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IR IMAGING SURVEYS OF AGB STARS IN THE MAGELLANIC CLOUDS

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Abstract. AGB stars are ideal IR targets because they are cool and bright. Most of them escaped detection in optical or shallow IR surveys in the eighties contributing to the puzzling missing number of AGB stars with respect to theoretical predictions and former stages of evolution. Observations and AGB models have advanced steadily in the following decades providing us with an almost complete view of the AGB stars in the Magellanic Clouds. Their properties are tracers of structure and chemistry across galaxies. New surveys will be able to fill-in the gaps, in terms of sensitivity and monitoring, providing new constraints for the formation and evolution of the Magellanic Clouds.

1 Introduction

Asymptotic Giant Branch (AGB) stars are post-main sequence stars that represent the most luminous stage of evolution for low- and intermediate-mass stars. One of the main properties of AGB stars is that they loose $50-80\%$ of their mass (gas and dust), they therefore chemically enrich the interstellar medium (ISM) and represent the main source of dust in the Universe. AGB stars are also indicators of distance, structure and metallicity. They contribute to the integrated light of galaxies and exist in large numbers in the neighbouring Magellanic Clouds.

All stars with an initial mass comprised between 0.8 and 8 $M_\odot$ become AGB stars. The AGB phase is rather brief (< 0.01 Gyr) compared to other stellar evolutionary phases where stars spend most of their life, e.g. the main sequence. AGB stars are characterized by a double shell burning of H and He, respectively, around their C- and O-rich nucleus. Throughout the AGB structure a complex chemistry is developed: molecules form right above the photosphere and these are responsible for two classes of AGB stars, C-rich (or C-type) where carbonaceous molecules like CN and C_2 develop and O-rich (or M-type) where oxides like TiO and VO develop, after the formation of stable CO. The chemical path-way an

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AGB star will take depends on the ISM metallicity prior to their origin and on the efficiency of the dredge-up process that brings elements synthesized in the stellar interior to the surface. At a given distance from the centre of the star, where temperature and pressure are appropriate, dust forms, Dust will also be predominantly of carbonaceous or silicate type and this is related to the molecular composition in the AGB stars atmospheres. Above the dust layer other molecules, like OH and HCN, develop in the so-called circumstellar region.

The AGB phase is a dynamical phase because stars experience surface luminosity variations with long periods and large amplitudes, and mass-loss. These and further details on the AGB stars can be found in Habing & Olofsson (2003).

2   Infra-Red images

Before Infra-Red (IR) images of AGB stars were obtained the Magellanic Cloud stellar population was characterized by optical images. Initially the sensitivity was limited to bright super giant and carbon stars (e.g. Westerlund et al 1964). Later, fainter sources were studied by Blanco et al (1980) in several fields in the both the Large Magellanic Cloud (LMC) and the Small Magellanic Cloud (SMC). These observations were extended to additional fields by Blanco & McCarthy (1983). At the same time the variability of AGB stars was investigated by Hughes & Wood (1990) who referred to AGB stars as Long Period Variables (LPVs).

These authors discovered that there are several C-rich AGB stars. There were, however, not enough luminous AGB stars compared to the prediction by theory and to the known large number of Cepheid stars. The latter are the precursors of AGB stars of moderate mass. It emerged that because AGB stars are cool (red) they are potentially obscured by dust preventing their observation in the optical. Therefore, IR observations were needed to progress in this field. Note that the deficit of AGB stars was several hundreds!

2.1   First IR images

The first IR images of AGB stars in the Magellanic Clouds were obtained by Frogel & Richer (1983). They used the CTIO 1.5m telescope to observe a field in the bar west region of the LMC (Fig. 1). The observations were sensitive to stars as faint as $K = 11$ and the spatial resolution corresponded to an aperture of $27''$. A few red, but not very luminous AGB stars, were identified.

The study of the AGB population advanced in parallel with the investigation of their variability aspect; this is still the case at present. Using the K-band magnitude it was discovered that LPVs obey a period luminosity relation that represents an alternative distance indicator to Cepheid stars (Hughes et al 1990).

2.2   Mid-IR space observations

In 1983 the IR Astronomical Satellite (IRAS) scanned the sky. The instrumentation on board opened a new window into the study of AGB stars, especially for
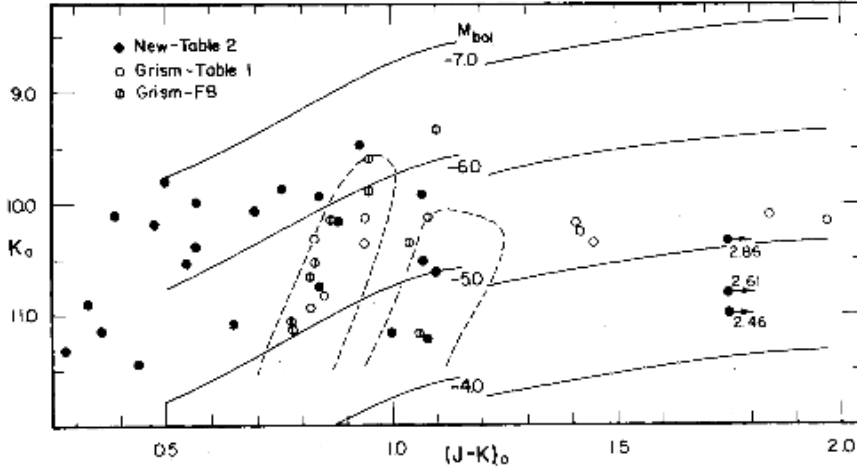
Fig. 1. Colour-magnitude diagram of LMC bar-west sources (Frogel & Richer 1983). Solid lines are lines of constant bolometric magnitude while the dashed areas indicate the region occupied by upper RGB stars.

those surrounded by dust. IRAS also allowed for making the transition between studying individual AGB stars to using them in large numbers to investigating properties of the hosting galaxy (i.e. the Milky Way). The exploitation of the IRAS catalogue is still on-going. IRAS discovered 50 obscured AGB stars in the LMC and 25 in the SMC (van Loon et al 1999). The distribution of cool stars in the IRAS colour-colour diagram, [12]-[25] versus [25]-[60], was presented by van der Venn & Habing (1989). Regions occupied by AGB stars of a different type and with a different dust shell thickness were identified, as well as the region where Planetary Nebulae (PNe), the successors of AGB stars, are found. It was suggested that ageing AGB stars develop pulsation variability and thicker dust shells.

In the following decade the IR Space Observatory (ISO; 1995-1998) performed targeted observations of the AGB stars discovered by IRAS. The power of the ISO instrumentation relied both in the imaging and spectroscopic capabilities that allowed for studying the type of dust, O-rich if absorption is present at 9.7 μm and C-rich if emission is present at 11.4 μm or absorption at 3 μm, and to relate this with the photometric colours and stellar models.

ISO performed also a mini-survey of Magellanic Clouds (Loup et al 1999). This survey covers an area of 0.8 deg^2 and 0.28 deg^2 of the LMC and SMC, respectively. Imaging observations were obtained in the [4.5], [7] and [12] μm filters. The considerably improved spatial resolution and sensitivity of ISO with respect to IRAS showed that IRAS missed $\sim 50\%$ of the dust obscured AGB stars and that these stars are as luminous as C-rich AGB stars with thin dust shells (Fig. 3). The ISO imaging data were combined with the near-IR data obtained
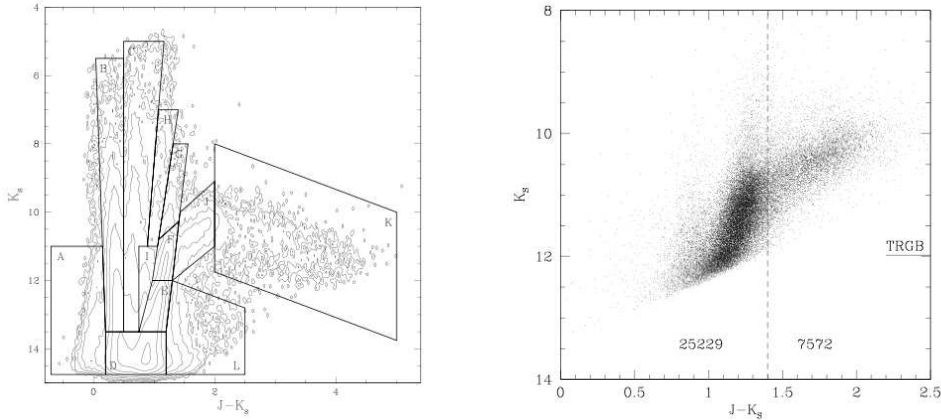
Fig. 2. (Left) Colour-magnitude diagram of the LMC observed by 2MASS where different regions are occupied by different types of stars (Nikolaev & Weinberg 2000). (Right) Colour-magnitude diagram of AGB stars in the LMC selected from DENIS data, the region occupied by O- and C-rich AGB stars is clearly indicated (Cioni & Habing 2003).

from the DENIS survey (Cioni et al 2000).

More or less simultaneously mid-IR space observations were obtained from the Mid-course Space Experiment (MSX; 1996-1997). This satellite observed ~ 100 deg^2 of sky at better spatial resolution but worse sensitivity than IRAS. The colour-colour diagram, $[K]$-$[8]$ versus $[J]$-$[K]$, showed obscured AGB stars but with a non-negligible overlap with PNe and HII regions (Egan et al 2001).

2.3   Near-IR images

The most comprehensive near-IR sky surveys that provided a wealth of data for studying the Magellanic Clouds were the 2MASS (1997-2001; JHK_s filters) and DENIS (1995-2001; IJK_s filters) surveys. Among their highlights: (i) the distribution of stars in the colour-magnitude space, e.g. $J - K_s$ versus K_s (Nikolaev & Weinberg 2000), and (ii) the distinction between O-rich and C-rich AGB stars of the earliest spectral types (Cioni & Habing 2003) − see Fig. 2. Both surveys detected the almost complete population of AGB stars with absent or thin dust shells, as well as several obscured AGB stars.

The view of the Magellanic Clouds changed dramatically from that of typical irregular galaxies with central features traced in the optical by young stars and star forming regions, to smooth and regular extended structures traced by giant stars (Cioni et al 2000) in the near-IR. The LMC shows a large thick bar confined within an outer elliptical structure with hints of spiral arms. The SMC resembles a dwarf elliptical galaxy. The ratio between C-rich and O-rich AGB stars, the C/M ratio, provides also a view of the metallicity distribution within these galaxies (Cioni & Habing 2003). This ratio shows a positive gradient within the LMC and

a clumpy distribution consistent with a flat gradient in the SMC.

The conversion and interpretation of the C/M ratio versus [Fe/H] abundance has been investigated recently by Cioni (2009). The smoothly declining LMC AGB gradient agrees with that of old (several Gyr) stellar clusters and RR Lyrae stars, but it does differ significantly from the gradient traced by young (a few Gyr) red giant branch (RGB) stars and stellar clusters that appears rather flat. The latter suggest a flattening of the gradient with time and is perhaps influenced by the effect of the bar. In the SMC nor AGB stars nor other indicators such as: RGB stars, PNe, stellar clusters with a different age, show a significant gradient. This can also be due to the bar or to the projection effect of two populations with a different mean age, a young one in the disk and an old one in an outer spheroid. Their average metallicity is consistent with that in the Magellanic Bridge and of the LMC at ~ 4 kpc from its centre supporting tidal stripping resulting from the dynamical interaction between the Magellanic Clouds.

2.4   Recent IR surveys

The Spitzer space telescope, launched in 2003, has surveyed the Magellanic Clouds in different filters as part of two major projects: the SAGE and S^{3}MC surveys of the LMC and SMC, respectively. These surveys have provided a large and homogeneous database for studying AGB stars, their evolution and mass-loss properties.

SAGE (Meixner et al 2006) covered 49 deg^2 and acquired two epochs, separated by three months, that allowed for identifying variable stars as well as their location in colour-magnitude and colour-colour diagrams. Vijh et al (2009) discusses the distribution, variability and dust properties of the SAGE stars: 66% of the extreme/obscured AGB stars are variable, 6.1% of the C-rich AGB stars and 2% of the O-rich AGB stars with thin circumstellar shells are also variables in the mid-IR Spitzer filters (Fig. 3). The spectral energy distribution (SED) obtained from the combination between 2MASS and Spitzer band-widths shows that the lack of variability data has a strong influence on the integrated flux and on the estimated mass-loss rate. The sensitivity and spatial resolution of Spitzer represent a tremendous improvement versus previous data. In particular a spatial resolution of $1 - 2''$ in the $3.5 - 8.0$ μm range is comparable to the resolution of ground based near-IR surveys, consenting a more secure identification of counterparts. The sensitivity in the mid-IR has surpassed that in the near-IR leaving unmatched many newly discovered objects.

The IR survey facility telescope (IRSF; 2001-2006) observed a large area encompassing the LMC, SMC and the part of the Magellanic Bridge close to the SMC wing (Kato et al 2007). This is the most sensitive near-IR survey of the Magellanic Clouds to-date reaching a 10σ limit at $J = 18.8$, $H = 17.8$ and $K_s = 16.6$. The instrument resolution corresponds to 0.45 $''$/pix while the observations were obtained with an average seeing of $1.2''$. AGB stars were not easily found in the Bridge and in general no AGB stars were found down to $K_s = 13.5$ at $J - K_s = 6$.

The AKARI telescope, launched in 2006, has completed the observation of 10 deg^2 in the north-east area of the LMC and is currently undertaking an all-sky
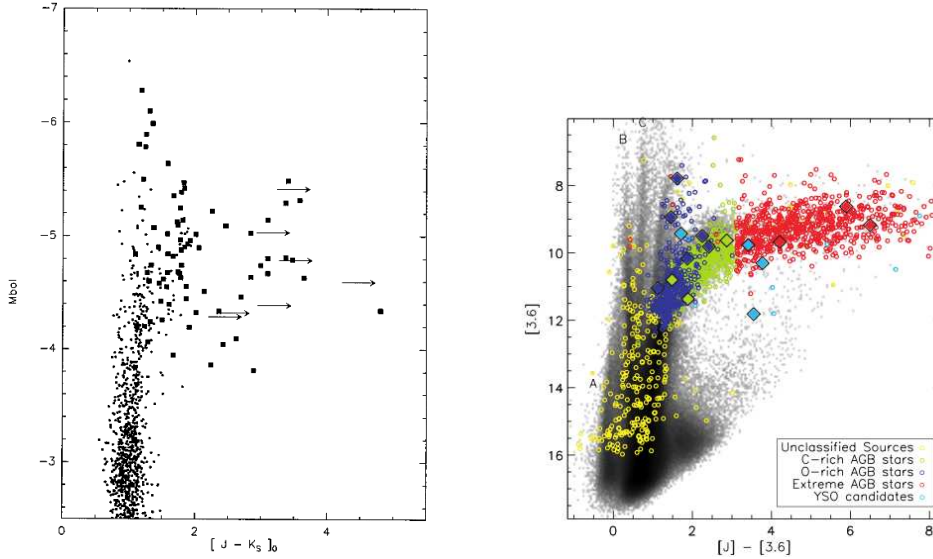
Fig. 3. (Left) Luminosity distribution of AGB stars from ISO and DENIS (Loup 1999). Squared symbols indicate ISO matches. (Right) Colour-magnitude diagram of AGB stars from Spitzer and 2MASS (Vijh et al 2009). Coloured symbols indicate Spitzer variables.

survey covering the range $1.8 - 180$ μm. A preliminary catalogue of point sources has been published by Ita et al (2008). The band-widths are similar to Spitzer, but for the 11μm one, and have been matched with IRSF near-IR magnitudes. Their combination reaches sources ~ 0.5 mag fainter than the Spitzer-2MASS combination. The colour-magnitude diagram, [3]-[11] versus [11], shows interesting new features traced by AGB stars: a faint plume of sources just brighter than the RGB tip and bending to red colours indicating O-rich giants with Al oxide dust (Blum et al 2006, Lebzelter et al 2006).

2.5 Forthcoming IR surveys

In the near-IR domain the VISTA wide-field telescope is currently being commissioned at the European Southern Observatory (ESO). The core programme for the next five years at VISTA includes six public surveys of which two are devoted to the observation of stars, the others are extragalactic surveys, and one is focused on the Magellanic system.

The VISTA survey of the Magellanic system (VMC; Cioni et al 2009) will provide the missing link to optical surveys, with a similar sensitivity, as well as counterparts for the mid-IR sources. VMC will cover 180 deg^2 distributed across broad areas in the LMC and SMC, the entire length of the Magellanic Bridge connecting the two galaxies (for a width of $1.5 - 4.5$ deg) and a couple of fields in the Magellanic Stream (Fig. 4).
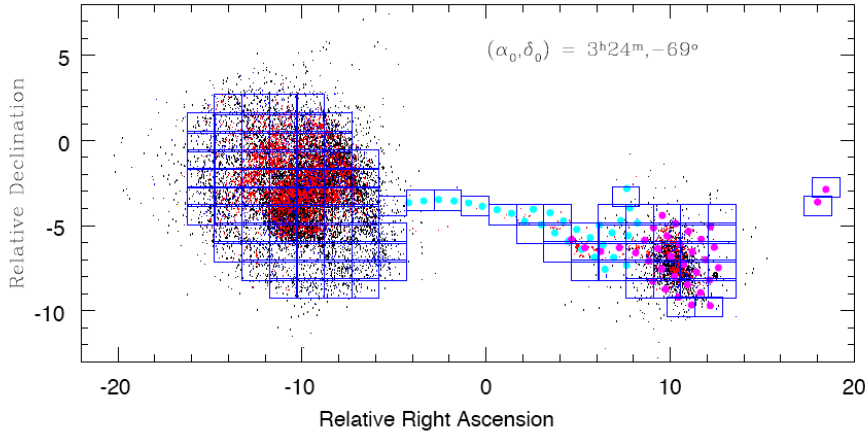
Fig. 4. Distribution of VISTA tiles across the Magellanic System. Underlying small dots indicate the distribution of C stars, clusters and associations while thick dots show the location of observations to be performed with the VST in the optical.

Observations will be obtained in three filters, YJK_s providing a 10σ limit at $Y = 21.9$, $J = 21.4$ and $K_s = 20.3$. They will be executed in service mode to guarantee homogeneous conditions and data quality. The instrument resolution is $0.51\ ''/$pix and observations will be obtained with an average seeing of $0.6 - 0.8''$ depending on crowding. VMC is also a multi-epoch survey because it will reach its nominal sensitivity by combining 12 independent epochs in K_s, and 3 in Y and J, respectively. The completion of the survey requires 1840 hours.

The main science goals of the VMC surveys are to derive the spatially resolved star formation history (SFH) and to measure the three-dimensional (3D) structure of the Magellanic system. The VMC data will also be used to find stellar sub-structures (clusters and streams), emission line objects (like PNe), to derive distances and measure proper motions, to study star formation, to re-construct the system using dynamical models and eventually find extra-galactic objects (starburst galaxies and dusty active galactic nuclei at high redshift), as well as form many other scientific applications.

The VMC survey will be complementary to an on-going optical survey of the outer regions of the Magellanic Clouds ($8 - 20$ kpc from the galaxy centres). This area will also be surveyed by VISTA as part of the VISTA Hemisphere Survey (VHS) but to a shallower depth than the VMC depth, and to the space astrometry mission GAIA that will measure the metallicity and motion of evolved giant stars of the Magellanic System.

Simulations of the stellar population that VMC will detect show that stars just below the oldest main-sequence turn-off will be well detected. The increased in the parameter space, e.g. near-IR photometry, at this depth will allow for de-

termining the metallicity and age distribution with improved accuracy (Kerber et al 2009). The 3D structure will be measured using different distance indicators and in particular the period-luminosity relation for short period variable stars, RR Lyrae stars and Cepheids. VMC will provide the near-IR magnitude and the period will be obtained from large optical catalogues in the literature (e.g. OGLE-III and EROS-II) or from observations at the VLT Survey Telescope (VST), for the Bridge and SMC parts only.

Although VMC is a deep survey targeting faint stellar populations it will find counterparts to faint AGB stars and, via an accurate analysis of the SFH of the system, it will relate them to their progenitors.

2.6 Future surveys

The Magellanic Clouds will be targeted by different new missions. During this meeting the Herschel satellite was successfully launched. Herschel will probe the mid- to far-IR regime for AGB stars in the Magellanic Clouds.

The next step in ground-based IR astronomy may be taken really in Antarctica with the development of a telescope like PILOT (see other contributions in this proceeding). This will be a 2m class telescope that will explore the dark side of the K-band and possibly extend to the L-band, reaching an unprecedented depth, and will also be ideal to monitor AGB stars in the Magellanic Clouds.

3   Conclusions

IR imaging of AGB stars in the Magellanic Clouds were aimed at finding the most luminous and dusty, thus obscured, sources. Different criteria were developed to distinguish and classify AGB stars into O- and C-rich. Multi-wavelength and multi-epoch (optical only) observations have allowed to quantify mass-loss rates and the coupling with AGB pulsation and evolution.

Major progress in the study of AGB stars has occurred not only on the observational side but also on the theoretical side with the development of models that are able to interpret the location of AGB stars in the IR (Marigo et al 2008). These authors have produced isochrones including molecular opacities in O- and C-rich AGB stars, the hot bottom burning process, the effect of the pulsation mode (first overtone or fundamental mode) to the AGB lifetime and the mass-loss with respect to the different surface chemistry. By exploring the range of ages typical for AGB stars, these models, reproduce well the distribution of the AGB population in the Magellanic Clouds in both near- and mid-IR diagrams.

The most luminous AGB stars experience the strongest mass-loss rate. This result has been greatly re-affirmed with the investigation by Fraser (2008) that involves the combination between Spitzer and 2MASS data with optical monitoring data from the MACHO project. The bolometric magnitude and the mass-loss rate were obtained from the SED of individual AGB stars and the period extracted from their optical light-curve. The major uncertainty still present in the period-luminosity relations is directly reflected in the uncertainty attributed to the

bolometric magnitude. To obtain average bolometric magnitudes it is necessary to monitor the SED across a few years. The reduced scatter around the period-luminosity relations will also contribute to refining AGB stars as a powerful tool to measure distances in the Universe.

There is at present a paucity of IR monitoring (2 epochs by Spitzer, 12 epochs by VMC) and a lack of foreseen projects to improve this condition. Mean bolometric luminosities are the next step in the investigation of the mass-loss mechanism and in measuring distances from the period luminosity relation. The Magellanic Clouds are the closest examples of interacting galaxies and represent an ideal laboratory for stellar evolution. The design of PILOT, a telescope for the Antarctica site, is well suited to advance the study of AGB stars in these neighbouring galaxies by providing better sensitivity, spatial accuracy and wide-field monitoring.

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