Part 5. Stellar Populations and Surveys

Section A. Invited Reviews

Jay Gallagher (right) tells Klaas de Boer "I'm under attack here!" (see page 579).

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Overview of the Field Stellar Population of the Magellanic Clouds

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Abstract.
The stellar populations in the LMC, the SMC, and the Bridge region are discussed and shown to be composed of a number of well separated generations. Asymmetries are seen in the distributions of the intermediate-age and youngest generations. The possibility is considered that all generations, apart from the oldest one, have been produced by bursts of star formation.

1. Introduction

Analytical studies of stellar populations require color-magnitude diagrams (CMD) and the luminosity functions (LF) of main-sequence (MS) and red-giant stars. Stars *below* a turn-off point at about $M_V \sim 3.5$–4.5 are useful for the determination of the stellar composition of the Clouds only if objects of different ages and metallicities can be separated. This may be difficult for low-mass stars of 10 Gyr and 1 Gyr as most isochrones for low-metal objects, $Z \leq 0.008$, appear to merge there. *Above* $M_V \sim 3.5$ isochrones differ appreciably for ages younger than ~10 Gyr and the effects of different metallicities are obvious. The structure of the red-giant clump gives important information about the composition of the older generations. The age distribution of some classes of variables and from the planetary nebulae also provide valuable clues to the underlying population.

Significant differences exist between the field populations of the LMC and the SMC. As a rule each generation in the SMC is younger than the corresponding one in the LMC. The SMC trails the LMC in evolution. The location of the various field populations in space causes no real problems in the LMC but is of major concern in the SMC. In the latter some classes of objects appear to form separate clouds in the line-of-sight. The old and intermediate-age populations define, however, a single body with, most likely, a more limited extension in the line of sight. A summary of the content of the generations in the Clouds may be found in Table 3.12 of Westerlund (1997).

2. The Youngest Populations

Most stars of the youngest generation have formed in super-associations (SAs). The supergiant shells (SGS) correspond to the SAs or sometimes form part of them. In several SAs a separation of the supergiants according to age is seen

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with the more evolved ones in the central regions and the OB stars in the outer parts. This may be due to a stochastic self-propagating star formation process (SSPSF) though contradictions exist. Young clusters are found inside the rim of SGS LMC-4, and the LFs for a number of small areas inside the LMC-4 indicate ages between 9 and 16 Myr without correlation with the distance to its center. One triggering event may have started star formation inside the *whole* SGS with the SSPSF acting at its rim, only (Braun et al. 1997). However, the clusters may have needed a longer time to form than single stars (Dopita 1987), and the age distribution within the SGS may have been achieved by a fast traveling SSPSF process.

Slight but important differences exist between the SAs: those in the West of the LMC have in the mean more evolved supergiants than those in the East. This causes the east-west asymmetry, seen in the FIR/6.3 cm brightness ratio – it is lower in the eastern parts – and in the diffuse X-ray emission.

2.1. The SMC Wing and the Bridge Region

The Wing extends $\sim 7°$ from the SMC core and is the beginning of a Bridge linking the SMC to the LMC. It may have been formed by tidal interaction with the LMC. HI clouds and 78 non-random groups of blue stars have been identified in it. The distances of the groups decrease from the West to the East. At the tip of the Wing the age is estimated to 10–60 Myr; further East it is 10–25 Myr. Star formation may have started in the Wing and caused a burst of formation in the Bridge (Demers & Battinelli 1998).

3. The Old and Intermediate-age Generation in the LMC

To the oldest generation, aged ≥ 10 Gyr, belong old globular clusters and a relatively rich population of RR Lyrae variables. The latter are about 1 Gyr younger and have a higher metallicity than the globular clusters. An old field population has been traced out to $\sim 7°$ from the LMC center. Photometric investigations using the *HST* have reached very faint magnitudes (see e.g., Elson, Gilmore, & Santiago 1997, hereafter EGS97; and Geha, Holtzman, & Mould 1998, hereafter GHM98). EGS97 analyze a field near the SE end of the LMC Bar, GHM98 a field near NGC1866 and two fields, N and NE of the center. The CMDs suggest similar stellar populations in these parts of the LMC.

Enhancement of the star formation rate may have occurred 6–8 Gyr ago in LMC regions East of the Bar, and about 2–3 Gyr ago in regions in the West and North (Vallenari 1997). Our reanalysis of the stellar populations in those fields and in fields observed by Battinelli & Demers (1998), EGS97, Hodge (1987), and Westerlund et al. (1995, 1998) shows that an old generation, $\sim$ 10–12 Gyr old, exists all over the LMC and that intermediate-age generations, 0.8–4 Gyr old, are found in many parts. Fields in the SW, e.g., the LW55 (Westerlund et al. 1995) and the LMC-5 (Vallenari 1997) fields deviate with steeper LFs and a lack of MS stars more luminous than $M_V \sim 1.5$–2.

Enhanced star formation at several epochs is observed in several fields. In the EGS97 field four separate generations are shown by peaks in the $(V-I)_0$ histograms for $20 \leq V \leq 22.5$ (Fig. 3 of EGS97). Those at intermediate colors represent generations aged slightly less than 1 Gyr and 2–4 Gyr.

The number of intermediate-age MS stars in a field depends upon the distance from the center of the LMC and on the star production rate in the region. Fields in (N2004) or close to presently star-forming regions (LMC-30, LMC-45, N1787 and SL196) are rich in intermediate-age stars, 0.2–0.6 Gyr (See Table 14 of Westerlund et al. 1998).

Bimodal RGCs are seen in the CMDs of many fields: one peak corresponds to red horizontal branch (RHB) stars, and one, more ill-defined, to younger, more massive and slightly more luminous stars, with ages as young as 0.3–0.6 Gyr.

The rather massive LMC Bar has contributed to establish star burst conditions by causing gas clouds to fall towards it rapidly. A burst may have occurred around 1 Gyr ago as judged from the LF of the EGS97 field and the period-luminosity (PL) relation of the long-period variables (LPV) in the central Bar. Intermediate-age stars dominate the Bar. Bar-induced star formation is seen in a number of other features: (i) A distinct group of LPVs exists with $M_{\rm MS} \sim 5$–$6\,M_\odot$ and an age around 60 Myr. (ii) The PL distribution of the Cepheids supports a burst about 60 Myr ago (Hughes & Wood 1990). (iii) There are a number of SWB II clusters, 30–70 Myr old (Dottori et al. 1996).

4. The Old and Intermediate-age Generations in the SMC

The only globular in the SMC, NGC121, is younger than those in the LMC. To the oldest generation belong the normal RR Lyrae stars, aged ≥ 10 Gyr and more metal-poor, $-1.4 \geq$ [Fe/H ≥ -2.0, than NGC121.

The lower metallicity of the SMC is a consequence of a slower evolution and shows e.g. as a lack of M giants, as odd carbon stars, and as overluminous RR Lyrae stars. The latter are 1.5 mag brighter than the normal ones (and not known in the LMC) with [Fe/H] $=-0.4$ and an age of 0.25 Gyr.

The CMD of the SMC disk (Hardy & Durand 1984, hereafter HD84) shows a young population with a MS indicating a lower age of ≤ 0.1 Gyr. The RGB matches well those of the old SMC clusters K3 and L1, aged 8–10 Gyr. A well developed RGC is seen and a relatively strong sub-giant branch; the latter indicating an intermediate-age population older than 3 Gyr. The distributions of the RGC stars in the SMC disk (HD84) and of those in the LMC disk (Hardy et al. 1984) agree well and peak at M_V=0.3 if the distance moduli are 18.5 and 18.9, and the absorptions A_V =0.3 and 0.1 for the LMC and the SMC, respectively. Also the subgiant and giant branches agree well after normalization at the peak.

About 3000 C stars have been identified in the SMC (Rebeirot et al. 1993; Morgan & Hatzidimitriou 1995; Kunkel et al. 1997). The majority is in the central 12 deg^2. The C stars in the Bridge region are few; they may be halo/disk objects. Normal C stars in the Clouds have $-6 < M_{\rm bol} < -3$ mag. In the SMC about 80 C stars with $M_{\rm bol} > -3$ mag have been identified (Rebeirot et al. 1993). No such objects have so far been found in the LMC.

The C stars belong kinematically to a spheroidal population of which also the PN may be part. Neither the C-star velocities nor those of the PN show the multiple peaks seen in samples of Population I objects. A possible velocity gradient of the C stars just East of the Bar may be interpreted as motions towards the LMC (Hardy et al. 1989).

The distribution of the RGC/HB stars in the outer parts of the SMC has been interpreted as showing that the depth varies strongly. In the far NE, ≥ 2 kpc from the center, the depth may be 15–20 kpc; in the SW 7–13 kpc. In the N and NW the corresponding values are 4–9 kpc, and between the latter and the first field the depth is 12–16 kpc. The NE feature is interpreted as lying in front of the main structure of the SMC (Hatzidimitriou & Hawkins 1989; Gardiner & Hawkins 1991; Hatzidimitriou & Cannon 1993). The apparent bimodality in the RGCs may, however, be caused by a stellar population mixture; stars from 0.3–2 Gyr to 10 Gyr may contribute. The former age group is identified by the MSs, the latter age group has been observed by Hatzidimitriou & Gardiner (1992) in fields 2–2.5 kpc from the optical center. If the RGC is composed of more than one generation, the depth of the SMC may be appreciably smaller than suggested.

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Discussion

Despina Hatzidimitriou: Two comments: First, on the problem of the size of the red clump in the NE regions in the SMC: you suggested that this could be due to a young population of a few 10^8 yr. There are three pieces of evidence that I believe contradict that interpretation:

1. there do not seem to be enough young MS stars to account for the number of observed brighter clump stars;

2. if the brighter clump was indeed due to a younger population (and more metal rich according to the age-metallicity relation) then there should be some evidence of increased "size" of the RGB redwards. On the contrary, the RGB seems to be more extended blueward, just as you would expect if you just moved half the stars on the CMD upwards (distance modulus effect); and

3. there is magnitude (distance)-radial velocity correlation which can be more naturally understood in terms of a structural rather than an age effect.

The second comment refers to your reference to the age of the field population in the SMC varying with location. What I think is actually happening is that the mixture of older and younger populations is a function of radius. It is not a variation on the time when a major period of SF occurred.

Westerlund:

1. The younger part of the RGC should only be about 1/10 of the older. Maybe there is enough of a MS for this.

2. I have seen theoretical CMDs for 400 Myr and 4 Gyr with $Z = 0.008$ which represent the situation rather well without any obvious change in colour. (See also the poster by Harris & Zaritsky)

3. I cannot comment on this at present as I do not know it in detail.