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Mass-losing AGB stars: infrared observations and evolutionary implications

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Abstract. We have selected a wide database of mid-infrared observations, for AGB stars from both ground-based and space-borne observatories, with the aim of characterizing the efficient mass loss mechanisms that lead to the formation of their extended dusty envelopes. Our sample includes more than 400 sources in our Galaxy, distributed along the evolutionary sequence that gradually changes the spectral characteristics of M giants to MS, S and then C-stars. Thanks to a reanalysis of existing estimates of mass loss at radio frequencies and to improved measurements of distance (often provided by the Hipparcos mission), we compile a homogeneous set of corrected mass-loss rates and of near and mid-infrared colours. We show the existence of clear correlations. This suggests that mass loss can be inferred from photometric colours in mid-infrared, once these have been suitably calibrated. This provides a tool to predict the efficiency of stellar winds for other less known sources and is a decisive step in view of the determination of observationally based criteria for inclusion of mass loss in stellar models. In this paper we discuss in particular our sample of C-rich stars.

Key words. Stars: AGB and post-AGB – Mass Loss – Carbon Stars – Infrared Photometry

1. Introduction

Stars of low and intermediate mass (all those below $M = 7-8\,M_{\odot}$) terminate their evolution through the Asymptotic Giant Branch phase (Busso, Gallino & Wasserburg 1999), in which they lose mass efficiently thanks to stellar winds powered by radiation pressure on dust grains (Habing 1996). After this stage, they generate planetary nebulae and start a blue-ward excursion and ultimately gives birth to a white dwarf. Moreover winds from AGB stars replenish the Interstellar Medium with about 70% of all the matter returned after stellar evolution; this is done with the formation of circumstellar envelopes through the processes of mass loss (Winters et al. 2002)).

One of the main open problems that still affects our knowledge of AGB stars is the history of mass loss, the efficiency of which controlsthe duration of the AGB phase and the amount of matter returned to the ISM. We do not yet have a quantitative description of stellar winds in AGB stars, though hydrodynami-

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cal modelling of pulsating stellar atmospheres and of the induced mass loss is undergoing important improvements (Winters et al. 2002, 2003). Also observational studies have become more and more quantitative because of new data at long wavelengths from space and from the Earth (Le Bertre et al. 2001, 2003), as well as an improved knowledge of stellar distances (Knapp et al. 2003).

We believe there is now a need to devise a quantitative basis for associating each phase of the physical and chemical evolution of an AGB star with a suitable mass-loss rate estimated observationally. Here we perform an analysis of mass loss for AGB stars looking for quantitative correlations with their photometric properties. As a first step, we have collected a sample of 400 AGB stars of class C (carbon-rich). For these are available ground-based near-infrared observations. Moreover for 250 of these sources we derive the photometric properties in the mid-infrared (in the 10 μm band from space-borne observations) where cool dust normally dominates over the residual photospheric flux. We do this to verify, with a larger sample, the criteria previously suggested by Busso et al. (1996), Marengo et al. (1997), Marengo et al. (1999) and Corti et al. (2003) according to which colours computed through moderate-width filters between 8.5 and 12.5 μm are good indicators of the mass-loss rate and also permit an initial classification of the chemical properties of the circumstellar envelopes (Ciprini & Busso 2003). We aim to use the results of this study to build observationally-based simple relations that connect the strength of the stellar winds to the photometric properties and then to the chemical properties of AGB stars.

2. The sample

The sample of C-stars in this analysis comprises 249 sources and these have been divided in 5 classes, 1) Miras (35), 2) semiregulars (26), 3) irregulars (10), 4) post-AGB (20)and 5) stars of unknown nature (159). We made this division mainly following the indications of the Combined Great Catalogue of Variable Stars (GCVS).

3. Mass-loss rates

In this work we adopt the estimates of mass loss from the models of Loup et al. (1993 as also used by Winters et al. 2003) and from Olofsson et al. (1993 as used by Groenewegen et al. 1998). For sources with both estimates of mass loss we use the more general model of Loup et al. (1993) in which the assumptions made by Olofsson et al. (1993), of a constant value for the CO envelope and of an optically thick CO emission, are dropped. Our upgrade of mass-loss rates mainly concerns the use of improved and more recent measurements for the distance, provided through the Hipparcos mission or the period-luminosity relation given by Groenewegen & Whitelock (1996). A detailed exposition of the methods used to obtain our revised estimates of mass loss can be found in Guandalini et al. (2004).

4. Infrared photometric data

We have collected photometric data in the near-infrared filter centred at 2.2 μm (K) from the catalogues of the ground-based observations of 2MASS and DENIS. We form our database of mid-infrared observations by merging the measurements of 2 space-borne observatories, ISO (Infrared Space Observatory) and MSX (Midcourse Space eXperiment). For ISO we used the observations made by SWS (Short Wavelength Spectrometer). We have reduced these observations through a rebin of the spectra made over the response curves, available from the TIRCAM consortium (Persi et al. 1995), of standard mid-infrared photometric filters 1 μm wide centred at 8.8, 11.7 and 12.5 μm. Concerning the photometric fluxes given by MSX, we have reprocessed them by correlating the A and C filters used in this experiment with the mentioned filters at 8.8 and 12.5 μm. In this case the flux at 11.7 μm cannot be derived because MSX did not observe at this wavelength. A detailed presentation of all these procedures can be found in Guandalini et al. (2004).

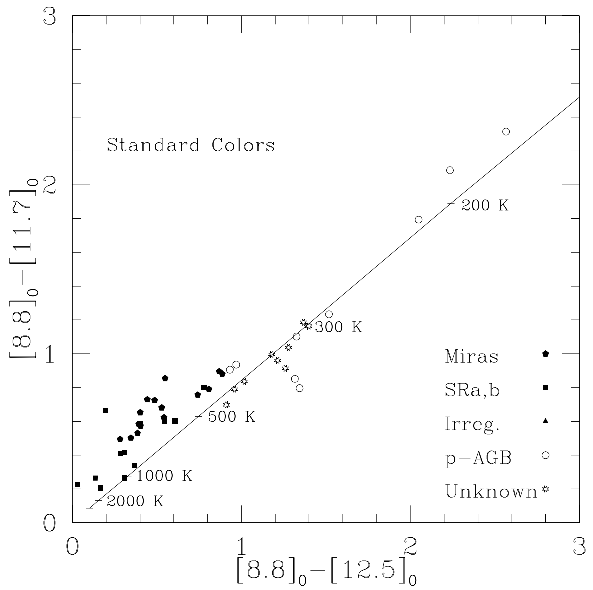

Fig. 1. A mid-infrared colour-colour diagram from only the ISO data.

5. Discussion

The colours that we adopt in this discussion correspond to standard mid-IR filters, like those mounted on the mid-infrared camera TIRCAM at the TIRGO telescope. Moreover we adopt the standard K filter in the near-IR.

In Figure 1 we obtain a colour-colour relation in the mid infrared for our sample of AGB stars and in this case we show that the different classes are quite clearly separated by their colours. In particular, a better distinction appears between semiregulars and Miras and the same is true for Miras and post-AGB objects. The unknown AGB stars tend to cover the region of Miras and Post-AGB stars. However in this case there are too few data for unknown stars.

In our analysis we also examine the correlation between mass loss and the [K]-[12] colour proposed by Le Bertre & Winters (1998). In our case we use the similar colour [K]-[12.5] because we have chosen a mid-infrared filter centred at 12.5 μm instead of that adopted by Le Bertre & Winters (1998). In Figure 2 we can see that the relation proposed by Le Bertre appears to be confirmed by our data but there is a rather wide dispersion and this can be especially seen for Miras and unknown stars.

In Figure 3 (left) we can see how a correlation between mass loss and mid-infrared colour exists, although the different classes of C stars generate some scatter. In particular some overlap between Miras and semiregulars can be seen, probably due to the uncertain limits between these two classes. Miras seem to dominate at higher mass-loss rates while semiregulars behave the same way for low mass-loss rates. It is interesting to note how post-AGB stars occupy a region characterized by high mass-loss rates and redder colours. This might be an indication that they are experiencing a superwind phase. They are rather close to the Mira stars. Moreover we can see that the unknown-type stars again tend to occupy the area of Miras and post-AGB stars, probably because there is a certain selection effect in IR catalogues toward the reddest and brightest sources. One last thing to note in this relation is that there is a clear correlation between mass loss and the mid-infrared colour: there is less dispersion of the data in this re-

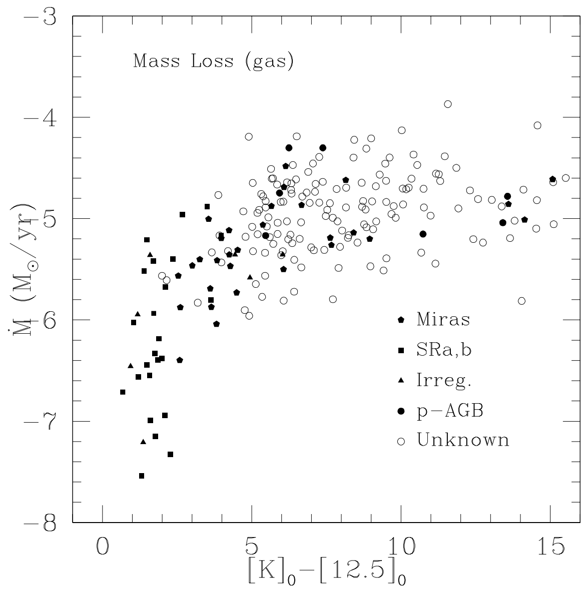

Fig. 2. Relation between mass loss and the colour [K]-[12.5], for both ISO and MSX data with the mid-infrared filter intertwined with both 2MASS and DENIS data for the near-infrared filter.

lation (Figure 3 left) than in the previous one (Figure 2). The correlation between mass loss and the [8.8]-[12.5] colour has a good level of accuracy and seems to discriminate the different type of stars in a better way than the [K]-[12.5] colour. More details on this can be found in Guandalini et al. (2004).

In Figure 3 (right) we obtain a relation between mass loss and mid-infrared luminosity in the filter centred at 12.5 μm for our sample of carbon-rich AGB stars. In this case there is a surprisingly strong correlation that confirms the good discrimination in the mid-infrared between the different types of C-rich AGB stars. Miras and post-AGB stars show a well defined behaviour while semiregulars and irregulars are more scattered. Moreover we can see that in this case too the unknown stars tend to be identified as possible Miras and post-AGB stars.

In Figure 4 (left) we can see a relation between luminosity and colour in the mid-infrared for our sample of carbon stars and in this case we show that there is overlap between Miras and semiregulars. However in the mid-infrared Miras are clearly more luminous. The unknown-type stars are also placed in the area of higher luminosity. This seems to be another indication that there is a selection effect in the infrared catalogues toward the reddest and brightest sources.

Finally in Figure 4 (right) is shown the relation between the luminosity in the filter [K] and the colour [K]-[12.5]. We can see that the luminosity in [K] seems to fade away for carbon stars of Mira, post-AGB and unknown type. This could be an indication of the presence of a thick circumstellar envelope for these classes. There are a few stars, particularly semiregulars and irregulars, that are more luminous than expected. These sources could perhaps be misclassified super-AGB stars, particularly when we also consider the uncertain classification of variability for semiregular and irregular stars.

6. Conclusions

In conclusion we have found that there is a clear correlation between mass-loss rates and the [8.8]-[12.5] colour for C-stars that has a good level of accuracy and can discriminate

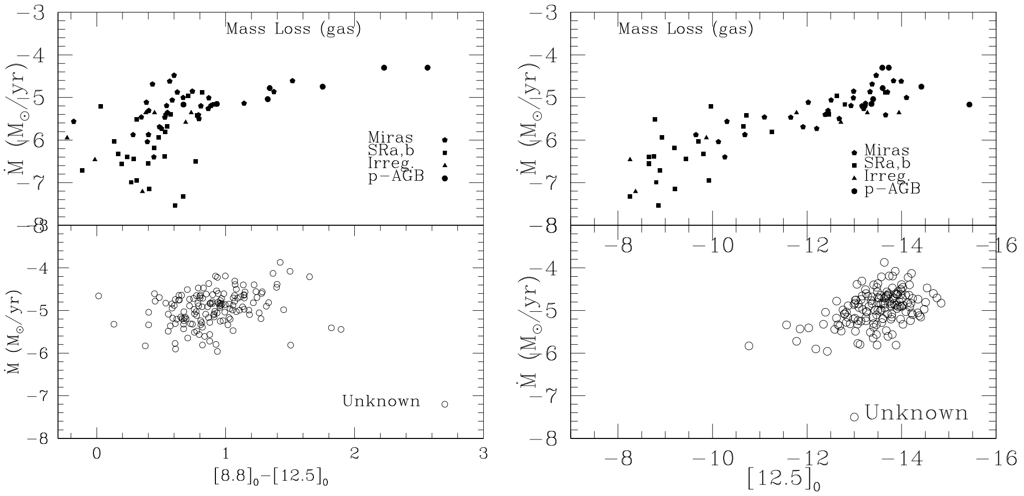

Fig. 3. Left panel: relation between mass loss and the mid infrared colour [8.8]-[12.5] for both ISO and MSX data. Right panel: relation between mass loss and mid-infrared luminosity (expressed in magnitudes) for both ISO and MSX data.

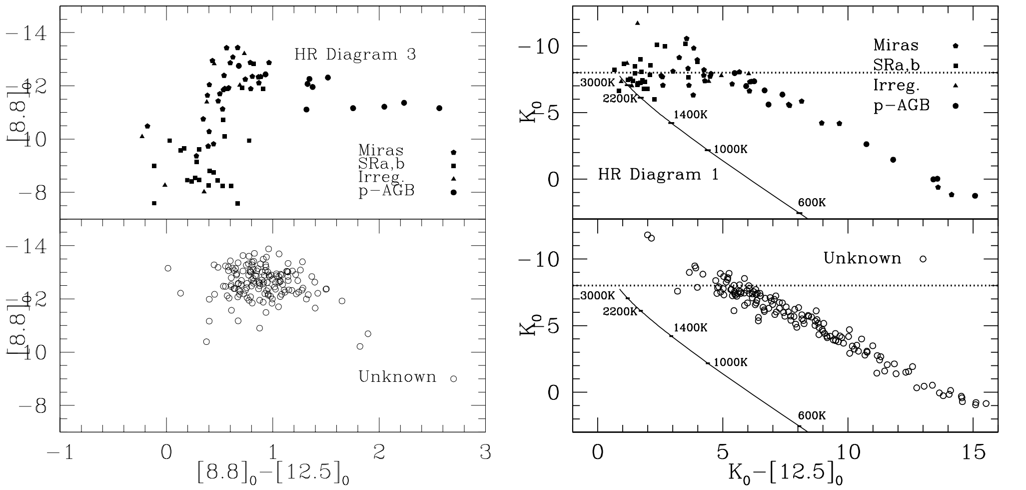

Fig. 4. Left panel: a mid-infrared luminosity–colour diagram (in magnitudes) for both ISO and MSX data. Right panel: a luminosity–colour diagram (in magnitudes) for both 2MASS and DENIS data for [K] and both ISO and MSX data for [12.5].

the different types of stars. The results also show that C-stars as a whole are quite a homogeneous class. For all the figures the different classes of C-rich AGB stars appear to be roughly discriminated by their different behaviour, especially the semiregulars, Miras and post-AGB objects. Moreover, from Figure 3 (right), we have found a surprisingly good correlation between mass-loss rates and mid-IR luminosity. Finally the unknown stars in our sample seem to be mainly attributable to the Mira and post-AGB star classes and are roughly placed in the region of higher luminosity in the mid-IR. Perhaps there is a certain selection effect in the infrared catalogues towards the reddest and brightest sources.

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