AGB STARS IN THE MAGELLANIC CLOUDS

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1. Introduction

The Magellanic Clouds (MCs) are an ideal testing ground for theories of the late stages of stellar evolution. They are nearby and yet far enough that to first order the depth of the MCs may be neglected, and all stars can be considered to be at the same distance (approximately 50 and 63 kpc for the LMC and SMC, respectively).

One of the primary observables is the luminosity function of oxygen-rich and carbon-rich AGB stars. Until the late-eighties AGB stars were searched for in the optical, either spectroscopically (using grisms or direct spectroscopy of red stars) or by identifying variable stars in the appropriate period range. Infrared observations were usually done as follow-up. When the IRAS Point and Faint source catalogues became available people started identifying AGB stars from those catalogues. These searches find a different population of AGB stars that are more luminous and more redder and that have been missed by the previous optical searches.

To illustrate this, I have used a dust radiative transfer model to calculate the expected magnitudes of a short period, low luminosity and a long period, high luminosity carbon Mira at the distance of the LMC (see Table 1). The estimates of the luminosities and mass loss rates are from the period-luminosity relation of Groenewegen & Whitelock (1996) and the period-mass loss rate relation of (Groenewegen et al. 1997).

It is clear that low and intermediate luminous carbon stars (but similarly for O-rich AGB stars) are bright in the optical but are far below the detection limit of IRAS, which was approximately 200 mJy at 12 μm. Stars more luminous than approximately 10 000 $L_{\odot}$, or less luminous stars with a very high mass loss rate could have been detected by IRAS. In addition one should not forget that most AGB stars are large-amplitude LPV's (long period variables). The full-amplitude of Miras are $\gtrsim$2.5 mag in V,

$\gtrsim$0.9 mag in I and $\gtrsim$0.4 mag in K and at 12μm. IRAS could therefore also have detected less luminous stars that happened to be near maximum light at the time of the IRAS observations.

It is clear that both the optical surveys and IRAS must be biased. From Table 1 it appear that the near-infrared (NIR) region may be the most unbiased way to search for AGB stars. In fact, there are two projects underway that will do so, namely the NIR sky-surveys DENIS and 2MASS.

In addition ISO provides the opportunity the make detailed observations of individual objects with unprecedented sensitivity and at wavelengths not accessible from the ground.

In Sect. 2 the surveys that have been conducted to identify AGB stars are described. In Sect. 3 and 4 first results from DENIS and ISO are presented. I conclude in Sect. 5.

TABLE 1. Expected fluxes for carbon Miras in the LMC

Period (days)	Lum. ($L_\odot$)	$\dot{M}$ ($M_\odot yr^{-1}$)	V (mag)	I	J	H	K	[12] (mJy)	[25] (mJy)
320	3000	1.7×10^{-8}	17.2	14.4	12.5	11.7	11.0	6.0	1.6
680	10000	8.4×10^{-6}	26.8	20.9	16.1	13.9	11.7	177	76

2. Surveys

To construct the luminosity function of AGB stars one must first identify them, and then perform some follow-up observations to be able to determine the apparent bolometric magnitude. In the section the most well-known and recent surveys, and references to follow-up work are described. I distinguish between LMC, SMC, the inter cloud region and clusters.

2.1. LMC

- Westerlund et al. (1978) discovered 302 C-stars over an 62.5 sq. degree area and give coordinates, charts and photographic I. Follow-up observations were performed by Richer et al. (1979) who present photoelectric RI for 112 of them, and Cohen et al. (1981) who present JHK photometry for 25.
- Blanco et al. (1980) discovered 186 C-stars and 102 M5+ stars in three fields of 0.12 sq. degree each (the 'bar west', 'optical center' and 'radio center' fields) and present photographic RI photometry, charts and coordinates. Follow-up work was done by Cohen et al. (1981) who present JHK photometry for 53 and $m_{\rm bol}$ for all carbon stars in the three fields based on bolometric corrections, and by Richer (1981) who give VRI and $m_{\rm bol}$ for 71 carbon stars in the 'bar west' field.

- Blanco & McCarthy (1983) discovered 1045 C and 480 M6+ stars in 52 fields of 0.12 sq. degree, which include the Blanco et al. fields. A total number of 11 000 carbon stars in the LMC is estimated. Follow-up is presented by Blanco & McCarthy (1991) who give charts and coordinates for 849 C-stars, and by Costa & Frogel (1996) who present RI photometry for 888 and JHK observations for 204 C-stars, and estimate $m_{\rm bol}$ for all of them.
- Frogel & Blanco (1990) present an extended survey for M-giants in the 'bar west' field. They present JHK and $m_{\rm bol}$ for a sample of 128 M-giants.

Searches for AGB stars have also been done using the variable star character of AGB stars. The largest survey so far is that by Hughes (1989) who found 471 Miras and 572 SRs over 53 sq. degrees in the LMC. They give mean I magnitudes and amplitudes, charts, periods and light curves. In a follow-up paper Hughes & Wood (1990) present JHK photometry for 267 Miras and 117 SRs, and classify 121 O- and 87 C-stars from optical spectra. Other recent work includes that of Reid et al. (1995) who find 302 periodic variables, at least 190 of which are Miras, for which they present charts and JHK photometry. Sebo & Wood (1995) identify 19 LPV's near the cluster NGC 1850.

2.2. SMC

- Blanco et al. (1980) found 134 C- and 5 M5+ stars in 2 fields of 0.12 sq. degree each, and give RI photometry, charts and coordinates. Cohen et al. (1981) present JHK photometry for 20 of them.
- Blanco & McCarthy (1983) presented 789 C- and 57 M6+ stars in 37 fields of 0.12 sq. degree each, including the 2 Blanco et al. fields. A total number of 2900 carbon stars in the SMC is estimated.
- Westerlund et al. (1986) discovered 449 C-stars in 2 fields of 0.78 sq. degree each, 405 of which are new discoveries. They derive $m_{\rm bol}$.
- Reid & Mould (1990) presented a photographic VI survey of 0.8 sq. degree and identify AGB stars candidates from $V-I$ color. Spectroscopic observations confirm 18 C-, 18 M- and 43 K-giants.
- Rebeirot et al. (1993) presented 1707 C-stars in 13 fields of 0.78 sq. degree each (including the 2 Westerlund et al. fields) and give charts and coordinates. Westerlund et al. (1995) present JHK data for 50, and medium-dispersion spectra for 39 of them.
- Morgan & Hatzidimitriou (1995) surveyed 220 sq. degrees of the outer parts of the SMC. They find 1634 C-stars of which 449 are also in Rebeirot et al. (1993).

In Fig. 1 the luminosity function (LF) of carbon stars in the LMC and SMC is compared. The apparent $m_{\rm bol}$ data for the LMC is taken from Costa &

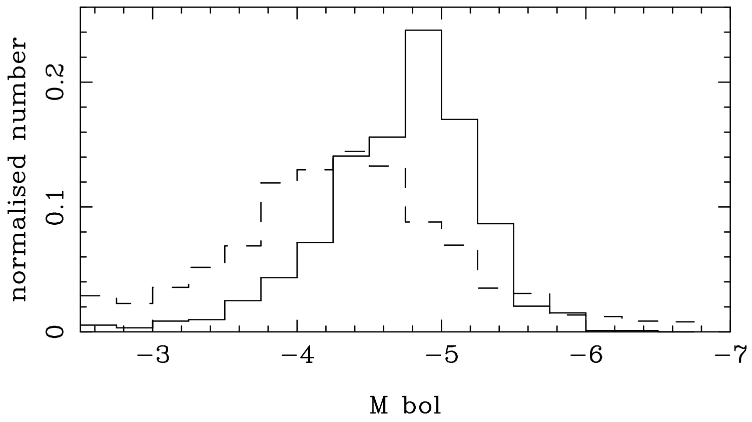

Figure 1. Luminosity function of carbon stars in the LMC (solid line; data from Costa & Frogel 1996) and SMC (dashed line; derived by me from data in Rebeirot et al. 1993). First bin contains all stars fainter than $M_{\rm bol} = -2.5$.

Frogel (1996) and I assumed a distance modulus of 18.5. For the SMC, I took the 1636 stars from Rebeirot et al. (1993) with good magnitudes and colors, used the bolometric correction relation from Westerlund et al. (1986), and assumed a distance modulus of 19.0.

The two LFs are significantly different. The LF of SMC carbon stars is much broader although this may be partly due to the bolometric correction calculation which introduces some spread. The difference in the peaks of the LFs appears real however. The mean luminosity of carbon stars in the LMC is about 7000 $L_\odot$, that of their SMC counterparts about 4300 $L_\odot$. A qualitative explanation may be that due to the lower metallicity oxygen-rich AGB stars need fewer dredge-up events to become carbon stars and hence do so at lower luminosities. Another explanation may be that the population of SMC stars contains relatively more low mass stars that are intrinsically fainter. The challenge of AGB population synthesis models (like Groenewegen & de Jong 1993, 1994, Groenewegen et al. 1995) is to explain this difference quantitatively.

Another interesting feature is the relatively large number of very faint carbon stars, with luminosities below the tip of the RGB at $M_{\rm bol} \approx -3.5$. This was already noted by Westerlund et al. (1992).

2.3. INTER MAGELLANIC CLOUD REGION

Demers et al. (1993) find 57 red stars ($B - V > 1.765$). From spectra they find that 33 are C- and 12 M-stars. Feast & Whitelock (1994) present JHK photometry for all of them.

In a recent paper, Kunkel et al. (1997) discover 392 carbon stars in the outer parts of the SMC and inter cloud region, and give radial velocities, coordinates and charts.

2.4. MAGELLANIC CLOUD CLUSTERS

Many of the work on this subject in the early-1980's is by the late M. Aaronson, J. Mould and J. Frogel. Recent work is by Frogel, Mould & Blanco (1980), Westerlund et al. (1991), Ferraro et al. (1995), Tanabé et al. (1997).

2.5. IRAS TRIGGERED RESEARCH

In the late-eighties a whole new field of MCs AGB research was born when people started to look for AGB stars in the direction of the MCs using the IRAS data products. The list below summarises this work.

- Whitelock et al. (1989) discuss five objects in the direction of the SMC.
- Reid et al. (1990) and Reid (1991) combined IRAS with optical data and performed JHK photometry to end up with the identification of ten "cocoon" stars in the direction of the LMC.
- Wood et al. (1992) provided detailed observations of 3 objects in the SMC and 16 in the LMC. Six show OH-maser emission which confirms they are oxygen-rich and allows their terminal wind velocity to be determined. The sources are monitored in the infra-red from which pulsation periods in range 930-1390 days are found for nine of them. This are periods much longer than for optical LPVs.
- Groenewegen et al. (1995) presented the first ground-based 8-13 μm spectra of two AGB stars in the MCs, one in each cloud. These happened to have about the same pulsation period and by comparing with a galactic OH/IR source of roughly the same period, it was found that the ratio of the dust optical depth was Galaxy:LMC:SMC = 15:10:1. This suggested a ratio of mass loss rates of 5:4:1 and hence the first, albeit rough, quantitative estimate of the dependence of mass loss rate on metallicity.
- Zijlstra et al. (1996), Loup et al. (1997a), van Loon et al. (1997a,b) is a series of paper by essentially the same group of people.
  Loup et al. classify 91 IRAS sources in the SMC and 635 in the LMC: 59 are optically known AGB or RSG (red supergiants); 36 are confirmed obscured AGB/RSG stars based on NIR photometry of Zijlstra et al. and the other papers listed above; 23 are PNe; 209 are candidate AGB/RSG stars; 91 are ruled out as AGB stars, 164 are foreground objects and 154 could be any type of objects.
  van Loon et al. present additional and follow-up observations in the optical, near- and mid-infrared. Work in progress consists of determining the pulsation periods, and obtaining 3 μm spectra to classify the objects.

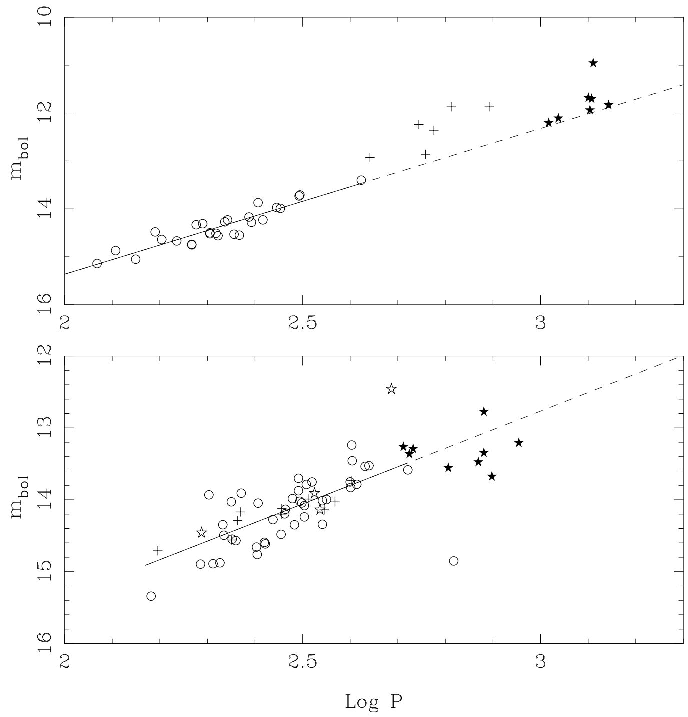

Figure 2. Period-Luminosity relation for O-rich (upper panel) and C-rich (lower panel) AGB stars in the LMC. The solid and dashed lines are least-square fits (and the extrapolations, respectively) to the data points represented by the open symbols in the upper panel and open symbols and crosses in the lower one (except the two obvious outliers). The filled symbols represent IRAS detected stars. Taken from Groenewegen et al. (1996), where more details are provided.

– Groenewegen & Blommaert (1997) identify 29 IRAS AGB candidates in the direction of the SMC. NIR photometry has been obtained and some optical spectra and photometry as well.

Based on literature data and new preliminary pulsation periods for IRAS detected AGB stars available early 1996, we have made model fits to the spectral energy distributions (SEDs) to obtain the mean luminosity and plotted them in a period vs. luminosity diagram to compare them to the $P - L$-relations that had been derived for short period Miras. The result is in Fig. 2 (taken from Groenewegen et al. 1996). The conclusion is that the IRAS stars appear to be on extensions of these relations.

3. First DENIS results

DENIS (Deep Near-Infrared Survey) is a survey of the southern sky in IJK, to limiting 3σ magnitudes of 18.5, 16.3, 14.0. It uses the 1m telescope at La Silla, Chile. More information can be found in Epchtein (1997), Epchtein et al. (1997), and in Skrutskie et al. (1997) on a similar US all-sky JHK

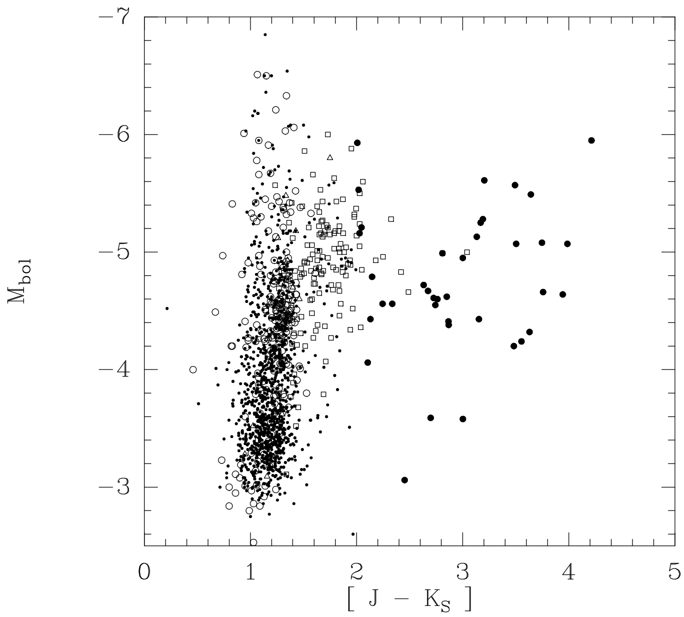

Figure 3. DENIS observations of two 0.18 sq. deg. fields covering part of the Blanco et al. (1980) fields. $M_{\rm bol}$ is based on K and $J-K_s$. Plotted are the 1200 objects with errors in their colors smaller than 0.15 mag. Open circles represent known M-stars, open squares known C-stars, open triangles known LPVs of unknown spectral type. Solid points are new DENIS sources. From Loup et al. (1997b), where more details are provided.

survey called 2MASS. Figure 3 shows some DENIS results of two fields in the LMC.

4. First ISO results

Almost all ISO observations of AGB stars in the MCs are being done with PHT and CAM, as the objects are to faint to be observable with SWS and LWS. There is one exception and that is the supergiant WOH G064 that will be observed with SWS. For other observations of this interesting object see the poster paper by van Loon in this volume.
Guaranteed and open time proposals regarding the MCs are as follows.

- PHT
  There are the proposals by Trams et al. (see his contribution in this volume) and Blommaert et al., who focus on individual IRAS detected stars in the LMC and SMC, respectively. Some PHT-S spectra are obtained for the LMC sources, and both projects aim to observe at 12, 25 and 60 μm (see Fig. 4 for an example of an ISO 60 μm observation).
- CAM
  There are complementary programs by the same two authors to complete the SEDs at shorter wavelengths. In addition CVF spectra are

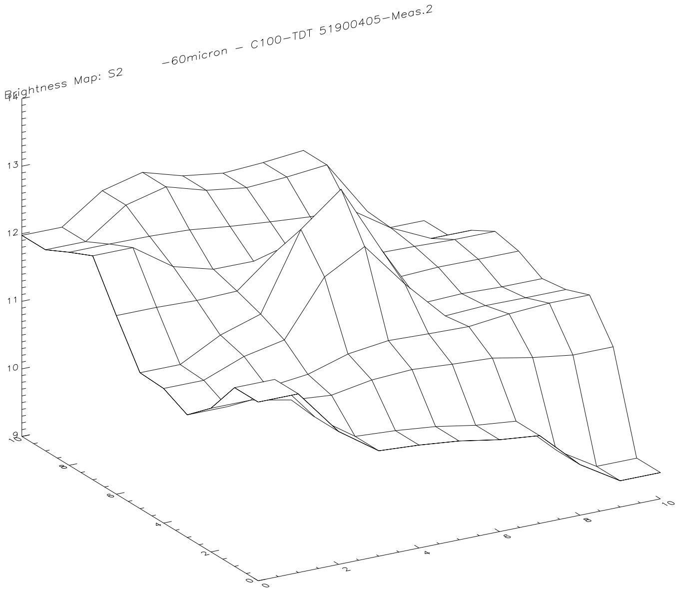

Figure 4. ISOCAM 3×3 raster map observations with C100 at 60 μm of a star in the SMC. The preliminary analysis results in a flux of 59 mJy. The axes represent surface brightness versus pixels.

obtained for some sources (see Blommaert's contribution in this volume).

There are two mini-surveys being carried out: by Tanabé et al. using 3 filter observations of 18 globular clusters (see the contribution in this volume), and by Loup et al. using 2 filter observations of 7 fields in the LMC for a total 0.5 sq. deg. (see the poster paper by Josselin et al. in this volume).

The most exciting to come out of these ISO results so far is the detection of extremely red, relatively low luminosity objects. The most extreme example is shown in Fig. 5. This SMC star was not detected by us in K down to $14th$ magnitude. Fitting its SED results in a luminosity of 5300 $L_\odot$ and a estimated mass loss rate of 7×10^{-5} $M_\odot yr^{-1}$. Its optical depth is as large as that of the reddest known Galactic carbon Mira, which happens to have also the longest known period for a carbon Mira. However, that object, using the $P - L$ relation has a luminosity of 16 400 $L_\odot$ (!), whereas the mass loss rate is comparable.

5. Conclusions

ISO provides the opportunity to observe AGB stars in the MCs with unprecedented sensitivity and at wavelengths that are inaccessible from the ground. It is in a way unfortunate that the majority of ISO time is spent on follow-up observations of IRAS detected stars, as we know that this sample

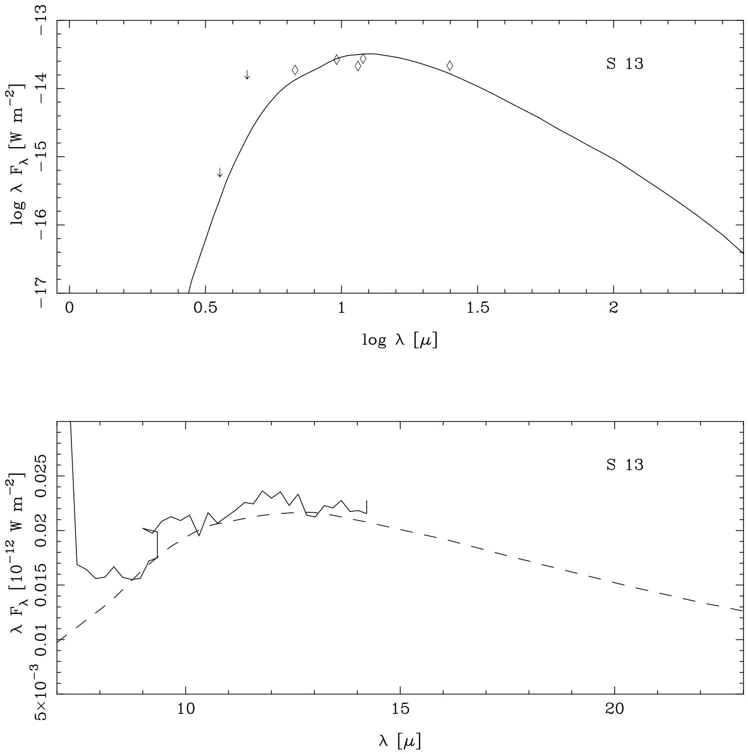

Figure 5. Model fit to the ISOCAM broad-band and CVF spectra of the object S13. It is as red as the reddest known carbon star in our Galaxy. Amorphous carbon dust is assumed. The sharp drop of flux below 8 μm in the CVF spectrum is instrumental.

is biased. Only one program uses the survey capability of CAM to observe field stars, but even that is restricted to 0.5 sq. degree in the LMC only.

There is life after ISO: the near-infrared surveys DENIS and 2MASS will observe the whole of the MCs, and in this respect will provide the most unbiased view of the AGB population. In addition, the multi-wavelength photometric and spectroscopic capabilities of the VLT, the multi-object optical spectroscopic capability of de 2dF instrument on the AAT, and the MACHO/EROS projects that identify LPVs ensure that extra-galactic AGB research will be an interesting research topic in the future.

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