DENIS results on the Magellanic Clouds

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The large–scale IJK$_s$ simultaneous DENIS coverage of the Magellanic Clouds has allowed us to distinguish populations of objects of different kind and age, to derive the structural parameters of the galaxies and to obtain an indication of the metallicity distribution. This photometry combined with the results from long–term monitoring programs provides important constraints on the evolution of stars. Although we have extracted a great deal of information from the dataset, the data mining benefits have yet to be exhausted.

The DENIS (DEep Near Infrared Survey of the Southern Sky) instrument was built by several European laboratories starting in 1990. It was mounted at the 1m ESO telescope in La Silla and observed the southern sky from the middle of 1994 until September 2001 simultaneously in the I, J and K_s wave bands. Technical details and scientific drivers are described in *The Messenger* No. 87 (Epchtein et al. 1997).

Though the survey was designed to observe the whole Southern Hemisphere a strong effort was devoted to complete the observations of the Magellanic Clouds (MCs). These are among the most suitable objects visible from August to March in the Chilean sky. They are our companion galaxies and because they are relatively close to us (≈ 60 kpc) we can study their stellar content in great detail. They are located in a region of low galactic extinction and this facilitates the interpretation of observations at combined wavelengths and especially in the near–infrared (near–IR) bands where the extinction does not affect the magnitudes of stars too much.

The Large Magellanic Cloud (LMC) is classified as an irregular dwarf galaxy; its most prominent feature is a central bar, similar to that of barred spiral galaxies. Its eastern side is closer than its western side. Underlying the bar is a circular disc of older stars. The appearance of the Small Magellanic Cloud (SMC) is also characterized by a bar, less pronounced, and an eastern extension called "the Wing". Lines-of-sight through the SMC appear to cover extensive depths (≈ 12 kpc); the Wing and the northeastern part of the Bar are closer to us than the southern parts.

Data in the near–IR allow us to access stages of stellar evolution that are marginally covered by optical data, such as the red giant branch (RGB) and the asymptotic giant branch (AGB) phases. These are usually referred to as late– type evolutionary phases. During the RGB phase, stars are burning Hydrogen (H) in a shell around the nucleus until they reach the tip of the RGB (TRGB), when Helium (He) combustion begins in the stellar nucleus. During the AGB phase, both H and He are burning in shells. Carbon enriches the chemical atmospheric abundance as a consequence of the third dredge–up process which brings processed matter to the surface. It may happen that the atmosphere becomes carbon dominated instead of oxygen dominated defining two different flavour of AGB stars: M–type (or O–rich) and C–type (or C–rich). AGB stars are characterized by variations in luminosity with a long period and a large amplitude and experience mass–loss at a rate that eventually concludes the AGB phase.

DENIS Catalogue of the Magellanic Clouds (DCMC)

More than one hundred thousand images in the direction of the MCs were pre–processed at the Paris Data Analysis Center and then sent to Leiden Observatory for subsequent analysis: extraction of the sources from the images, astrometry and photometry.

Using the pipeline developed by Erik Deul, which includes the SExtractor program (Bertin & Arnout 1996) for source extraction, we have compiled the DCMC, a catalogue of about 1.3 million sources and 300, 000 sources towards the LMC and SMC, respectively. These sources were detected in at least two of the three DENIS photometric wavebands. The derived standard position accuracy has an RMS of 0.001″ with a maximum excursion of 1.32″ on top of the RMS of 0.3″ of the astrometric reference catalogue (USNOA2.0). Magnitudes are estimated within a circular aperture of 7″ in diameter. The zero point of the magnitude scale was determined every night, observing about 8 standard stars and assuming a fixed extinction coefficient. The overlapping region of adjacent images was used to correct for remaining differences in zero–points. Finally we obtained a general photometric calibration specific for each Cloud on average better than 0.05 mag. All extracted objects were matched on the basis of their coordinates and geometrical parameters assuming an elliptical shape. Associated with each source are a series of flags that identify problems of different kinds in the images as well as those discovered during the source extraction process. Most cosmic rays, glitches and optical ghosts have been eliminated. Sources detected in three bands are complete to I = 15, J = 13.75 and K_s = 12.75 in the LMC and about 0.25 mag fainter in the SMC. The maximum source density is 500 sources per 0.25×0.1

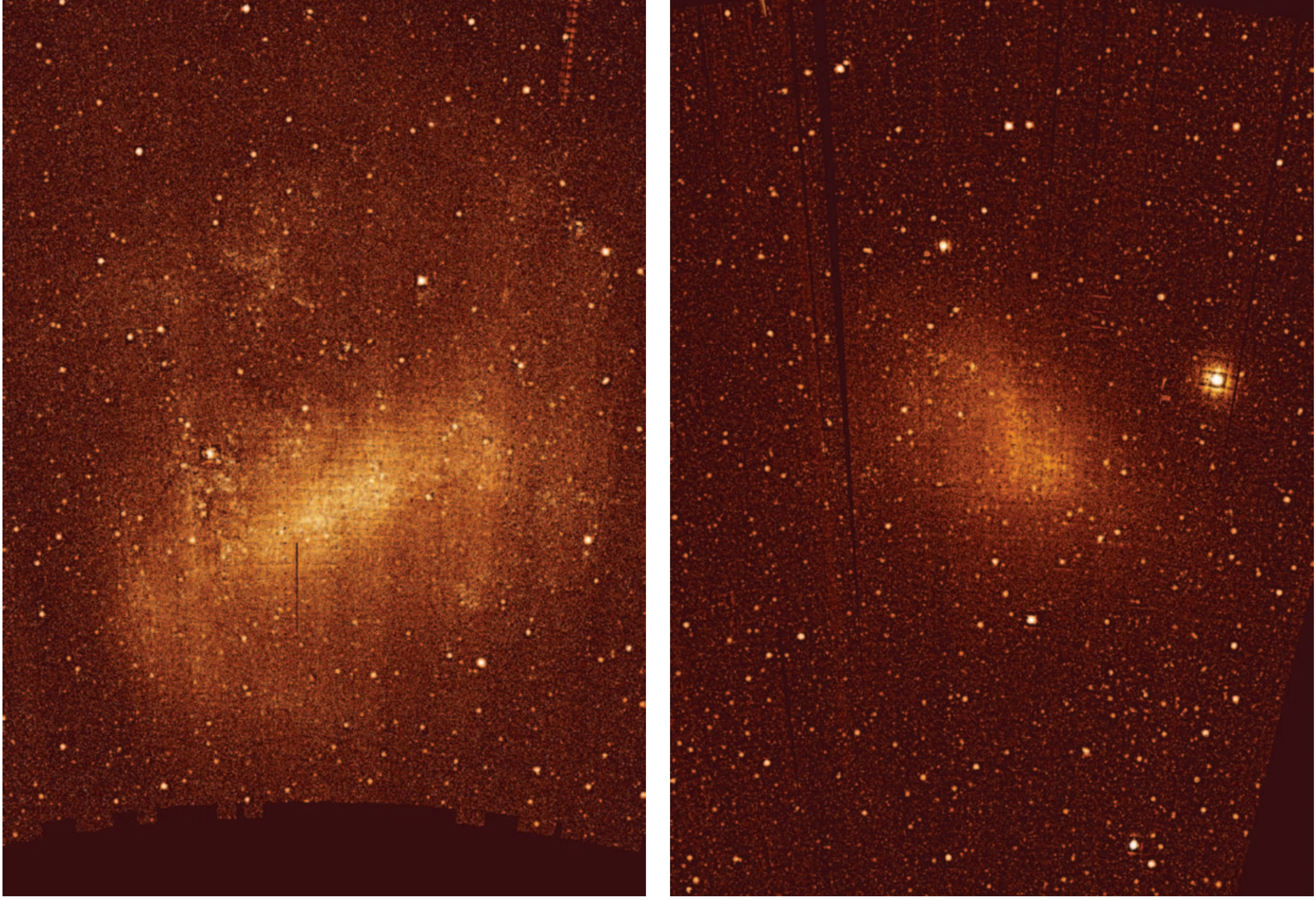

Figure 1: Combination of 21420 and 15840 *I*– band images of the LMC (left) and the SMC (right), respectively, taken with DENIS at the 1m ESO telescope on La Silla (Chile).

square degree in the centre of the LMC which corresponds to 1 source per 200 square arcsec. This is well below the IRAS confusion limit (explanatory supplement, vol. 1, VIII4) for a detected source with a typical size that does not exceed 2″.

Seventy per cent of the detected sources are true members of the MCs and consist mainly of RGB stars, AGB stars and super–giants. Galactic sources in the foreground have not been removed from the catalogue. However, they can be statistically disentangled using a combination of colours and magnitudes. They are mostly associated with ordinary dwarf stars and red giant stars. The catalogue covers an area of 19.87×16 square degrees centred on (α, δ)=$5^h27^m20^s$, $-69^d00^m00^s$ for the LMC and 14.7×10 square degrees centred on (α, δ)= $1^h02^m40^s$, $-73^d00^m00^s$ for the SMC at the epoch J2000 (Fig. 1). The two parts of the catalogue, containing the detected sources, are ordered by increasing right ascension. A third table describes the quality of the detections on a strip by strip basis. All tables are electronically available from CDS at http://cdsweb.u-strasbg.fr/denis.html. The catalogue is presented in more detail in Cioni et al. (2000a).

At about the same time, 2MASS released simultaneous JHK_s data on the whole sky. Nikolaev & Weinberg (2000) also studied the Magellanic Clouds (i.e. distribution of stars in the colour–magnitude diagrams and surface distribution) obtaining similar results as described in this paper. Both catalogues provide highly sensitive near–IR data covering both the LMC and the SMC in their entirety and are not limited to specific objects. Note that the concentration of points in region A at $I \approx 13$ belong to the galactic globular cluster 47 Tuc.

Selection of different stars

Different types of sources are well characterized in colour–colour and colour–magnitude diagrams (Fig. 2). This figure shows sources of both MCs. Note that SMC sources have the same distribution though their location is shifted to bluer colours (because of smaller metallicity) and to fainter magnitudes (because of larger distance). The quantity of the shift is approximately 0.1 mag in colours and 0.4 mag in magnitudes.

In the (I–J,J–K_s) plot we distinguish seven different regions populated statistically by different stars. At blue colours two clumps are associated with dwarfs and giants of the Milky Way Galaxy (MWG), respectively. Their numbers vary with galactic latitude and in the galactic plane, because of large extinction, they tend to merge into a single elongated structure. All other stars belong to the MCs. Those with both colours around 1.3 are RGB stars. Those brighter and redder are AGB stars: M–type at almost constant $J - K_s$ colour and increasing $I - J$ colour with increasing M subtype, and C–type having $J - K_s > 1.2$. AGB stars with J–$K_s > 2.0$ are of either chemical type and are heavily obscured by circumstellar dust, which explains their red $J - K_s$ colour.

In the (I–J,I) diagram the largest concentration of sources defines the upper RGB. The TRBG, the brightest and terminal point of this distribution, is a useful distance indicator and is further discussed in Sect. 4. The plume of objects above that represents the AGB population. Two vertical sequences at bluer colours include mostly stars of the MWG, though some Cepheids and upper Main Sequence stars of the MCs are also included, but not easy to split off. The vertical extent of the foreground sources reflects the different distance at which the stars are located within the MWG. The third vertical sequence is populated by super–giant stars of the MCs.

In the (J–K_s,K_s) diagram AGB stars are broken up in into M–type and C–type stars. These are all stars in region B and most of

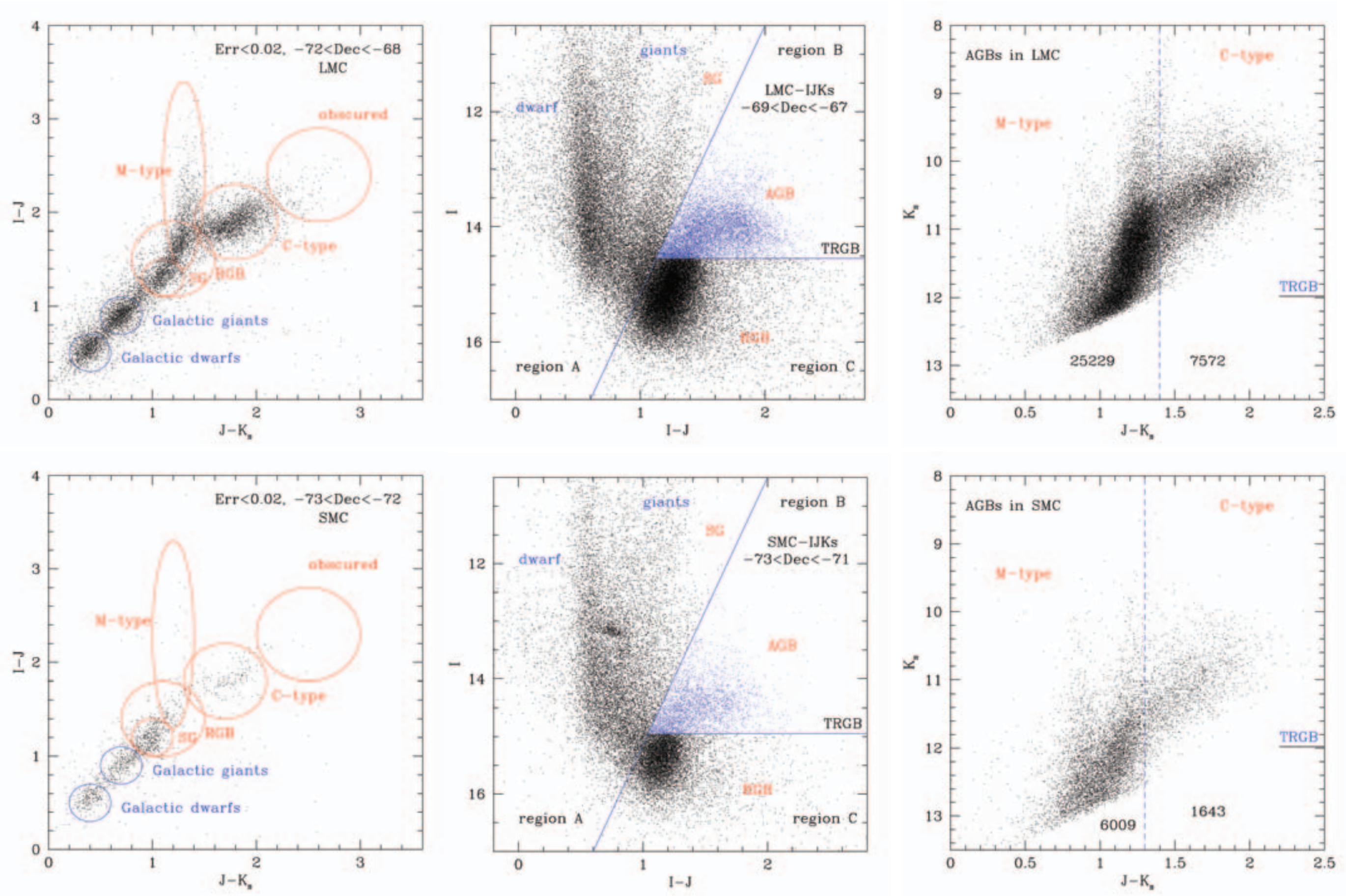

Figure 2: Colour–colour diagram ($I-J$, $J-Ks$) (left), colour–magnitude diagram ($I-J$, I) (centre) and ($J-Ks$, Ks) (right) of sources detected simultaneously in I, J and Ks in the LMC (top row) and in the SMC (bottom row). The horizontal line marks the position of the TRGB, and the slanted line at $I = -4.64(I-J) + 19.78$ defines the regions A, B and C explained in the text. The vertical dashed line discriminates M– type from C–type stars.

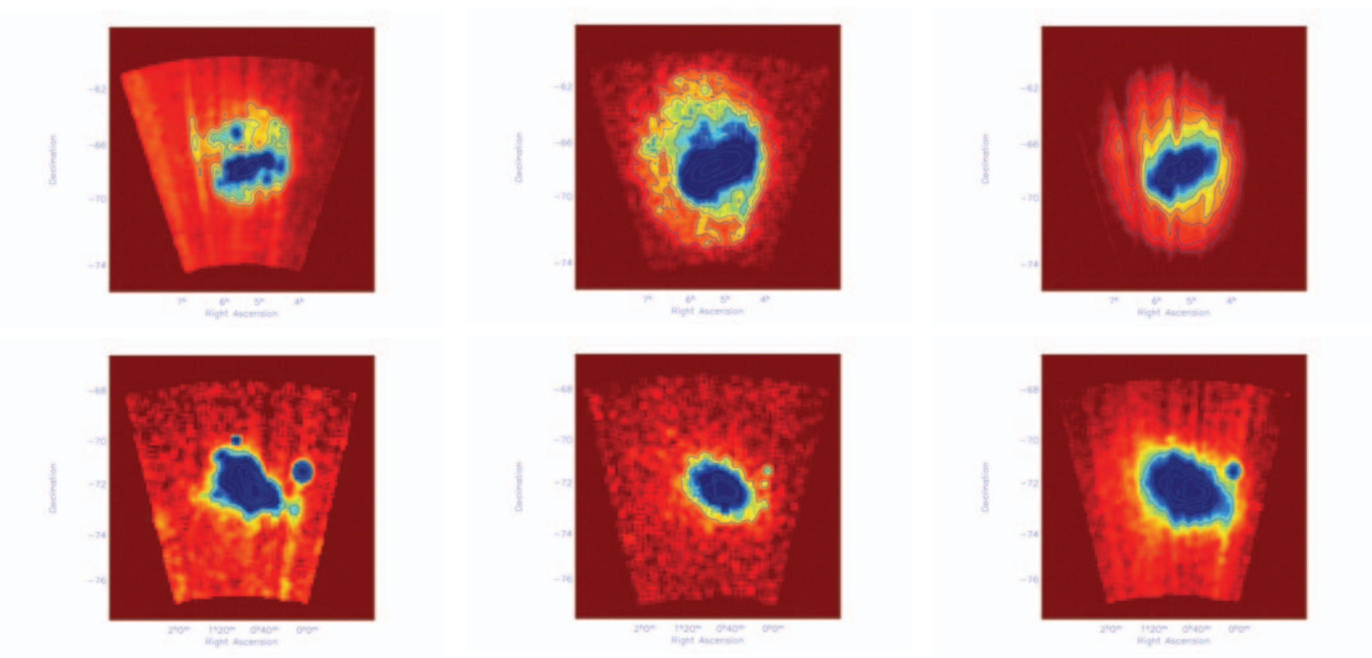

Figure 3: Star counts of the LMC (top row) and of the SMC (bottom row) – class A (left), B (centre) and C (right) objects as indicated in Fig.2 – per 0.04 deg^2. East is to the left and north on top. Coordinates are in the J2000 epoch.

the foreground sources have thus been rejected. However, the faint extension at $J–Ks$ = 0.9 does contain some foreground objects, this can be estimated from sky area far away from the MCs extension, well mixed with genuine faint MCs supergiants of spectral type K or M. Because the photometric accuracy at the AGB magnitudes is well below 0.05 mag the number of sources that have been put in the wrong side by photometric errors is negligible. For the SMC we obtain 6009 M–type and 1643 C–type AGB stars.

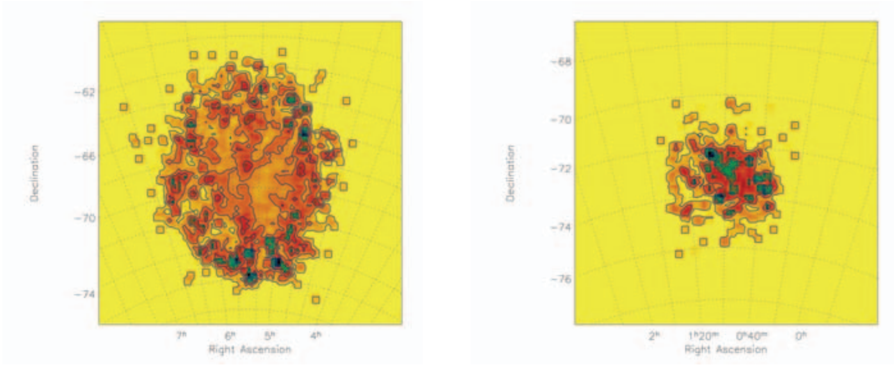

Figure 4: The C/M0+ ratio in the LMC (left) and in the SMC (right). Contours are, for both Clouds, approximately at: 0.1, 0.3, 0.4, 0.5, 0.6. Darker regions correspond to a higher ratio. Coordinates are in the J2000 epoch.

Morphology and structure

This large photometric data–set at different wavelengths and with improved sensitivity and spatial coverage allows us to investigate the large scale properties of the MCs.

In Fig. 2 we have seen a simple and straightforward tool to select three classes of objects: young, middle-aged and old stars. Sources in region (A) represent the youngest population of the MCs: the brightest main sequence stars, blue–loop stars and supergiants, excluding the foreground component, are younger than about 0.5 Gyr at the average metallicity of the MCs. Sources in region (B) are AGB stars about 1 Gyr old. Sources in region (C) are mostly RGB stars older than about 1 Gyr.

For each class of objects in each of the two Clouds, we derived their distribution in the plane of the sky by counting the sources in bins of 0.2° × 0.2°, applying a light smoothing to the resulting structure (Fig. 3). Young stars (left) show a rather clumpy and irregular distribution. The LMC is characterized by a bar and regions of star formation (i.e. Shapley III constellation at $\delta = -67°$). Two high density circular regions in the SMC coincide with galactic globular clusters 47 Tuc (west) and NGC362 (north). Note the increase in the foreground stars in the direction of the Galactic centre (upper left panel). AGB stars delineate a fairly regular structure which is even better outlined by the distribution of older RGB stars. Note that there is contamination between the extremes of the age groups (i.e. the vertical region lacking RGB stars and with an excess of young stars at $\alpha = 6^h$ in the LMC).

In summary, the morphological appearance of the MCs is quite different when stars of different age are selected. The classical irregular shape changes to that of an elliptical galaxy with increasing age. In fact sinusoidal brightness variations with a peak–to–peak amplitude of about 0.25 mag were detected as a function of position angle from the analysis of spatial variations in the apparent magnitude of the mode of the AGB distribution and the TRGB.

This is a natural distance effect, showing that one side of the LMC plane is closer to us than the other. The best fitting geometric model of an inclined plane yields an inclination angle $i = 34.7° \pm 6.2°$ and line–of–nodes position angle $\Theta = 122.5° \pm 8.3°$. Compared to the values obtained with traditional methods, van der Marel & Cioni (2001) concluded that the shape of the LMC disc is not circular, but elliptical.

Distance

The TRGB has been used successfully for several decades to estimate the distance of resolved galaxies (e.g. Lee et al. 1993). The corresponding magnitude depends weakly on age and metallicity, and yields precision comparable to that of classical distance indicators such as Cepheids and RR–Lyrae variables.

We selected from the DCMC sources detected simultaneously in three wave bands, excluding those objects with non–null (problematic) flag values. We calculated the apparent bolometric magnitude (m_{bol}) for those sources with $J–Ks > 0.4$ assuming an average extinction $E(B–V) = 0.15$. In order to identify the precise position of the TRGB in all DENIS wave bands and in m_{bol}, we used the magnitude distribution of these sources, corrected for the contribution of the foreground stars. This was estimated by comparison with magnitude distributions obtained in sky areas far away from the Cloud extension. The resulting statistics of the subtracted histogram are impressive, despite the restricted source selection (Fig. 4).

The maximum of this so-called luminosity function (LF) corresponds to giants that lie on the upper part of the RGB. Towards brighter magnitudes we encounter a strong kink in the profile, which is associated with the position of the TRGB discontinuity. Brightward of the kink follows a bump of AGB stars. At very bright magnitudes the LF has a weak tail, which is composed of stars of luminosity type I and II as well as residuals from the foreground subtraction. The algorithm constructed to quantify the position of the TRGB uses the peak of the second derivative of the LF distribution. In Cioni et al. (2000c) you will find a thorough discussion of this procedure and on the error budget.

Using an appropriate calibration (Salaris & Cassisi 1998) we derive a distance modulus of 18.55 ± 0.04 (formal) ± 0.08 (systematic) and 18.99 ± 0.03 ± 0.08 to the LMC and the SMC, respectively. The distance of the LMC is one of the main stepping stones in the cosmological distance ladder, yet has remained somewhat uncertain and controversial.

Metallicity

The ratio between M–type and C–type AGB stars is a simple and robust indicator of metallicity, that may be used to study the variation of metallicity over the face of a galaxy. Cioni & Habing (2003) have found that it varies strongly across the surface of the MCs (Fig. 5). The C/M ratio correlates with metallicity in the sense: lower metallicity, more carbon stars because in a lower metallicity environment the process that turns O–rich AGB stars into C–rich stars is more efficient, AGB stars are hotter and the number of late M–type stars is considerably reduced.

In the LMC the C/M ratio increases radially; however, the distribution is rather clumpy and that has prevented previous authors from detecting such a gradient. In the SMC the ratio is higher in some regions in the centre and lower in the wing and more generally all over the outer SMC body, but there is no clear radial trend. Using an empirical relation between the mean C/M and the mean [Fe/H] of Local Group galaxies we derive a spread of about 0.75 dex within both MCs which corresponds to the spread obtained from globular clusters.

Variability

DENIS and 2MASS magnitudes combined with the light–curves obtained from microlensing projects such as EROS, MACHO and OGLE have provided interesting constraints on the evolution of AGB stars (i.e. Cioni et al. 2001). Most AGB stars are

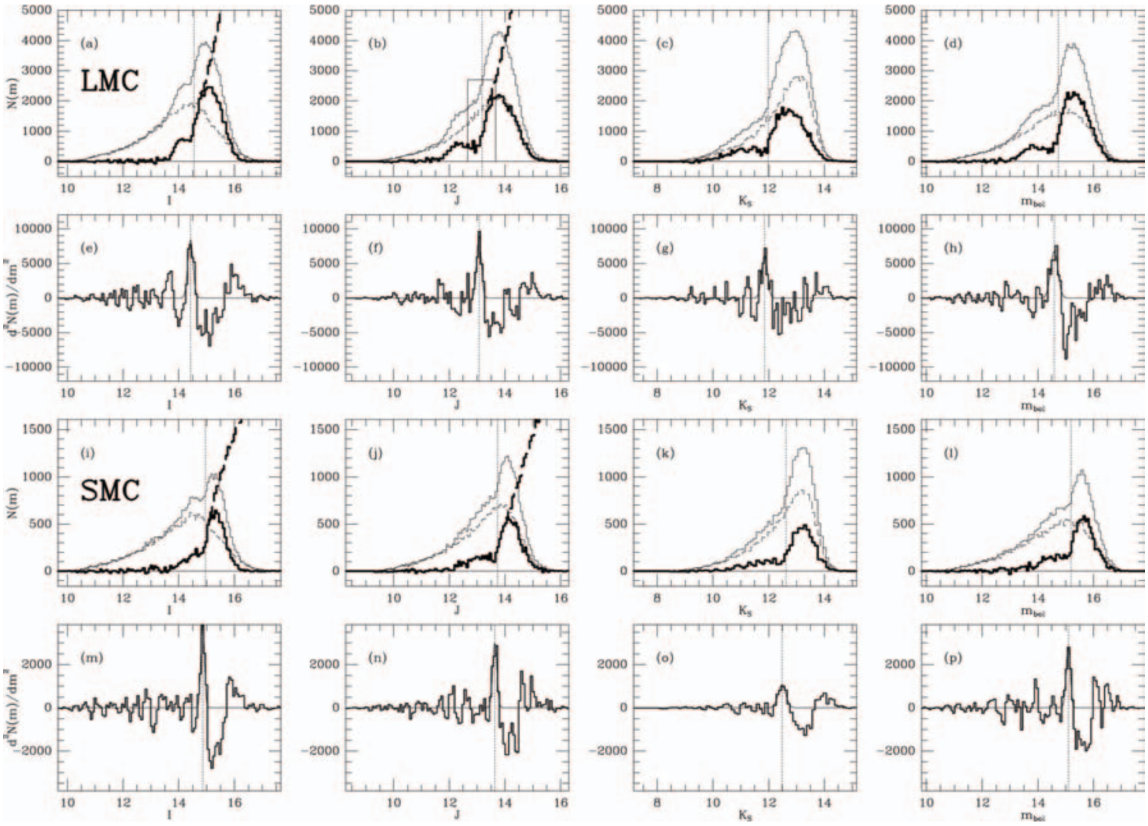

Figure 5: For each DENIS wave band and for m_{bol} the distribution of stars N (m) per 0.07 mag bin and the derivative d^2N (m)/dm^2 are shown for the LMC (a–h) and the SMC (i–p). Upper histograms for the main field, middle histograms for the scaled o_set field and lower histograms for the foreground–subtracted field. The vertical line indicates the TRGB discontinuity.

long period variables (LPVs). They pulsate with periods between a few tens to several hundred days and amplitudes up to several magnitudes in the optical and slightly less in the near–IR wave bands. The analysis of light–curves provides amplitude and period for any given pulsation mode.

Fig. 6 shows the period–magnitude sequences as discovered by Wood (1999) for AGB stars in the MCs. Each sequence probably corresponds to a given mode of pulsation. However, pulsation–related models fail to reproduce multi–periodic stars of sequence D. Alternatively they might belong to a binary system where the long period (sequence D) is the orbital period and the pulsation period of the AGB companion lies in sequence A, B or C. A comparison with the theoretical models developed by Vassiliadis & Wood (1993) indicates that most of the AGB stars are from 0.6 to 2 Gyr old.

Stars in both galaxies obey the same relations; however, the histogram of the amplitude of pulsation of M–type and C–type AGB stars has a similar distribution but on average the C–stars have a larger amplitude in the SMC. This may indicate that either most of the C–stars in the SMC are of Mira type ($\Delta I > 1$, period = 300^d and regular pulsation), or that the metallicity affects the amplitude in such a way that in a lower metallicity environment the amplitude of pulsation is larger. This effect cannot yet be checked in other metal–poor galaxies in the Local Group because, despite the fact that many AGB stars have been discovered, there is not enough information on their variability and type. In the LMC, C–stars occupy only the brightest part of the relations, contrary to the SMC.

The comparison between DENIS and 2MASS J and K_s magnitudes confirms that these sources are variable also in these bands.

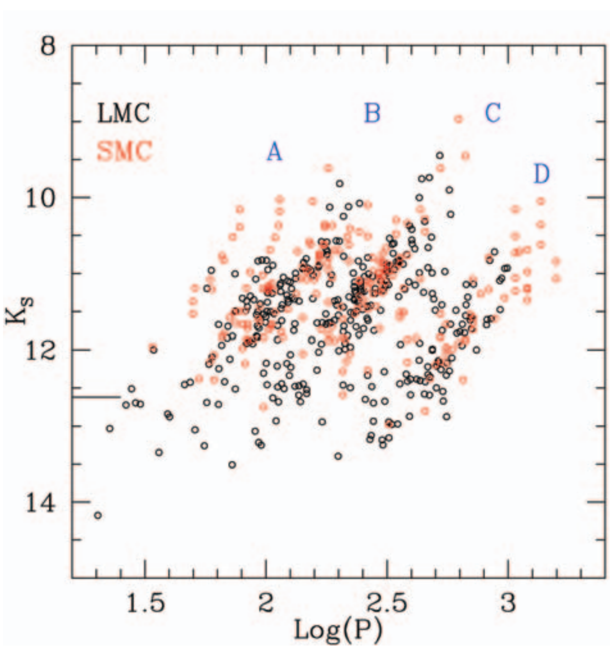

Figure 6: Period–magnitude relations for LMC (black) and SMC (red) LPVs. For comparison LMC sources have been shifted to the SMC distance. The horizontal line indicates the TRGB position. Each sequence is labelled A, B, C and D.

Acknowledgements

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