STELLAR POPULATIONS IN THE OUTSKIRTS OF THE SMALL MAGELLANIC CLOUD: NO OUTER EDGE YET

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ABSTRACT

We report the detection of intermediate-age and old stars belonging to the SMC at 6.5 kpc from the SMC center in the southern direction. We show, from the analysis of three high-quality 34' × 33' CMDs, that the age composition of the stellar population is similar at galactocentric distances of ∼4.7, ∼5.6, and ∼6.5 kpc. The surface brightness profile of the SMC follows an exponential law, with no evidence of truncation, all the way out to 6.5 kpc. These results, taken together, suggest that the SMC “disk” population is dominating over a possible old Milky Way–like stellar halo and that the SMC may be significantly larger than previously thought.

Subject headings: galaxies: evolution — galaxies: halos — galaxies: stellar content — Magellanic Clouds

Online material: color figure

1 INTRODUCTION

Many important clues about the galaxy assembly process lie in the faint outskirts of galaxies. For example, recent galaxy formation simulations suggest that almost all galaxies, even the smallest, should contain an extended old, metal-poor, stellar halo (see, e.g., Bekki & Chiba 2005; Read et al. 2006a). Furthermore, evidence of recent merging and/or interaction should remain in the form of extended tidal debris (see, e.g., Muñoz et al. 2006). The distribution and extent of such debris, or a characteristic underlying old stellar halo, are both sensitive to the total mass and extent of a galaxy. Thus, probing the faint edges of galaxies can also give us constraints on their dark matter content.

The extended extreme edges of galaxies are observed to be so faint (μ ≥ 28 mag arcsec−2; see, e.g., Gallart et al. 2004) that their study has been limited so far to just the Local Group dwarf galaxies, in which we can study the flux from the individual stars. Such studies began with the discussion by Sandage (1962) on the outer parts of IC 1613, which showed faint red stars significantly extended beyond the galaxy’s central irregular body. More recently, evidence for outer, faint stellar envelopes has been found, for example, in WLM (Minniti & Zijlstra 1996) and Leo A (Vanswvičius et al. 2004). However, it may be premature to label these extended stellar distributions as an old stellar halo such as that observed in the Milky Way. There is evidence to suggest that the faint outer stellar populations of nearby dwarf irregulars are composed of a range of ages (old MS turnoff photometry: Gallart et al. 2004, Hidalgo et al. 2003; C stars: Letarte et al. 2002; CMD modeling: Aparicio & Tikhonov 2000). In some cases, the extended stellar light is almost certainly tidal debris (e.g., the case of Carina; Muñoz et al. 2006).

In this Letter, we present the first evidence for an extended distribution of stars in the southern direction of the SMC, up to ∼6.5 kpc (5.8′) from the optical center of the galaxy. We provide unambiguous information about the age composition of this population from a CMD reaching the oldest MS turnoffs. Photometric studies of the outer SMC began with Gardiner & Hatzidimitriou (1992), who studied the age composition with CMDs reaching a magnitude limit at R = 20 and hence with MS stars, for which it was possible to determine precise ages up to ∼2 Gyr ago. Their contour plots of the surface distribution of horizontal branch (HB)/clump stars reached a galactocentric radius of ∼6 kpc in the semi-major axis direction (toward the LMC), but the star counts in these outer parts are within the noise level. Carbon stars were also detected in the outer regions of the SMC (Hatzidimitriou et al. 1997; Kunkel et al. 2000). Few of these intermediate-age tracers were found in the southern direction up to ∼7 kpc. Demers & Battinelli (1998) observed five fields in the outer SMC wing and in the Magellanic Bridge, finding that a burst of star formation occurred between 10 and 25 Myr ago. Harris (2007) presented a detailed analysis of the star formation history of the young inter-Cloud population along the ridgeline of the H I gas that forms the Magellanic Bridge and searched for the older population in this area. He found an intermediate-age and old population at 4.4′ and 4.9′ from the SMC center in that direction, but only a young population at 6.4′. Recently, Noël et al. (2007) presented the age distribution of 12 SMC fields, through CMDs that reach the oldest MS turnoff with an excellent photometric accuracy. From the CMD of their outermost field, they inferred that, at ∼4 kpc from the center, the intermediate-age population is still substantial. Here we extend this analysis using images obtained with the WFI at the ESO 2.2 m telescope in La Silla, Chile. We present the surface brightness together with the age composition of three fields in the southern direction of the SMC, at 4.2′ (∼4.7 kpc), 4.9′ (∼5.6 kpc), and 5.8′ (∼6.5 kpc) from the SMC optical center, through the analysis of the CMDs of each of these fields.

2 OBSERVATIONS AND DATA REDUCTION

In order to characterize the stellar content of the outer SMC and to search for the SMC outer edge, we obtained B- and R-band images of three SMC fields centered at 4.2′, 4.9′, and 5.8′ from the SMC center, respectively. The observations were taken from 2004 June to 2006 June, using the WFI attached to the 2.2 m telescope at La Silla Observatory, Chile, with a 4 × 2 mosaic of 2048 × 4096 CCDs. Each chip covers a sky area of 8.1′ × 16.2′. This combination gives a field size of 34′ × 33′ (approximately 0.64 × 0.615 kpc) with a scale of 0.238′ pixel−1. Figure 1 shows the spatial distribution of our SMC fields. The large squares represent the WFI fields we present in this Letter; they are far from the optical center of the SMC and lie well away from any observed H I gas (Stanimirović et al. 1999). The small symbols denote the fields observed using the 100 inch telescope at the LCO, presented in Noël et al. (2007).

The coordinates of the WFI fields and the data obtained for each of them are detailed in Table 1. The first column denotes the field name; the second and third columns the right ascension and the declination, respectively; the fourth column, the gal-
actocentric distance ($r$); and the fifth and sixth columns the integration times in $B$ and $R$, respectively. Seeing was typically between 0.7” and 1.2”.

For the basic reduction, bias exposures, sky flats, and dome flats were taken every night. The reduction was performed using the MSCRED package within IRAF. Profile-fitting photometry of the SMC fields was obtained using the DAOPHOT and ALLSTAR/ALLFRAME software packages (Stetson 1987, 1994). We photometered every chip separately, as in Noël et al. (2007). To compensate for the low density of stellar objects in the analyzed fields, we combined all chips to obtain a single deep CMD for each field. The aperture corrections were obtained from synthetic aperture photometry by measuring several isolated bright stars through a series of increasing apertures and the construction of growth curves (Stetson 1990). Errors in the aperture corrections were calculated as the standard error of the mean of these differences and were typically between ±0.001 and ±0.003. During the photometric nights, Landolt (1992) standard-star fields SA 92, SA 95, SA 104, SA 110, SA 113, and RU 149 were observed several times for calibration purposes. The total zero-point errors of the photometry—including the error in the extinction—in the aperture corrections, and the uncertainties in the calibrations, were ∼0.03 mag in both the $B$ and $R$ bands.

3. THE CMDs OF THE SMC OUTSKIRTS

Figures 2a–2c show the [(B − R), R] CMDs of the three SMC fields in order of increasing distance from the SMC center. BaSTI isochrones (Pietrinferni et al. 2004) are overlapped (see caption for details). Stars with at least one valid measurement in each filter have been selected using the following limits for the error and shape parameters given by ALLFRAME: $a_{i,b-d}[=a_i^b + a_i^b] \leq 0.15$, $\mid$ sharp $\mid \leq 0.6$, and $\chi \leq 5$. A total of 10,230 stars down to $R \leq 23$ were measured in field F1 (Fig. 2a), 7685 in field F2 (Fig. 2b), and 5642 in field F3 (Fig. 2c).

The CMD of the innermost field, F1, shown in Figure 2a, reaches 1.2 mag below the old MS turnoff, while the CMDs of field F2 (Fig. 2b) and field F3 (Fig. 2c) reach 1 mag below this point. Each of these CMDs shows, for the first time, the details of the age structure of the stellar population at these outer parts of the SMC. At 4.7 and 5.6 kpc from the SMC center (Figs. 2a and 2b, respectively), the areas around the 3 Gyr isochrone are quite well populated. It is noticeable that, at 6.5 kpc from the SMC center, there is still galaxy, with intermediate-age and old stars, as seen in Figure 2c. Most of the main features of a CMD are present in F3: a quite well populated intermediate-age and old MS and a well-defined subgiant branch. The areas around the 5, 7, 10, and 13 Gyr isochrones are well populated in all of the CMDs, and there is a lack of a blue extended HB in all of them.

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**Table 1**

| Field | R.A. (J2000.0) | Decl. (J2000.0) | $r$ | $B$-band Exp. | $R$-band Exp. |
|-------|---------------|----------------|-----|---------------|---------------|
| F1 ... | 00 53 00      | −77 00 00     | 4.2 | (21 $\times$ 407.9) | (17 $\times$ 256.9) |
| F2 ... | 00 52 52      | −77 46 00     | 4.9 | (12 $\times$ 407.9) | 15 $\times$ 256.9 |
| F3 ... | 00 52 40      | −78 34 00     | 5.8 | (13 $\times$ 407.9) | (12 $\times$ 256.9) |

*Note.* Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

*Distance from the SMC center: R.A. = 00h52m44.8s, decl. = −72°49′43″ (J2000.0).*
Fig. 2.—(a–c) CMDs of our outer SMC fields in order of increasing distance from the center of the galaxy. From left to right, the galactocentric distances are 4.7, 5.6, and 6.5 kpc. BaSTI isochrones (Pietrinferni et al. 2004) were overlapped. Only the 5 Gyr isochrone is drawn up to the upper red giant branch (RGB) in order to show the extension in color and magnitude of the RGB stars. The expected position of the red clump is and indeed an enhancement in the number of stars is observed in fields F1 and F2 around this position. Stars as young as 3 Gyr old are still present in fields F1 and F2, while there are a non-negligible amount of stars around the 5 Gyr isochrone in our most peripheral field, F3. (d) TRILEGAL simulation of the foreground stars (Girardi et al. 2005) in field F2. The dot-dashed boxes indicate the portion of CMD devoid of SMC stars taken for the scaling (see text for details). BaSTI isochrones were overlapped in this simulation to show the loci of the SMC stars. The thick solid lines denote the areas of the CMD selected to obtain the SMC surface brightness.

Figure 2d shows the [(B – R), R] CMD of the simulated foreground Milky Way stars in the direction of our SMC field F2, as obtained using the TRILEGAL code (Girardi et al. 2005). In the simulation, we used the (l, b)-coordinates of each of our SMC fields, an area in the sky of 34′ × 33′, down to a magnitude of 23.4 in R, an IMF from Kroupa (2001) corrected for binaries, dA/dσ0 = 0.00015 mag pc−1, thin and thick disks (squared hyperbolic secants), and a halo. BaSTI isochrones were also overlapped in order to show the loci of the stars in the SMC fields. When the CMDs of our SMC fields (Figs. 2a–2c) are compared with the foreground simulations, it is clear that the main features of the CMDs mentioned above are not presented in the latter. There are only a few stars in the region occupied by the few gigayears old MS. There is a gradient in the population of predicted foreground stars in the range (B – R) ≤ 0.8, which increases while going farther south.

4. THE SURFACE BRIGHTNESS PROFILE: REACHING THE SMC OUTER EDGE?

We have derived the SMC surface brightness in the three observed fields. In order to minimize the error in the subtraction of the foreground stars’ contamination, we integrated the flux only in the areas of the CMDs in which we expect SMC stars, as shown in Figure 2d (thick solid lines). We used the predictions of the TRILEGAL model described above for foreground-subtraction purposes, but scaling the flux predicted for the Milky Way stars inside the fiducial SMC area shown in Figure 2d by the ratio of the observed and predicted flux in regions of the CMDs clearly devoid of SMC stars (dot-dashed boxes).

In Figure 3 we present the surface brightness (in units of mag arcsec−2) of our fields measured in the B (Fig. 3a) and R (Fig. 3b) bands (circles), as a function of distance from the optical center of the SMC. The surface brightnesses of the fields from Noël et al. (2007) are also plotted. The open triangles represent the eastern fields, while the filled triangles are the western fields; the squares denote the southern fields.

The total error bar is the difference between the values of the foreground flux in the fiducial SMC area as predicted by the TRILEGAL code and after scaling by the ratio of observed and predicted fluxes. The foreground flux predicted by TRILEGAL and actually observed in the boxes devoid of SMC stars in field F1 differed by about 50% in both the B and R bands in all fields.

The measured surface brightness profile is well fit by an exponential law, with B(0) = 22.3 ± 0.3 and α = 47.62 ± 0.02′, and R(0) = 21.5 ± 0.2 and α = 52.63′ ± 0.01′. Note the slightly shallower profile in R, reflecting the larger extent of the intermediate-age and old populations.

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5. DISCUSSION

In this Letter, we have shown that, at 6.5 kpc from the SMC center, there is still a stellar population belonging to the SMC, with a substantial amount of intermediate-age stars. Fields located at 4.7 and 5.6 kpc show stars as young as 3 Gyr old, and the field at 6.5 kpc shows stars as young as 5 Gyr old. From the analysis of the CMDs, no strong population gradients are present in the outer SMC disk from ∼2.7/\text{H11034} outward (field qj0047-7530 in Fig. 1; see Noël et al. 2007). The origin of the intermediate-age population in the outer SMC fields presented here is still uncertain. If these stars formed at their current positions, it would imply that the SMC is significantly more extended (and therefore more massive) than previously thought. Its original gas envelope must have extended much farther away in the past.

Alternatively, these stars could represent tidal debris torn off through interactions with the Milky Way or the LMC. However, the surface brightness distribution in the outer parts is quite smooth. Detailed models of tidal interactions show flat or rising surface brightness distributions (e.g., Johnston et al. 2002; Read et al. 2006b), unlike the falling surface brightness profile we find here. In fact, the surface brightness profile is well fit by an exponential disk, indicating that the SMC disk is dominating over a possible old Milky Way–like halo. Our results indicate that the tidal radius of the SMC disk is larger than the 5 kpc proposed by Gardiner & Noguchi (1996) and the 6.3 kpc recently suggested by Connors et al. (2006). This strengthens the hypothesis of a larger size for the SMC. An upper limit for the SMC size in the direction of the Magellanic Bridge is provided by Harris (2007), who found no signs of an intermediate-age or old population (but only a young Bridge population) at 6.4° from the center. Note however that Harris’s field is located along the “minor axis” of the main body and therefore it could be misleading to do a direct comparison. More studies farther away from the SMC and with large spatial coverage are needed to confirm the actual extent of the SMC.

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