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Mid-infrared Studies of the AGB Star Populations in the Local Group Galaxies : the Magellanic Clouds

By

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Abstract: We present a brief summary of the ISO survey of AGB stars in 8 populous intermediate age clusters of the Magellanic Clouds. Totally, more than 100 AGB and RGB stars were observed at 4.5, 6.7 and 12 μm. We introduce a new method to estimate effective temperatures of oxygen-rich AGB stars, and derive precise $M_{\rm bol}$ and $T_{\rm eff}$ for a large population of AGB objects in both LMC and SMC. The derived stellar parameters are used to construct observed HR diagrams which are employed further to estimate cluster ages using the isochrone fitting. We show that proposed method gives a powerful tool to study AGB star populations within the Local Group galaxies, especially, when backed up with the observations from forthcoming mid-IR astronomical space facilities (ASTRO-F, SIRTF) and large ground-based telescopes (SUBARU, VLT, etc.).

1. INTRODUCTION

Asymptotic giant branch (AGB) stars, as being one of the brightest stellar populations, can be effectively used to trace star formation histories within the Local Group galaxies. However, due to the sensitivity of presently available mid-infrared and far-infrared detectors, such studies so far were mostly confined to the Magellanic Clouds (MC). Indeed, populous intermediate age clusters in both the Large and Small Magellanic Clouds (LMC and SMC hereafter) represent an ideal laboratory for studying stellar evolution. They span a range of ages and metallicities, which makes them suitable to trace the AGB evolution of stars with different masses and in different evolutionary stages.

In this work we present a brief summary of ISOCAM survey of AGB stars in the populous intermediate age star clusters in the LMC and SMC. Although several obscured AGB stars were discovered during the course of our survey (Tanabé et al. 1998, 1999), in this work we concentrate on non-obscured AGB stars. Since the radiation of these objects is not modified by the surrounding circumstellar shell, their spectral energy distributions (SEDs) can be effectively

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modeled using conventional model atmospheres, which allows a straightforward determination of $T_{\rm eff}$ and $M_{\rm bol}$.

Although the AGB stars are ideal candles to trace stellar ages on extragalactic distance scales, an efficient method to derive ages of stellar populations using AGB stars is not yet available. We show that a precise knowledge of the basic stellar parameters of the AGB objects may provide a clue for the solution of this problem too.

2. ISOCAM OBSERVATIONS

The populous intermediate age clusters in the LMC and SMC were observed in the raster imaging mode with the ISOCAM (Cesarsky et al. 1996) on board the ISO satellite (Kessler et al. 1996). Observations were made using the broad-band CAM filters LW1, LW2 and LW10 (corresponding to the effective wavelengths of 4.5, 6.7 and 12 μm, respectively), with a pixel field of view (PFOV) of 3″. The raster mode was typically 5 × 5 frames, with the raster step size equal to 8 pixels (24″). The fundamental integration time was set to $t_{\rm int} = 2.1$ sec, with a total number of 15 to 20 exposures per single raster position.

ISOCAM data were reduced using the CAM Interactive Analysis software (CIA version 3) [1], and photometry was performed with the IRAF DAOPHOT package. The absolute photometric uncertainty of our measurements is mainly due to the ISOCAM calibration uncertainties and the correction for the memory effect (transient) of the ISOCAM, which is estimated to be less than 20% (Biviano 1998). A typical ISOCAM image of one of the sample clusters (NGC 1783) is given in Figure 1.

The obtained ISOCAM fluxes of the AGB stars, combined with the optical and near-infrared photometry available from the literature, were used to construct the observed SEDs, which were further used to derive $T_{\rm eff}$ and $M_{\rm bol}$ of the AGB stars without circumstellar shells.

3. $T_{\rm eff}$ AND $M_{\rm bol}$ OF THE STUDIED AGB STARS

Though there are numerous methods to derive effective temperatures of the AGB stars, none of them works well in cases when limited information about the spectral energy distribution of a particular star is available (e.g. when only the broad-band photometric fluxes are available). Various calibrations of photometric colors vs. effective temprature have been used extensively in such cases (Bessell et al. 1983; Feast 1996; Montegriffo et al. 1998), though the accuracy of the derived $T_{\rm eff}$ generally is not better than ~ 200 K.

Since color indices measure only a portion of the observed SED, we suggest to use the entire SED as an indicator of the effective temperature. One of the possible ways is to employ synthetic SEDs of AGB stars, which would yield $T_{\rm eff}$ as a fitting parameter. In our analysis we have fitted the observed SEDs with the theoretical fluxes calculated from synthetic spectra of Fluks et al. (1994). Though the synthetic spectra of Fluks et al. (1994) are of solar metallicity, our analysis shows, that the influence of metallicity (and gravity) on the derived $T_{\rm eff}$ is minor (Kučinskas et al. in preperation). Therefore, this offers a flexible tool for estimating effective temperatures of AGB stars in stellar populations where the metallicity is not known *a priori*. It should be stressed, however, that this method would not be applicable in case of AGB stars with circumstellar shells.

[1] The ISOCAM data presented in this paper was analyzed using "CIA", a joint development by the ESA Astrophysics Division and the ISOCAM Consortium led by the ISOCAM PI, C. Cesarsky, Direction des Sciences de la Matière, C.E.A., France.

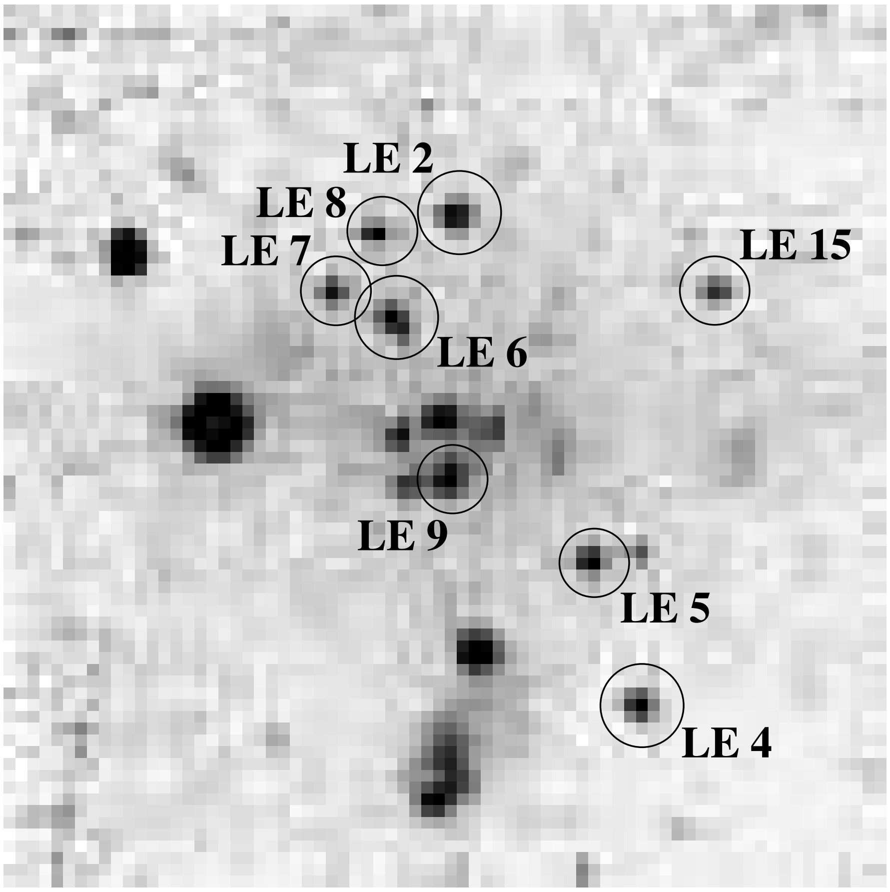

Fig. 1: ISOCAM image of the populous intermediate age cluster NGC 1783 in the Large Magellanic Cloud at 6.7 μm. Marked are objects with our effective temperature determinations (LE numbers are from Lloyd Evans 1980).

As an example, the observed SEDs and fitted synthetic SEDs are shown for the AGB stars in the LMC cluster NGC 1783 (Figure 2). Typically, the accuracy of such fits is better than $\pm$50K. This therefore gives a possibility to obtain precise effective temperature estimates of the AGB stars even if only the broad-band photometric fluxes are available.

Absolute bolometric magnitudes, $M_{\rm bol}$, of the studied AGB objects were obtained by flux integration in the observed SEDs. To obtain the total integrated flux, the observed SEDs were linearly interpolated between the two adjacent photometric fluxes, whereas the blackbody extrapolation was used for both the short- and long-wavelength tails of the SEDs. The apparent bolometric magnitudes were calculated then using the elementary formula :

$$m_{\rm bol} = -2.5\log(F_{\rm tot}) + ZP \tag{1}$$

where $F_{\rm tot}$ is the total integrated flux, and the zero point is taken to be $ZP = -11.478$ (Montegriffo et al. 1998). The apparent bolometric magnitudes were then converted into the absolute bolometric magnitudes using the distance moduli of 18.4 and 18.9 for the LMC and SMC, respectively.

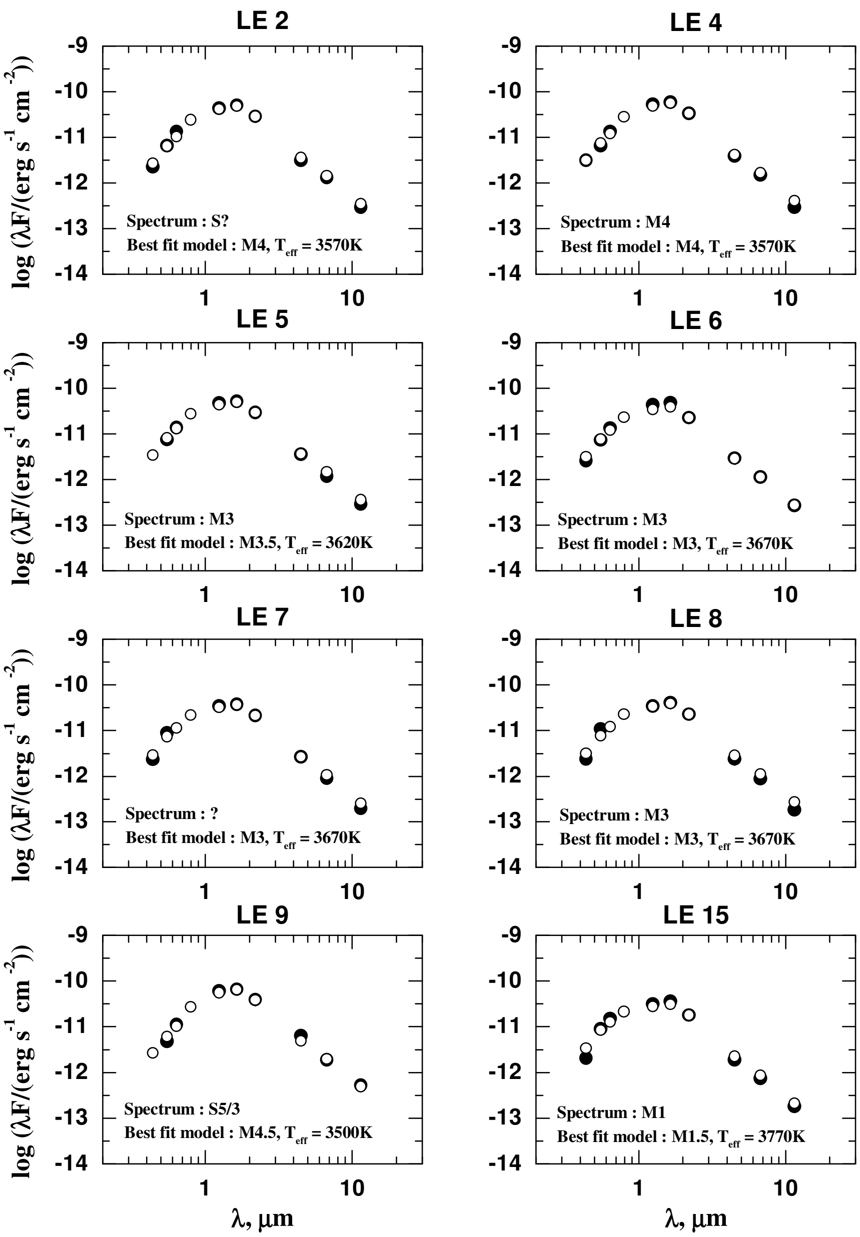

Fig. 2: Fits of the observed SEDs (solid circles) of oxygen-rich AGB stars in NGC 1783 with the synthetic SEDs (open circles). LE numbers are from Lloyd Evans (1980). Indicated are spectral classes extracted from the literature (Bessell et al. 1983; Lloyd Evans 1984; Frogel et al. 1990) and those derived in our work.

It should be stressed, that the knowledge of the mid-infrared fluxes of AGB stars is important in several aspects when deriving $T_{\rm eff}$ and $M_{\rm bol}$:

- mid-infrared fluxes constrain the total amount of energy emitted by the star and thus influences on the accuracy in determining $M_{\rm bol}$ (the improvement can reach up to 10% with the respect to $M_{\rm bol}$ derived from the SEDs constructed of optical and near-infrared observations only, where the red-tail of the SED is extrapolated as a blackbody);

- mid-infrared observations can reveal the excess flux due to the circumstellar dust, thus resulting in an easy discrimination between the AGB stars with and without circumstellar shells;

- mid-infrared data constrain fits of theoretical SEDs to the observed SEDs in the long-wavelength tail, and thus allow to derive $T_{\rm eff}$ more precisely.

4. AGES OF THE POPULOUS STAR CLUSTERS IN THE LMC AND SMC

The derived $T_{\rm eff}$ and $M_{\rm bol}$ of the non-obscured AGB stars were used to construct the observed HR diagrams, which were employed further to derive cluster ages using the isochrone fitting. We have used Bertelli et al. (1994) isochrones to work in $M_{\rm bol}$ versus $T_{\rm eff}$ plane. A typical example of the observed HR diagram and isochrone fitting is given in Figure 3 for the LMC cluster NGC 1783. The derived ages of all clusters in the sample and their comparison with the ages derived from the main sequence turn-off point (MSTO) fitting are given in Table 1. There is an excellent agreement between the ages obtained using these two methods.

It should be stressed, however, that metallicity plays an important role in the age determination. For instance, in case of NGC 1783 metallicity is not known precisely and the existing estimates vary between [Fe/H]$= -0.45$ and [Fe/H]$= -0.90$ (Cohen 1982; Bica et al. 1986; de Freitas Pacheco et al. 1998). The ages resulting from the isochrones of the corresponding metallicities would be 0.8 ± 0.2 Gyr and 2.2 ± 0.4 Gyr, respectively. It therefore shows, that *ab initio* knowledge of the cluster metallicity is an essential ingredient for obtaining a precise estimate of the population age.

Table 1: Ages of the sample clusters.

Cluster	MSTO estimate[1] (Gyr)	This work[2] (Gyr)
SMC		
Kron 3	8 ± 2	9 ± 3
NGC 152	0.8	1.0 ± 0.3
NGC 419	1.2 ± 0.5	1.4 ± 0.2
LMC		
NGC 1783	0.9 ± 0.4	0.8 ± 0.2
NGC 1846	–	1.3 ± 0.3
NGC 1978	2.0 ± 0.2	1.5 ± 0.5
NGC 1987	–	4.0 ± 2.0
NGC 2121	4.5	6.0 ± 2.0

[1] All ages in this column are from MSTO fits except for NGC 152 where it comes from the CMD fit without the MSTO region. References for the age estimates of individual clusters are as follows : Kron 3 - Alcaino et al. (1996); NGC 152 - Hodge (1981); NGC 419 - Durand et al. (1984); NGC 1783 - Mould et al. (1989); NGC 1978 - Bomans et al. (1995); NGC 2121 - Sarajedini (1998).

[2] Ages listed in this column were derived employing cluster metallicities used to obtain MSTO age estimates listed in Column 2. In case of NGC 1846 and NGC 1987 isochrones corresponding to the metallicity of $Z = 0.004$ were used.

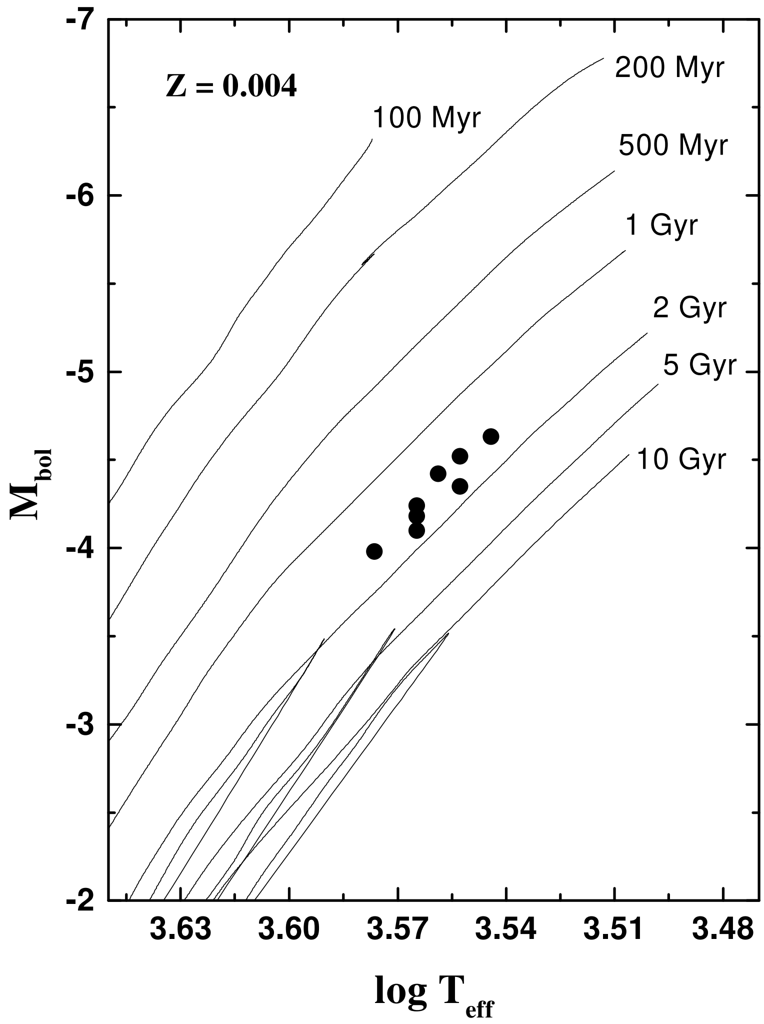

Fig. 3: HR diagram of the oxygen-rich AGB stars with synthetic SED fits in NGC 1783. Isochrones are from Bertelli et al. (1994) for the metallicity of $Z = 0.004$ (corresponding to the average metallicity from the determinations of Cohen (1982), Bica et al. (1986) and de Freitas Pacheco et al. (1998)).

5. SUMMARY AND FUTURE PROSPECTS

We suggest an alternative way for obtaining precise effective temperatures of oxygen-rich AGB stars without circumstellar shells. The only information needed to use this method is the availability of photometric broad-band fluxes. The observed SEDs should span as large wavelength interval as possible (optical through mid-infrared), which makes the mid-infrared observations highly desirable.

The obtained fundamental parameters of non-obscured oxygen-rich AGB stars ($T_{\rm eff}$ and $M_{\rm bol}$) can be used further to derive population ages employing the usual procedure of isochrone fitting. This gives a possibility to study star formation histories in a wide range of ages and metallicities.

The present ISOCAM study allowed to detect non-obscured AGB and RGB stars in the

LMC and the SMC down to $M_{\rm bol} \sim -2.7$ ($L_\star \sim 1000 L_\odot$). The forthcoming infrared space missions (ASTRO-F, SIRTF etc.) and the ground-based instrumentation for large telescopes (SUBARU, VLT etc.) will allow to detect and study extragalactic AGB stars in most of the Local Group galaxies (Zijlstra 1999; Kaufl et al. 1999). Therefore, such observations combined with the proposed method to estimate $T_{\rm eff}$ and age offer a powerful tool to study evolution of stellar populations in diverse astrophysical environments.

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