EVOLUTION AND MASS LOSS OF AGB STARS IN THE MAGELLANIC CLOUDS *

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ABSTRACT

We used ISOCAM and ISOPHT to observe the spectral energy distribution (SED) between 3.6 and 60 μm of Asymptotic Giant Branch (AGB) stars in the Magellanic Clouds (MCs) detected by IRAS. PHT-S and CAM-CVF spectra are made which enable us to establish the carbon- or oxygen-rich nature of the stars. The 9.7 μm silicate feature gives a measure of the optical depth of the dust shell. Ground-based near-infrared data has been obtained for the full sample.

We are analysing the SEDs using radiative transfer models which provide accurate determinations of the luminosities and mass-loss rates of the objects. Combining the data on the SMC, LMC and existing data on the Galaxy will answer the open question of the metallicity dependence of mass loss in late-type stars. This in turn is important in the ejection of matter by AGB stars to the interstellar medium over the age of the Galaxy.

Key words: ISO; infrared astronomy; Carbon stars; AGB stars; Mass-loss; Circumstellar matter; Magellanic Clouds.

1. INTRODUCTION

AGB stars
Stars with initial masses in the range of $1-8M_{\odot}$ go through the Asymptotic Giant Branch (AGB) phase before becoming Planetary Nebulae and ultimately White Dwarfs. An important characteristic of AGB evolution is the large mass-loss rates, from 10^{-7} to 10^{-4} $M_{\odot}$ per year. Through this mass loss a large circumstellar shell is created where dust grains transform the visible radiation from the star into infrared radiation ($1-60$ μm). This mass loss process (which completely dominates the final evolution of the star) is still a poorly understood phenomenon.

Why the Magellanic Clouds?
Studies of AGB stars in our own Galaxy suffer from interstellar extinction and the fact that the distances to the objects are in most cases unknown. For this reason studies of AGB stars in the Magellanic Clouds (MCs) are very useful. Searches for AGB stars in the MCs have been made using optical spectroscopic surveys. However, these surveys missed the AGB stars with high mass loss rates like the red dust-enshrouded OH/IR stars and infrared carbon stars, of which very luminous examples did turn up in the IRAS point source catalog.

Another important aspect is that metallicity differences exist between the stellar populations of the MCs and our Galaxy. By comparing AGB stars in these different galaxies one can study the influence of metallicity on AGB evolution. As an example of this, Groenewegen et al. 1995 compared the spectral energy distribution and $8-13\mu m$ spectra of an AGB star of comparable pulsation period in the galaxy, Large Magellanic Cloud (LMC) and Small Magellanic Cloud (SMC) and showed that the dust optical depth of the LMC star was two-thirds of that of the galactic one but that of the SMC star only one-fifteenth.

Here we present the first results obtained in programs to study mass losing AGB stars in both MCs: ISO observations on AGB stars in the LMC form part of a Guaranteed Time program (PI Trams). A second (Open Time) ISO program (PI Blommaert) was aimed at IRAS sources in the SMC.

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2. THE SMALL MAGELLANIC CLOUD

2.1. Sample selection

Twenty-nine stars from the IRAS Faint Source Catalog (FSC) were selected. The sources needed to have a flux quality (FQ) at 12 and 25 $\mu m \geq 2$, $F_{60} < F_{25}$ and FQ(60) < 2. Fifty-one sources complied with these criteria. Simple radiative transfer models were calculated to estimate the luminosity and mass-loss rate *if* these stars are indeed in the SMC. In this scheme foreground objects typically have low mass-loss rates and high fiducial luminosities. Only those stars were retained that have luminosities below the 10^5 $L_\odot$ typical for AGB stars. In addition, the results for all 51 stars were inspected individually and cross-correlated with information in the SIMBAD database. The final sample contains 29 objects. The analysis of NIR photometry and optical spectroscopy on this sample is presented in Groenewegen and Blommaert (1998).

2.2. Observing Strategy

Our ground based JHK images ($1' \times 1'$) were obtained in October 1995 using the IRAC2 camera behind the ESO 2.2m telescope (Chile). These observations revealed red sources in all fields. On the other hand, the colours were not always as expected. Sometimes the IRAS colours implied much redder near-infrared (NIR) colours than actually observed. In other cases the positional difference between the NIR and IRAS positions was much larger than the formal uncertainty in the IRAS FSC positions. It seemed possible at that time that there were more than one red AGB star near the IRAS position. Because of this we decided to split up the observations in 2 campaigns. A first one in which we made ISOCAM rasters in 2 wavelengths, centered on the near-Infrared position. A second one to observe the SED of the then selected source.

2.3. Campaign I

ISOCAM rasters:

- LW2 (6.7μm) and LW10 (12 μm)
- FOV = $2' \times 2'$
- centered on the NIR position, but also including the IRAS one
- integration time per filter, per raster position is 40 sec.
- 20 sources observed at revs: 298, 299, 369 and 411

2.4. Campaign II

Per source concatinated observations within $3.6 - 60\mu m$, using:

A) Staring observations with ISOCAM:

Filter	wavelength [μm]	PFOV [$''$]	Tot. integr. Time [s]
SW1	3.6	1.5	470
LW1	4.5	1.5	158
LW2	6.7	3	105
LW7	9.6	3	101
LW10	12.0	3	84

B) Observations with ISOPHT:

- 25 μm; P2, triangular chopping, $52''$ aperture, 256 sec on source integration time.
- 60 μm; C100, 3x3 raster map, step size = pixel size ($45''$), 128 sec per raster position.

In total, ISOPHT and ISOCAM measurement of 13 sources were performed. In the program of N. Trams et al. additional CVF measurements were made in the range of $7 - 14.5\mu m$ for a subset of 7 sources.

2.5. Results

1) Outcome of the 21 raster images (Campaign I):

Almost all NIR sources correspond to the IRAS source. In other words, at the centre of the raster (i.e. the NIR position) we find a red object with a flux density at 12 μm within a factor of 3 to the IRAS flux (allowing for variability of the AGB stars (maximum factor ≈ 2.5) and the uncertainty in the measurements). No other red source of similar 12 μm flux densities is found in the raster.

Only in 3 cases (14% of the sample) we find a source in the centre of the ISOCAM 12 μm raster image which is much weaker than the IRAS flux. Only in 1 of the 3 we see that the IRAS coordinates differ considerably with the NIR ones ($41''$), so that part of the IRAS error ellipse may fall out of the raster. In the two other cases it is not clear whether extreme variability or simply the fact that we had a spurious source in the FSC is the cause of the discrepancy.

2) Pointed observations and modelling (Campaign II):

Thirteen sources for which the SED's have been observed were modelled using the code of Groenewegen (1993). We find that:
Four sources are Oxygen-rich (showing silicate features). They have high luminosities ($L_* > 20,000 L_\odot$), of which 2 are near or above the limit of AGB stars ($L_* > 55,000 L_\odot$). $\dot{M}$ ranges from 10^{-8} to $10^{-6} M_\odot/yr$.

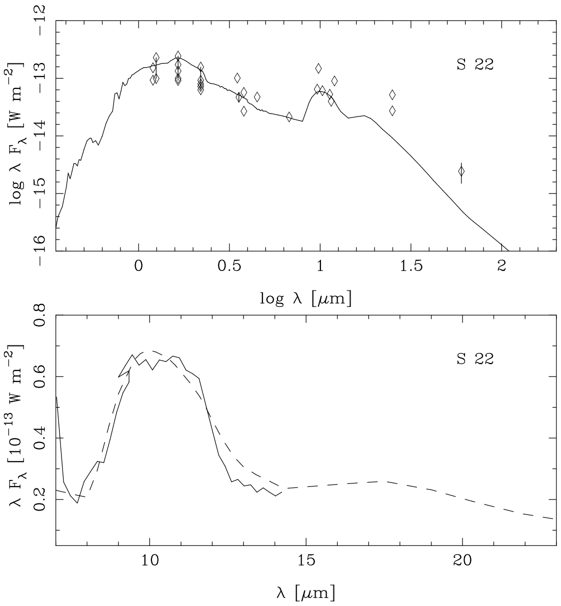

Figure 1. Model fit to the SED and CAM-CVF spectrum of one of the oxygen-rich sources in the SMC. Luminosity and mass-loss rate are 34,000 $L_\odot$ and $3 \times 10^{-6} M_\odot/yr$

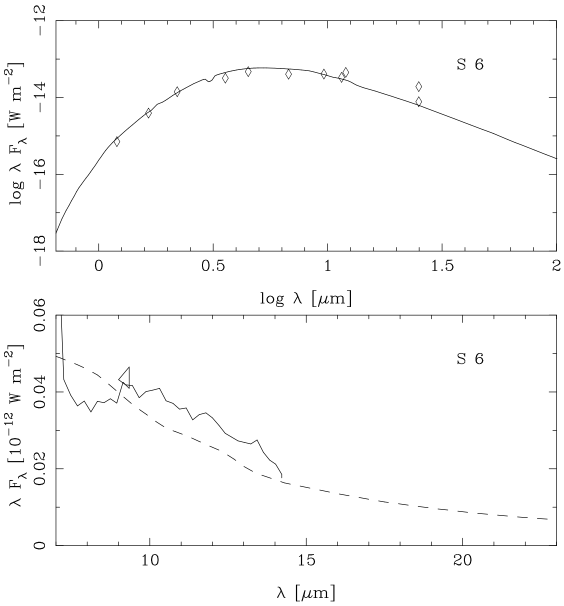

Figure 2. Model fit to the SED and CAM-CVF spectrum of one of the carbon-rich sources in the SMC. Luminosity and mass-loss rate are 11,310 $L_\odot$ and $7.5 \times 10^{-6} M_\odot/yr$

Six are Carbon-rich. Five have relatively low luminosities ($L_* \leq 10,000 L_\odot$). One sources has a luminosity of $\approx 20,000 L_\odot$. All suffer extreme high mass-loss rates ($\dot{M} \geq 10^{-5} M_\odot/yr$, assuming a *'galactic'* dust/gas ratio of 1/200). This is quite remarkable because first, one would assume that the metallicities are lower in the SMC and thus the dust to gas ratio may even be much lower than assumed here. This would further increase the resulting mass-loss rate. And second, we find evidence here that relatively low mass stars ($\approx 1 M_\odot$) also reach high mass-loss rates in excess of $10^{-5} M_\odot/yr$. Third, *no* high luminosity sources above 20,000 $L_\odot$ like in the LMC were found (see next section).

Three sources do not fall in one of the 2 above categories: IRAS 0369-7419 has been classified as a C-rich post-AGB star (Whitelock et al 1989). IRAS00535-7219 is classified as a symbiotic star. The nature of one other object is unclear.

3. The Large Magellanic Cloud

In the ISO Guaranteed Time project a sample of 57 stars was studied. They were mainly selected from a compiled list of AGB stars with IR excess emission detected by IRAS (Loup et al. 1997, Zijlstra et al. 1996) and a number of optically visible Harvard Variables (HV) and SHV variables (Hughes & Wood 1990), including a few red supergiants.

Ground based observations were performed to complement the ISO observations, aimed at obtaining the relevant (circum)stellar parameters for as many stars of the sample as possible (e.g. van Loon et al. 1998). NIR monitoring at SAAO resulted in pulsation periods and amplitudes for the entire sample. The luminosities of the obscured AGB stars are between 5,000 and 50,000 $L_\odot$, and mass-loss rates are typically 10^{-5} $M_\odot$ yr^{-1}. One of the most surprising results is the notion that carbon stars do reach luminosities of over 30,000 $L_\odot$. This contradicts the earlier consensus of a carbon star luminosity cut-off at 20,000 $L_\odot$ (Iben 1981).

3.1. ISO Photometry

ISO photometry through the IRAS-like 12, 25, and 60 μm filters was performed to cover the Spectral Energy Distribution (SED). ISOCAM was used to image at 12 μm faint sources of typically 10 to 100 mJy, while the PHOT photometer was used in triangular chopping mode to measure at 25 and 60 μm and the brighter sources at 12 μm. Typical observation durations lasted a few 100 seconds. Almost all sources are detected, except at 60 μm where the high background limits reliable photometry to about ten stars. Modelling of the SEDs by a dust radiation transfer code of de Koter, University of Amsterdam, is currently being done in order to derive mass-loss rates.

3.2. ISO Spectroscopy

ISO spectroscopy was performed for a selected number of stars, to determine the chemical composition of the circumstellar dust and to aid in constraining the modelling of the SED. CAM was used with the CVF to observe 12 sources from 7 to 14 micron at 0.2 micron steps. Aperture photometry per filter position guarantees a proper background subtraction. PHOT-S was used in staring mode for 15 sources from 2.5

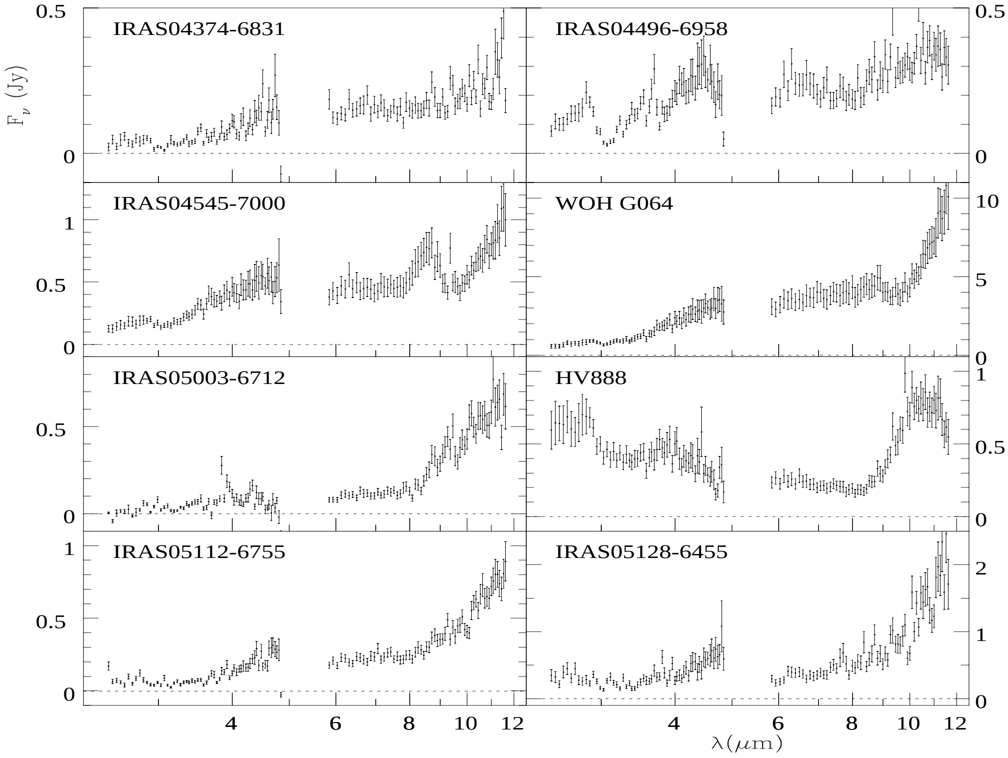

Figure 3. PHT-S spectra of a subsample of the LMC sources (no background correction applied)

to 12 micron at a resolving power of about 10. A small correction for background emission, mainly zodiacal light, will be applied in a later stage of the data analysis. Some sources have been observed both with CAM and PHOT.

The 10 micron silicate feature is indicative of oxygen-rich dust. It is seen in self-absorption in all known OH maser sources (e.g. IRAS04545−7000), and in emission in less obscured sources (e.g. HV888). Carbon stars may exhibit an emission feature at 11.3 micron attributed to SiC. Several stars have IR continuum emission that is featureless in the 8 to 12 micron region (e.g. IRAS05128−6455).

The combination of the ISO spectroscopy and photometry has enabled us to classify securely the AGB stars according to the chemical type of the circumstellar dust. We find that a high number of the obscured AGB stars in the LMC are C-rich.

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"The ISOPHOT data presented in this paper was reduced using PIA, which is a joint development by the ESA Astrophysics Division and the ISOPHOT Consortium".

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