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Letter to the Editor

The morphology of the Magellanic Clouds revealed by stars of different age: results from the DENIS survey

M.-R.L. Cioni, H.J. Habing, and F.P. Israel

Sterrewacht Leiden, Postbus 9513, 2300 RA Leiden, The Netherlands

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Abstract. The spatial distribution of sources populating different regions of the colour–magnitude diagram ($I - J$, I) extracted from the DENIS catalogue towards the Magellanic Clouds (DCMC – Cioni et al. 2000) reveal significantly different morphologies. Each region is associated to a different age group. The Large Magellanic Cloud (LMC) shows an extended circular shape with a prominent, off center bar, a nucleus and irregular spiral arms. The Small Magellanic Cloud shows a perturbated structure with a prominent central concentration of stars. Old and young populations are offset from one another.

Key words: galaxies: Magellanic Clouds

1. Introduction

The Magellanic Clouds are our closest neighbors allowing direct observation of individual constituent objects. They are bound to the Galaxy and show signs of strong interaction with the Milky Way about 0.2 Gyr ago (Westerlund 1997). The LMC is classified as an irregular dwarf galaxy, its most prominent feature is a central bar, much like those found in barred spiral galaxies. Its eastern side is closer than its western side (Caldwell & Coulson 1986). Underlying the bar is a circular disk of older stars (Westerlund 1997). The appearance of the SMC is characterized by a much less pronounced bar, and an eastern extension called the Wing. Lines-of-sight through the SMC appear to cover extensive depths; the Wing and the northeastern part of the Bar are closer than the southern parts (Westerlund 1997).

Newly obtained large photometric data sets at different wavelengths and with improved sensitivity and spatial coverage allow us to investigate the large scale properties of the Magellanic Clouds. In particular, data in the near infrared allow us to access stages of stellar evolution that are marginally covered by optical data, such as the RGB and AGB phases.

Very recently Zaritsky et al. (2000) found that the asymmetric appearance of the SMC is primarily caused by the distribution of young stars, and that the older stars have a very regular distribution. It is not possible from their Figures to evaluate the behavior of the density towards the center of the Cloud. Weinberg & Nikolaev (2000) point out the presence of intervening tidal debris up to ≈ 15 kpc from the LMC.

Send offprint requests to: mrcioni@strw.leidenuniv.nl

2. The data

Our morphological study of the Magellanic Cloud is based on a sample of stars extracted from the DCMC catalogue (Cioni et al. 2000). The sample includes all sources detected in both I and J, irrespective of detection in K_S. The DCMC catalogue contains sources detected in at least two of the three DENIS bands (I: 0.8μm, J: 1.25μm and K_S: 2.15μm) within a surface area of 20×16 square degrees centered on $(\alpha, \delta) = (5^h27^m20^s, -69°00'00'')$ toward the LMC and 15×10 square degrees centered on $(\alpha, \delta) = (1^h02^m40^s, -73°00'00'')$ toward the SMC; J2000 coordinates are used throughout this paper. The observations have been performed with the DENIS instrument (Epchtein et al. 1997) on the 1m–ESO telescope.

We have used the ($I - J$, I) colour–magnitude diagrams (Fig. 1 for the LMC only) to select three classes of objects in each Cloud. Sources labelled (A) with $I < -4.64 \times (I - J) + 19.78$ represent the youngest population in the Magellanic Clouds: the brightest dwarf stars, blue–loop stars and supergiants (third vertical sequence from the left), together with an unrelated foreground component of dwarfs and giants (first two vertical sequences from the left). Sources labelled (B) with $I > -4.64 \times (I - J) + 19.78$, located above the tip of the red giant branch (TRGB – Cioni et al. 2000a) are mainly asymptotic giant branch stars (AGB). Sources labelled (C) with $I > -4.64 \times (I - J) + 19.78$ located below the TRGB are mostly red giant branch stars (RGB) and represent the oldest population in the Clouds. For the sake of clarity, we have plotted in Fig. 1 only those sources that were detected in all three wave bands and that occur in the very central part of the Cloud. Sources detected only in I and J predominantly populate the lower part of the diagram. The position of the TRGB is indicated by a horizontal line. The I, J and K_S sensitivity limits are 18, 16 and 14 mag respectively. Photometric errors widen the sequences towards fainter magnitudes.

For each class of objects in each of the two Clouds, we show their distribution in the plane of the sky by counting the

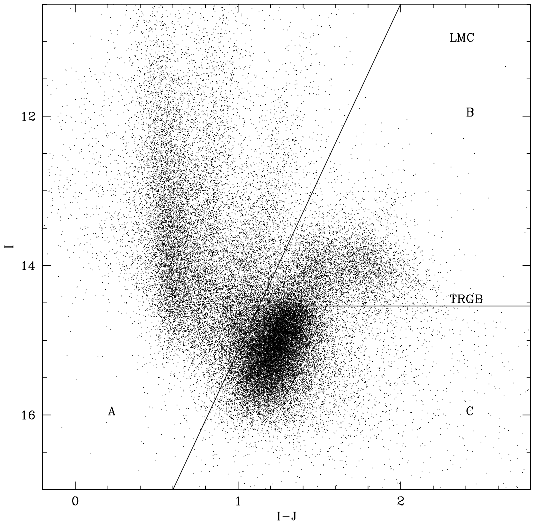

Fig. 1. Colour–Magnitude Diagram ($I-J$,I) of sources detected simultaneously in I, J and K_S towards the LMC ($-69 < \delta < -67$). The horizontal line marking the position of the TRGB (Cioni et al. 2000a), and the slanted line at $I < -4.64 \times (I-J) + 19.78$ define the classes A, B, and C discussed in the text.

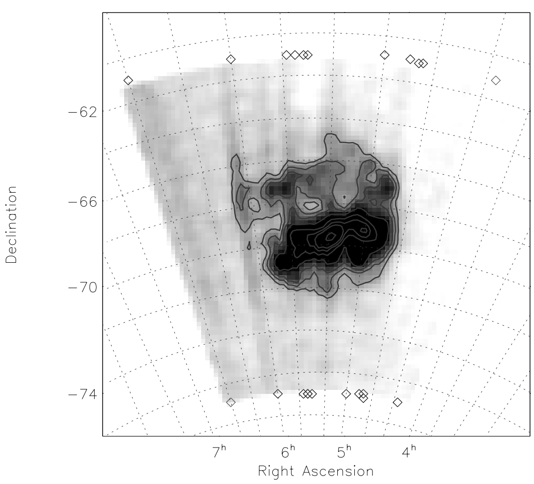

Fig. 2. Star count of the LMC – class A (Fig. 1); contours are at: 100, 125, 150, 200, 300, 400, 500, 800 per 0.04 deg^2.

sources in bins of $0.2° \times 0.2°$, applying a light smoothing to the resulting structure (Figs. 2–7); the contour values increase logarithmically. Regions corresponding to missing data (strips at constant RA indicated by diamonds) were filled in by interpolation. Their effect is mostly negligible except in Fig. 4 where strips of possibly lower photometric quality may be causing discontinuities in the outermost contours.

3. Spatial distribution

The contribution due to Galactic foreground stars has not been subtracted from the maps. Its influence is most clearly seen in Fig. 2 in the direction of the Galactic Plane. In the other maps, the foreground contribution is rather constant and does not affect the morphology of the Clouds.

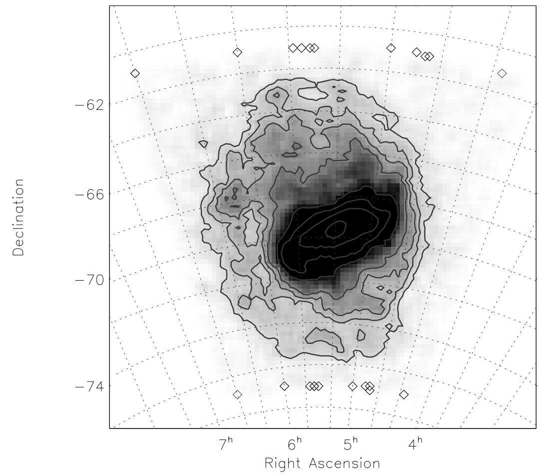

Fig. 3. Star count of the LMC – class B (Fig. 1); contours are at: 3, 5, 7, 10, 20, 30, 50, 100, 150 per 0.04 deg^2.

3.1. Structure of the LMC

The lower contours in Figs. 2–4 show an almost circular outline (axial ratios consistent with an inclination $i = 30° - 40°$) centered in all three cases near $\alpha = 5^h 20^m, \delta = -69°$ with major axis at about $13°$. Westerlund (1997) gives a similar diameter for the stars of the old disk. This stellar disk also coincides in shape and extent with the HI disk (Kim et al. 1998). The center of the disk is offset from the center of the Bar by about 30′ to the north (see Fig. 2). We confirm the conclusion by Westerlund (1997) that the LMC consists of two systems: a circular disk and an off center bar. Half of the total number of stars are in the bar and this factor (Fig. 2) increases for younger objects. Unless this is a transient configuration, it thus seems that the LMC must be embedded in a gravitational potential produced by an unseen mass component (see also Sofue 1999). This is in agreement with the conclusion by Stil (1999) that the class of dwarf galaxies to which the LMC belongs (‘fast rotators’) is dominated by dark matter.

The youngest component (younger than 0.5 Gyr) is composed of very bright main-sequence dwarf stars, blue–loop stars and supergiants. Their distribution (Fig. 2) is clumpy and irregular. The Bar, extending over about $4°$, is prominent and contains a well defined nuclear concentration at its center. The region of 30 Dor is represented by the small feature just above the north-eastern side of the Bar, and the Shapley Constellation III is the large structure at $\delta \approx -67°$. Elongations at either end of the Bar indicate the presence of spiral arms most clearly seen in the northwest at the location of the giant HII region complex N 11. Similar structures are seen in the distribution of stellar complexes (Maragoudaki et al. 1998), associations and HII regions (Bica et al. 1999). Clusters (Bica et al. 1995, Kontizas et al. 1990) have a distribution more similar to the one of AGB/RGB stars.

The distribution of AGB stars (Fig. 3), also relatively young (around 1 Gyr) likewise reveals a prominent Bar and nucleus. Shapley Constellation III is inconspicuous in AGB stars. A

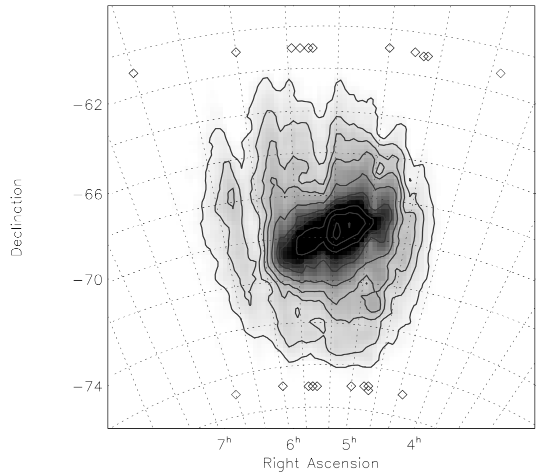

Fig. 4. Star count of the LMC – class C (Fig. 1); contours are at: 100, 150, 200, 250, 350, 500, 600, 800, 1000, 1200 per 0.04 deg^2.

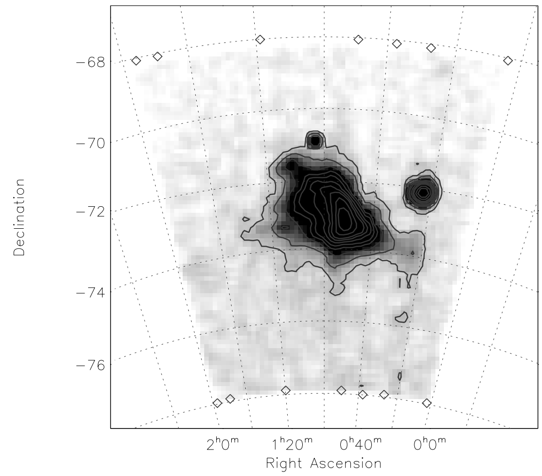

Fig. 5. Star count of the SMC – class A; contours are at: 20, 30, 45, 60, 75, 100, 125, 150, 200, 250 per 0.04 deg^2.

broad and faint spiral arm begins at the northwestern end of the Bar and bifurcates around $\alpha = 05^h10^m, \delta = -66.5°$. The spiral arm feature originating at the southeastern end of the Bar is clearly delineated in the AGB star population and can easily be followed to $\alpha = 4^h45^m, \delta = -73°$. It was noted before by Bothun & Thompson (1988) in their surface photometry study of the Magellanic Clouds – see their $1.1 < B - R < 1.35$ diagram. At least this spiral arm might be due to tidal action, as it appears to be connected to the Magellanic Cloud Bridge (cf. Staveley-Smith et al. 2000). The outernmost contour well matches the carbon stars by Kunkel et al. (1997).

The oldest population (from 1 to 5 Gyr), represented by RGB stars (Fig. 4), once again reveals a prominent Bar which is significantly broader than that defined by the younger populations. Galactic foreground stars may affect the outermost contours. The southern spiral arm is inconspicuous, but the two faint northern spiral arms seen in Fig. 3 (AGB) have weak counterparts in the form of extensions at $\alpha = 5^h \to 6^h, \delta = -64° \to -68°$.

Bothun & Thompson (1988) conclude that the LMC has a relatively large scale length more appropriate for galaxies with obvious spiral structure than for other dwarf galaxies. It is interesting that the asymmetric spiral structure delineated by the different components in Figs. 2–4 is in fairly good agreement with the HI map shown by Gardiner et al. (1998) and is nicely reproduced by their dynamical model.

3.2. Structure of the SMC

The structure of the SMC is still not understood (Westerlund 1997). Our maps show that populations of different age have different distributions. The youngest component has an asymmetric distribution(Fig. 5) elongated along a NE–SW axis (PA $\approx 45°$). In the south, the outermost contour defines four protuberances which might be associated with tidal features: at least the eastern (coincident with the SMC Wing) and western protuberances are aligned with that of the Magellanic Cloud Bridge (cf. Staveley-Smith et al. (2000). Higher contours show an extension in the northeast, aligned with the main body of the SMC Bar. The Bar structure itself is similar to that seen in the distribution of young clusters (Bica & Dutra 2000) and in the upper main-sequence map by Zaritsky et al. (2000). Clusters, associations and HII regions (Bica & Schmitt 1995) are also found at the locations of the southern protuberances. The young stars are strongly concentrated in the southwestern part of the SMC Bar. Outside the main body of the SMC, the two Galactic globular clusters NGC 104 = 47 Tuc (west) and NGC 362 (north) can be discerned. The HI column density contours in the map presented by Stanimirovič et al. (1998) outline the distribution of the young stars quite well.

The AGB stars have a more regular distribution (Fig. 6) with two prominent central concentrations matching the carbon stars by Hardy et al. (1989). The easternmost also coincides with the peak of the young–star distribution. The AGB distribution axis is much less inclined (PA $\approx 75°$) than that of the younger and very similar to that of the RGB star distribution. As in the case of the LMC, the stellar distributions become more regular and smoother with increasing age, also apparent in the B and V band images by Zaritsky et al. (2000) and for the outer contour in the carbon stars by Kunkel et al. (2000); carbon stars by Rebeirot et al. (1983) fill the second level countour (Fig. 6).

The distribution of RGB stars (Fig. 7) is similar to that of the AGB stars and also exhibits two major concentrations. The western most is more pronounced in RGB than in AGB stars. The eastern concentration on average appears to be significantly younger than the western concentration dominated by the older stars. Remarkably, the strongest HI concentration in the SMC map by Stanimirovič et al. (1998) appears to be just between the concentration of younger stars and that of older stars. It is also remarkable that the older star distribution extends over the full length of the suspected southwestern tidal feature, about $2°$ from the main body of the Bar. With respect to the overall distribution of the older stars, that of the HI appears to be displaced towards the east. The SMC Wing, prominent in HI and also traceable in

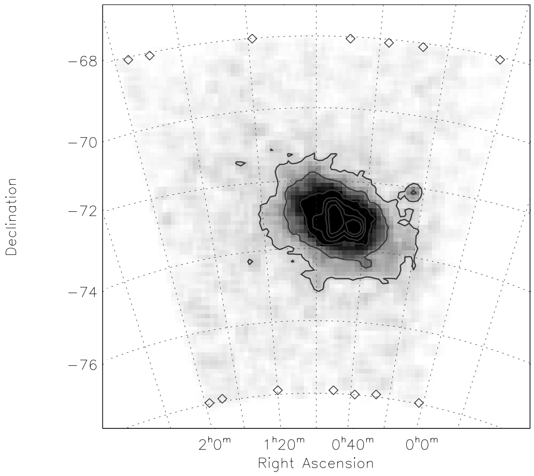

Fig. 6. Star count of the SMC – class B; contours are at: 2, 5, 10, 15, 20, 25, 50 per 0.04 deg^2.

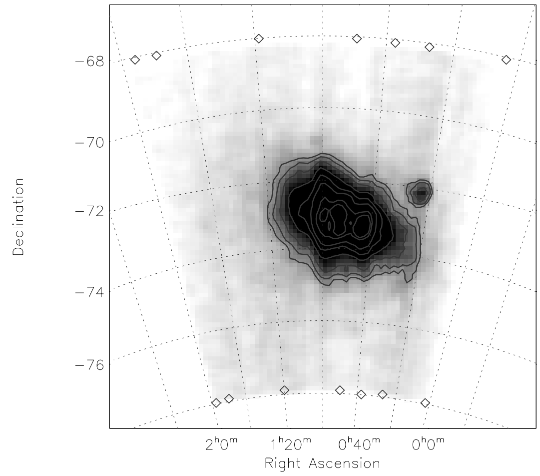

Fig. 7. Star count of the SMC – class C; contours are at: 50, 60, 75, 100, 125, 150, 200, 225 per 0.04 deg^2.

the younger stellar population, has no counterpart in the older stars.

4. Conclusions

Counts of sources towards the Magellanic Clouds extracted from the DCMC (Cioni et al. 2000) allow differentiation in the $(I-J, I)$ colour–magnitude diagram into three groups of objects with different mean ages. The spatial distribution of the three age groups is quite different: in either Cloud, the youngest stars exhibit an irregular structure characterized by spiral arms and tidal features while the older stars are smoothly and regularly distributed. The distribution of younger stars is well–correlated with those of clusters, associations, HII regions and HI. The significant offset of the LMC Bar with respect to the overall circular disk suggests that the LMC potential is dominated by dark matter. The well–defined southern spiral arm may be due to tidal interaction with the SMC. The nature of the two northern spiral arms is uncertain. In the SMC, the regular, but double–peaked, structure of the AGB and RGB stars is remarkable, as is its offset from the HI distribution, and the mean age difference of the two maxima. Relatively faint east–west features in the younger star population (including the Wing) are probably also due to tidal interaction.

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