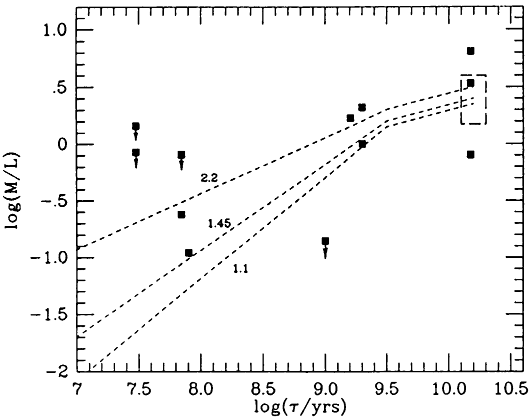

Figure 3 – The run of M/L vs. age for a number of Cloud clusters. For some, only upper limits are available. The curves refer to different fading rates calculated by Elson, *et al.* (1987) for the indicated IMF slopes.

above (Elson, *et al.* 1987) do in fact appear to describe the evolutionary fading of Cloud clusters reasonably well. Second, improved integrated photometry and spectroscopy of numerous Cloud clusters is now available in the UV (*e.g.*, Cassatella, *et al.* 1987) and IR (*e.g.*, Bica, *et al.* 1990). These data will provide important constraints on stellar synthesis models (*e.g.*, Chiosi, Bruzual, this volume; Barbaro and Olivi 1991) and should be of great interest to compare with direct CCD observations of the stellar content of populous Cloud clusters.

IV. The Age-Metallicity Relations and Star Formation Histories of the Magellanic Clouds

In a classic study, Butcher (1977) concluded that the bulk of the stellar population in the LMC is younger than about 3-4 Gyr based on the presence of a break in the main sequence luminosity function corresponding to the turnoff luminosity of an intermediate-age cluster. Subsequent studies using the same sort of analysis have confirmed this result for additional LMC fields (Stryker 1984; Hardy, *et al.* 1984). Most recently, Bertelli, *et al.* (1991) used synthetic color-magnitude (CM) diagrams based on the Padova stellar evolutionary models (Bertelli, *et al.* 1990) to estimate the star formation history in three LMC fields in greater detail than possible from a simple analysis of the luminosity functions. From the models, indices based on the ratios of the numbers of stars in strategically chosen regions of the CM diagram were identified as useful indicators of the age of a postulated 'burst' in star formation, the slope of the IMF, and the duration of enhanced star formation. For example, the ratio of the number of main sequence stars with $1.5 \leq M_V \leq 3$ divided by the number of subgiants in the same absolute magnitude interval is strongly affected by changes in the star formation rates at different epochs. Using three indices of this sort, Bertelli, *et al.* (1991) were able to isolate a consistent set of parameters describing the star formation history of the LMC fields. All three fields confirmed and extended the results of the earlier studies to a remarkable extent: the star formation rate throughout the LMC increased dramatically (by at least a factor of five) about 4 Gyr ago and has remained high ever since. Furthermore, the age of the 'burst' derived from the field stars is remarkably similar to that implied from the lack of LMC star clusters with ages (derived from CM diagrams) between about 4 and 10 Gyr (*e.g.*, Mateo 1988; Jensen, *et al.* 1988; Olszewski 1988). The latter is very likely not a selection effect since it is clearly possible to identify and study 7-10 Gyr old clusters in the SMC without difficulty (*e.g.*, Mateo, *et al.* 1986). Interestingly, an 'eyeball' application of the Bertelli, *et al.* (1991) analysis applied to the SMC field observed by Hardy and Durrand

(1984) implies that the bulk of the field stars in the SMC is substantially older than the LMC field stars, in agreement with the apparent age distribution of the SMC clusters (van den Bergh 1991).

Likewise, the chemical abundance patterns of the Clouds appear to be distinct from one another and from that of the Galaxy. These differences were apparent from the first spectroscopic studies of individual stars in Magellanic Cloud clusters (Cohen 1982; Cowley and Hartwick 1982), and have been subsequently confirmed by analyses of the photometric data of stars in clusters (*e.g.*, Da Costa 1991) and more extensive spectroscopy of cluster members (Olszewski, *et al.* 1991). The LMC appears to have been enriched in metals by over a factor of 30 during the epoch when the star formation rate was exceptionally low, while the SMC appears to have maintained a nearly constant abundance during the era when stars and clusters were being formed efficiently. The details hidden by this schematic description have only recently begun to be explored. For example, fine analyses of high dispersion spectra of Magellanic Cloud supergiants have provided information on the present-day abundances of individual elements (*e.g.*, Spite, *et al.* 1986; Russell and Bessell 1990; Spite and Spite 1990); previously, this sort of information could only be determined for emission nebulae in the Clouds (Dufour 1984). One particularly curious problem has emerged from these studies. Spite, *et al.* (1986) noted that the mean heavy-metal abundance of the SMC cluster NGC 330 is considerably lower than the mean abundance derived for luminous, young SMC field supergiants; Richtler, *et al.* (1989) and Reitermann, *et al.* (1990) reached a similar conclusion for the young LMC cluster NGC 1818. Given the complexities of these analyses of luminous supergiants (Russell and Bessell 1990) and their importance for our understanding of the chemical abundance histories of the Clouds, additional studies are clearly needed.

Two general conclusions seem to emerge from the discussion in the previous paragraphs. First, the star formation and chemical enrichment histories of the Magellanic Clouds are undoubtedly very different; this implies that tidal interactions have not been the dominant trigger of star formation activity in the Clouds *if* they have been bound during most of their lifetimes (Murai and Fujimoto 1980). Second, populous star clusters appear to be good tracers of the star formation histories of the Clouds, lending confidence to their use in more distant galaxies as probes of the overall stellar age distribution (*e.g.*, Schommer, *et al.* 1991). The same cannot be claimed regarding the use of clusters as reliable tracers of the chemical enrichment history of the Clouds (Richtler, *et al.* 1989). Precise abundance *and* age estimates of Magellanic Cloud field stars (*e.g.*, along the lines suggested by Mould 1991) are needed to compare with the cluster age-metallicity relations in both galaxies.

V. The Kinematics of the Stellar Populations of the Magellanic Clouds

Considerable information is available on the internal kinematics of the Magellanic Clouds (see Westerlund 1990). In this section, I will focus on recent work dealing with the LMC primarily because the kinematics of the SMC are so complex. For example, Martin, *et al.* (1989) identified no fewer than four distinct velocity groups in the SMC from an analysis of the radial velocities of objects associated with the young stellar population of that galaxy. In contrast, the kinematics of the older population of the SMC are consistent with a single spherical distribution (*e.g.*, Hardy, *et al.* 1989).

Although complex in their own right, the kinematics of the LMC appear considerably simpler by comparison. For example, Freeman, *et al.* (1983; FIO) analyzed radial velocity data for a large sample of populous LMC star clusters; they noted that (a) the kinematics of the youngest clusters were similar to that of the HI gas and consistent with both rotating in a flattened disk, (b) the intermediate-age and old clusters also rotate in a disk of comparable thickness as that defined by the youngest clusters, and (c) the old-cluster disk appeared to be tilted and offset (in systemic velocity) relative to the young-cluster disk. Four recent

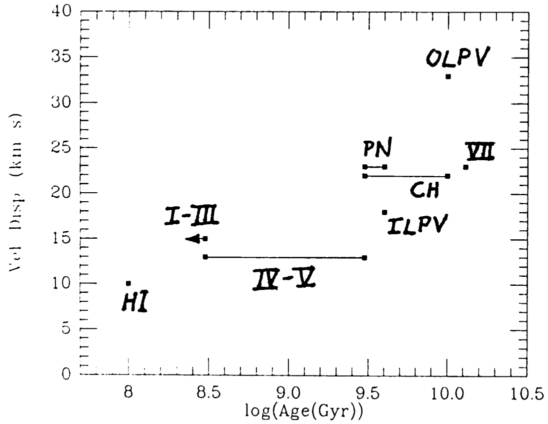

Figure 4 – The variation in the LOS velocity dispersion as a function of Age in the LMC. PN refers to planetary nebulae; OLPV and ILPV to old and intermediate-age LPVs, respectively; CH to CH stars; VII to the oldest LMC clusters; IV-V to intermediate-age clusters; I-III to young clusters; HI to neutral hydrogen.

studies of different stellar population tracers have extended and refined the FIO results:

1) Hartwick and Cowley (1988) measured velocities of 74 CH stars in the LMC. One subgroup of their sample has kinematics consistent with that of the HI, while the remaining stars (mostly located near the LMC center) exhibit much less rotation, and a higher line-of-sight (LOS) velocity dispersion. Interestingly, the two CH star subgroups have different systemic velocities, reminiscent of one of the more curious FIO results.

2) Hughes, *et al.* (1991) obtained radial velocities of 144 long-period variables (LPVs). Sixty-three are short-period LPVs (100-250 days) for which pulsational and evolutionary theory give ages of $\gtrsim$ 10 Gyr; the remaining 81 intermediate-period LPVs (225-450 days) have a mean age of 4 Gyr. The older LPVs showed little rotation and an LOS dispersion consistent with a spheroid axis ratio of $c/a \sim 0.3$. In contrast, the intermediate-age subgroup showed more rotation and a smaller LOS dispersion characteristic of a more flattened distribution.

3) Meatheringham, *et al.* (1988) studied a sample of 95 planetary nebulae in the LMC. By comparing their velocities with that of the HI (reanalyzed by them using the results of Rohlfs, *et al.* 1984), they found that the planetaries rotate with the HI gas but have a much higher LOS dispersion. Based on a simple diffusion argument, they concluded that the mean age of the nebulae in their sample is 3 Gyr.

4) In a recent paper, Schommer, *et al.* (1991) report velocities for 83 intermediate-age and old LMC clusters; most are located in the outer parts of the galaxy. They conclude that all of the clusters in their sample (which included most of the older FIO clusters) lie in a *single* disk; moreover, the systemic velocity offset noted by FIO was not confirmed, but ascribed to velocity errors in the earlier study. Thus, the most puzzling result of the FIO study appears to have been spurious; however, the conclusion that the oldest clusters lie in a flattened distribution, coplanar with the youngest clusters, was fully confirmed.

The LOS velocity dispersions from these studies are plotted as a function of age in Figure 4. There is a clear increase in the dispersion as a function of age as observed in the Galaxy (Wielen, Freeman, this volume). Is this increase due to heating by massive clouds or clusters in the LMC disk, or do the dispersions reflect conditions during different stages of the formation of the LMC? What is missing from Figure 4 is evidence for a true kinematic halo population with an LOS dispersion of about 50 km s^{-1} (Schommer, *et al.* 1991). Dispersions based on radial velocities of a large sample of unquestionably old objects (*e.g.*, RR Lyr stars) will clearly be needed to kinematically identify the halo of the LMC. Attempts to do this are in progress (Reid and Freedman, Freeman, private communications).

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B. Carney: There are two blue populous clusters I know of in the SMC: NGC 330 and NGC 346. The former's metallicity is very low according to echelle analyses by Francois and Monique Spite. The H II region surrounding NGC 346 is very deficient in C and N. Aside from the impact on the age-metallicity relation, could it be that metallicity is important in determining the mass of a cluster? Can you tell us something about the metallicities of the LMC blue populous clusters?

M. Mateo: I'll answer those in reverse order. As you know from your work on NGC 330, it's tough to get abundances from the CM diagrams of really young clusters; the high dispersion work is very important. The low abundances reported for some very young clusters (in both Clouds) make me nervous because the metallicities for somewhat older (about 1 Gyr; Olszewski, *et al.* 1991) clusters is considerably higher ([Fe/H] ~ -0.3). We really need to resolve this. As for the effect of metallicity on mass, I again refer to Olszewski, *et al.*; for clusters spanning a large range in luminosity (and presumably mass), the metallicities are similar. For [Fe/H] $\gtrsim -0.6$, there doesn't seem to be a strong correlation between [Fe/H] and cluster mass.

D. Hatzidimitriou: On the metallicity of NGC 330: M. Bessell presented some new results on the metal abundance of this cluster at the IAU General Assembly last week, showing a metallicity of [Fe/H] $= -0.75$. He claims that the significantly lower values given by, *e.g.*, Spite are due to problems with model atmospheres.

M. Mateo: And I believe he claims the reddening of the cluster is considerably different than what the Spite's assumed.

S. van den Bergh: I would like to quarrel a bit with your conclusion that the blue populous clusters in the LMC are young *globular* clusters. In a wide variety of environments (M 87, M 31, the Fornax dwarf) globular clusters have a Gaussian luminosity function. Data on the old (age $> 10^{10}$ yrs) clusters in the LMC are also consistent with such a luminosity function. It seems to me that the blue populous clusters in the LMC belong to a population with an *open* cluster luminosity function which is, however, somewhat enhanced in massive clusters compared to the open cluster luminosity function in the Galaxy.

M. Mateo: I really don't disagree. *Most* of the populous LMC clusters are in fact part of a population with a luminosity function like that of open clusters; only *a few* clusters appear to be luminous and massive enough that they will look like globular clusters when 15 Gyr old. Two excellent candidates are NGC 1866 and NGC 1978. If such objects make up only a small fraction of the total cluster population, they won't significantly perturb the luminosity function, especially if the open cluster population is rich as in the Clouds. They might account for the slight enhancement of the luminosity function you mentioned. Finally, since evolutionary fading is fastest at a young age, if there is a 2-3 Gyr range in the epoch of globular cluster formation, the resulting cluster LF won't necessarily look Gaussian at first (it may have a high-luminosity tail), even though after 15 Gyr it would.

J. Frogel: 1) I thought that earlier work showed that the integrated luminosities of the intermediate-age clusters would fade substantially if evolved to the age of Galactic globular clusters. 2) The estimation of a molecular mass based on CO observations always suffer from the converstion of H_2 mass via the Galactic ratio. If mean [Fe/H] of the LMC and SMC are low, then $M(H_2)$ will be significantly underestimated if based on a CO value.

M. Mateo: 1) The evolutionary fading was taken into account in my estimates of the cluster luminosities at an age of 15 Gyr. Most of the fading (if only stellar evolution is taken into account) occurs in the first 1 Gyr. I assumed a Salpeter slope ($x = 1.35$) for the IMF; the fading is much faster if x is smaller. Recent results suggest that the IMF slope in Cloud clusters is $\gtrsim 1.35$, so the fading will be slightly less than I mentioned. The biggest uncertainty, really, is ignoring dynamical effects. 2) The CO-H_2 conversions I used in Table 1 come from Cohen, *et al.* (1989). They claim to take the metallicity deficiency of the LMC into account.

E. J. Alfaro: This comment is concerning your last conclusion. Some regions of our Galaxy show an age-metallicity relationship more similar to that obtained for the LMC than for the solar neighborhood. In particular, seven clusters studied by Geisler in the Galactic anticenter and the cluster IC 1311 (in the Cygnus region) observed by myself and colleagues display CMDs and locations in the age-metallicity diagram which indicate a clear similarity between these and the intermediate-age open clusters in the LMC.

M. Mateo: I agree. My conclusion refers to the age-metallicity relation for the solar neighborhood.