

Infrared photometry and evolution of mass-losing AGB stars (Research Note)

III. Mass loss rates of MS and S stars

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ABSTRACT

Context. The asymptotic giant branch (AGB) phase marks the end of the evolution for low- and intermediate-mass stars, which are fundamental contributors to the mass return to the interstellar medium and to the chemical evolution of galaxies. The detailed understanding of mass loss processes is hampered by the poor knowledge of the luminosities and distances of AGB stars.

Aims. In a series of papers we are trying to establish criteria permitting a more quantitative determination of luminosities for the various types of AGB stars, using the infrared (IR) fluxes as a basis. An updated compilation of the mass loss rates is also required, as it is crucial in our studies of the evolutionary properties of these stars. In this paper we concentrate our analysis on the study of the mass loss rates for a sample of galactic S stars.

Methods. We reanalyze the properties of the stellar winds for a sample of galactic MS, S, SC stars with reliable estimates of the distance on the basis of criteria previously determined. We then compare the resulting mass loss rates with those previously obtained for a sample of C-rich AGB stars.

Results. Stellar winds in S stars are on average less efficient than those of C-rich AGB stars of the same luminosity. Near-to-mid infrared colors appear to be crucial in our analysis. They show a good correlation with mass loss rates in particular for the Mira stars. We suggest that the relations between the rates of the stellar winds and both the near-to-mid infrared colors and the periods of variability improve the understanding of the late evolutionary stages of low mass stars and could be the origin of the relation between the rates of the stellar winds and the bolometric magnitudes.

Key words. stars: AGB and post-AGB – stars: mass-loss – stars: evolution – infrared: stars

1. Introduction

Stars of low and intermediate mass (between ~ 0.8 and $8.0 M_{\odot}$) terminate their “active” evolution with the asymptotic giant branch (hereafter AGB) phase through the alternate burning of two nuclear shells of H and He. Detailed reviews on the main nuclear and evolutionary properties of AGB stars are presented in [Busso et al. \(1999\)](#); [Herwig \(2005\)](#) and references therein.

On the AGB, S-type stars are identified spectroscopically through the detection of enhanced s-process abundances. This is found in two classes of objects called “extrinsic” and “intrinsic” S stars. A star showing s-process elements after phenomena of mass-transfer in a binary system is called extrinsic. An intrinsic AGB star on the other hand brings s-elements to the surface through repeated third dredge-up episodes along the AGB phase. Sometimes this is revealed only by the presence of technetium, while other signatures of s-elements remain hard to detect ([Uttenthaler et al. 2007](#)).

Important gaps in the knowledge of crucial physical parameters still undermine our understanding of the whole evolutionary sequence along the AGB: this is particularly so for luminosities and mass loss rates. AGB stars lose substantial amounts of matter, as their winds are the main contributors for the replenishment of the interstellar medium ([Sedlmayr 1994](#)). Various attempts were made to describe the mass loss mechanism (see

e.g. [Salpeter 1974](#); [Knapp & Morris 1985](#); [Wachter et al. 2002](#)). Unfortunately, quantitative knowledge of stellar winds is still poor, forcing the adoption of parametric treatments where observations (at infrared or radio wavelengths) and distance estimates play a crucial role.

Similar problems also affect the other crucial parameter: the bolometric luminosity. The difficult estimates of distance have a large influence also in this case. Moreover, the luminosities derived from full stellar evolutionary models are affected by many uncertainties in the choice of their parameters (see [Straniero et al. 2003](#), and references therein).

We are performing an analysis of ground-based and space-borne IR observations of AGB stars trying to reduce the uncertainties still present in the determination of those two parameters and in their relations with the others, thus obtaining improved evolutionary constraints on the AGB phase. In the first paper of this series ([Guandalini et al. 2006](#), hereafter referred to as “Paper I”) we analyzed a sample of C stars reconstructing their SEDs up to $45 \mu\text{m}$ on the basis of space-borne infrared observations from the ISO and MSX missions. We found evidence for a relatively high average C-star luminosity, suggesting that the so-called “C-star luminosity problem” ([Cohen et al. 1981](#)) could be simply an effect of poor estimates of the luminosity, due to insufficient knowledge of the emission at mid-infrared wavelengths. In the same paper the available mass loss rates and their

Table 1. Relevant data for our sample of S-MS stars.

Source Name	Spectral type	Var. type (GCVS)	Distance ^a (kpc)	Bol. Magnitudes ^b (Paper II)	Mass Loss (M _⊙ /yr)	v _e (km/s)	Ref. ^c	I. – E.	dust/gas ratio
S Cas	S3,4e–S5,8e	Mira	0.85 ^B	–5.71	1.02E–5	20.5	R	I	2.16E–4
W Aql	S3,9e–S6,9e	Mira	0.34 ^B	–5.44	4.24E–6	17.2	R	I	5.66E–4
R Cyg	S2,5,9e–S6,9e(Tc)	Mira	0.55 ^B	–5.42	9.04E–7	9.0	R	–	1.18E–3
chi Cyg	S6,2e–S10,4e/MSe	Mira	0.18 ^A	–5.39	8.69E–7	8.5	R	I	1.15E–4
T Cam	S4,7e–S8,5,8e	Mira	0.50 ^B	–5.22	8.91E–8	3.8	R	I	6.73E–4
R Lyn	S2,5,5e–S6,8e:	Mira	0.95 ^B	–5.19	3.90E–7	7.5	R	I	3.70E–4
R Gem	S2,9e–S8,9e(Tc)	Mira	0.66 ^B	–5.23	3.91E–7	4.5	R	I	2.67E–4
GI Lup	S7,8e	Mira	0.80 ^B	–	7.20E–7	10.0	R	I	7.56E–4
WY Cas	S6,5pe	Mira	0.97 ^B	–5.50	2.26E–6	13.5	R	I	1.56E–3
pi1 Gru	S5,7e	SRB	0.16 ^A	–5.75	2.57E–6	14.5	W	I	3.71E–4
ST Her	M6–7IIIaS	SRB	0.30 ^A	–5.64	1.30E–7	8.5	R	I	4.62E–3
T Cet	M5–6SIIe	SRC	0.27 ^A	–5.63	4.93E–8	5.5	R	I	2.08E–3
Y Lyn	M6SIIb–II	SRC	0.25 ^A	–5.33	2.17E–7	7.5	R	I	7.83E–4
R And	S3,5e–S8,8e/M7e	Mira	0.41 ^B	–5.19	1.09E–6	8.3	R	I	3.67E–4
W And	S6,1e–S9,2e/M4–M1	Mira	0.38 ^B	–5.27	2.79E–7	6.0	R	I	1.64E–3
RT Sco	S7,2/M6e–M7e	Mira	0.45 ^B	–5.44	1.01E–6	11.0	R	I	9.84E–4
RS Cnc	M6elb–II/S	SRC	0.14 ^A	–5.21	2.80E–7	6.8	L	I	6.78E–4
AA Cam	M5/S	LB	0.78 ^A	–	3.83E–8	3.4	R	I	2.10E–2
S Lyr	SCe	Mira	2.27 ^B	–5.50	5.44E–6	13.0	R	I	4.41E–4
TT Cen	CSe	Mira	1.39 ^B	–5.48	5.17E–6	20.0	R	–	2.01E–3
ST Sgr	C4,3e–S9,5e	Mira	0.76 ^B	–5.24	3.44E–7	6.0	R	I	1.51E–3
UY Cen	SC	SR	0.69 ^A	–6.05	1.70E–7	12.0	R	I	2.35E–3
VX Aql	C9,1p/M0ep	Mira	1.99 ^B	–5.87	3.51E–7	7.0	R	I	4.40E–3

Notes. ^(a) References for the distances are: A) the revised Hipparcos catalogue (van Leeuwen 2007); B) the period-luminosity methods for the O-rich stars as used in Paper II.

^(b) Bolometric Magnitudes are taken from Paper II.

^(c) References for the mass loss rates (updated with our choice for distances) and for the outflow velocities are quoted as: R stands for Ramstedt et al. (2009); W is for Winters et al. (2003); L for Loup et al. (1993).

correlation with infrared colors were also presented. In the second paper (Guandalini & Busso 2008, hereafter referred as Paper II) we extended the analysis to the MS and S giants, where the enhancement of carbon is more moderate than in C stars. We examined there the “luminosity problem” only; here we want to combine these results with an analysis of stellar winds, thanks to the recent analysis made by Ramstedt et al. (2009). This research will be completed in a forthcoming work where we will examine the luminosities and mass loss rates of galactic M-type AGB stars in relation to the available infrared observations.

In Sect. 2 we present the sample of studied stars and discuss the choices made in selecting and organizing the sources according to the quality of the available data. In Sect. 3 we analyze mass loss rates as functions of various parameters (infrared colors, periods of variability, bolometric luminosity) looking for quantitative relations that will be commented upon keeping in mind the results of Paper II. Finally, in Sect. 4 some preliminary conclusions are drawn.

2. The sample

In the selection of the sample we started from the compilation of galactic S-type AGB sources presented in Paper II. We chose to use only sources for which reliable estimates of the distance are available, therefore only sub-samples A–C from that work were considered (the only exception is in Fig. 3). We searched these sub-samples for sources with reliable mass loss rates obtained through procedures similar to those suggested by Knapp & Morris (1985). The adopted estimates were taken from different sources in the literature and have been all updated with

new estimates of the distances. All these sources have, as a basis, radio observations of the CO lines. Whenever possible, we used the data from Ramstedt et al. (2006, 2009), obtained with a procedure involving the radiative transfer model presented in Schöier & Olofsson (2001); Olofsson et al. (2002); Ramstedt et al. (2008). As a second option, we selected the expressions from Loup et al. (1993) applied also by Winters et al. (2003). In this case a system of two equations permits us to evaluate both the mass loss rate and the CO photo-dissociation radius (see the references given above for more details). The results are listed in Table 1.

In the table the stars are divided in three subgroups separated with horizontal lines. In the first subgroup we can see all the sources of the spectral type S-MS. The second is made of four SC stars. In the last subgroup we have a single source with an uncertain classification, variously estimated as being O-rich or C-rich. For this last star (VX Aql) the data in the table are derived by considering it as being O-rich. The variability types have been taken from the GCVS catalogue (Samus et al. 2004), while the distances are taken from Paper II. These estimates were derived in two ways: a) from the revised Hipparcos parallaxes (van Leeuwen 2007); b) from the period-luminosity relations for O-rich AGBs (see the Appendix in Paper II for a detailed description).

Finally, we give a suggestion for the nature of the stars in our sample (either intrinsic or extrinsic). These indications come from Paper II, where we describe how they were obtained. (originally, they derive from Van Eck et al. 2000; Yang et al. 2006). Apart from a few uncertain cases, the sources considered in this case are all intrinsic AGB stars.

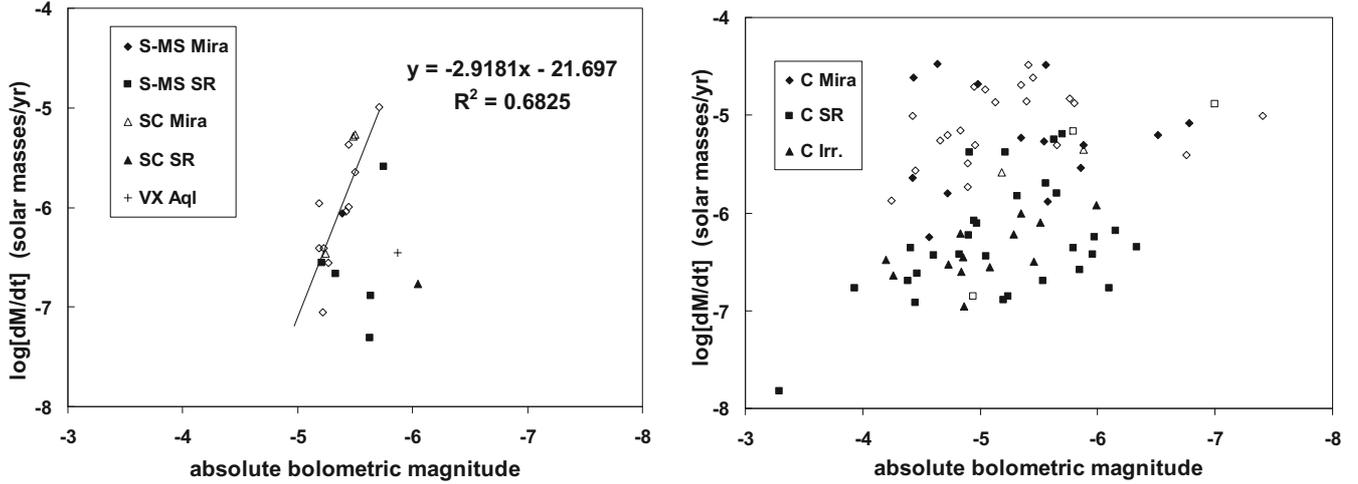


Fig. 1. *Left panel:* the mass loss rates for S-type stars plotted as a function of their absolute bolometric magnitudes. Here and in the other plots of Fig. 2: 1) rhombs and squares are Mira and Semiregular S and MS stars respectively; 2) full symbols indicate sources with distance estimates derived from the Hipparcos parallaxes; empty ones are Miras whose distance has been estimated with the period-luminosity relations; 3) empty triangles are SC Miras with the distances calculated through the period-luminosity relations; the unique full triangle is a SC Semiregular with the distance obtained with the Hipparcos parallax. The estimates of the bolometric magnitudes come from Paper II. The least-square fit considers only S and MS Miras. *Right panel:* the mass loss rates for C-rich stars plotted as a function of absolute bolometric magnitudes (data from Paper I). Sources shown with a full symbol are from Table 1 of Paper I, while sources indicated with an empty symbol are from Table 2 of the same paper.

3. Mass loss rates and other physical parameters

We now compare the mass loss rates presented in Table 1 with other relevant physical parameters. We apply the results published in Paper II and Paper I.

In Fig. 1 (left panel) we examine mass loss rates and absolute bolometric magnitudes. The luminosities were calculated in Paper II with the bolometric corrections presented there and obtained by studying the spectral energy distributions of available S-type stars up to $45 \mu\text{m}$. Mira sources of S-MS type are located inside a relatively narrow region. For these stars we can see that the mass loss rates increase when the luminosity increases. If we make a linear least-square fit (see Fig. 1), we obtain a correlation coefficient of $R^2 = 0.6825$. We have to remind the reader, as a word of caution, that the sample used is rather small, which may lead to some selection biases. However, if we look at the whole sample of ~ 600 sources from Paper II, we recall that those examined here are a representative sub-sample for Mira S-MS stars. Moreover, they are all part of the best studied sub-samples from Paper II. The SC sources are located in the same region of the plot, but we decided to not study them together with S and MS stars because of their peculiar chemical properties in the circumstellar envelopes, like the presence of compounds containing carbon. Mass loss rates for S stars reach values of almost $10^{-5} M_{\odot}/\text{yr}$. Although the highest values observed for C-rich stars are not reached (see Fig. 1, right panel and Paper I), nonetheless the rates we find are high enough, and also associated with high values of the luminosity, to again suggest that the evolutionary scheme MS–S–SC–C should not be taken as granted. The most luminous S-type stars with the strongest stellar winds might be already close to the AGB end, and would probably never become C-rich (see Paper II for more details on this topic).

As we compare the two panels of Fig. 1 we observe that the range of luminosities for this sample of S-MS stars is very narrow, around -5 . Instead, C stars from Paper I span a much wider range of bolometric luminosities, and, if considered together, they do not show a clear correlation between absolute

bolometric magnitudes and mass loss rates. However, we recall that in Paper I a revision of the parallaxes from the Hipparcos original release (Bergeat & Chevallier 2005) was used instead of the completely new release (van Leeuwen 2007) adopted here. Moreover, the crucial work from Whitelock et al. (2006) regarding the period-luminosity relations for Galactic Carbon Miras was published a few months after Paper I and its results could not be integrated in our previous work. The large scatter of C-rich sources observed in the right panel could be caused by poorer estimates of their distances. Finally, if we consider our entire sample of S-type stars from Paper II, we do not find sources totally obscured by dust. Yet some of them have a considerable IR excess: for instance, S Cas (observed by ISO-SWS) has the peak of luminosity in its spectral energy distribution at around $10 \mu\text{m}$. The same existence of totally-obscured S stars is doubtful, as they are on average of smaller mass than C stars (see Paper II) and might therefore lose mass at lower rates and cross the final superwind stage only briefly.

The estimates of absolute bolometric magnitudes and mass loss rates are not always independent. They are so only if the distance is derived from Hipparcos parallaxes, but unfortunately a Hipparcos distance is available only for one Mira of our sample. Where the distance is derived from the period-luminosity relations, the absolute luminosity and rates of the stellar winds are necessarily correlated. Indeed, the distance is derived from the apparent bolometric magnitude (obtained thanks to the bolometric corrections presented in Paper II) and the period-luminosity relations. This distance is then used to re-scale mass loss rates found in the literature.

We can try to disentangle the problem of the independence between these two parameters by checking the behavior of the mass loss rates if compared with parameters that are distance-independent: variability period and infrared colors.

1) *The period.* If we compare the mass loss rates with the variability periods (taken from Paper II) we find again a correlation between S-MS Miras and a coefficient of correlation for a linear least-square fit $R^2 = 0.6777$. This is obviously expected, because almost all the sources involved in the fit have the

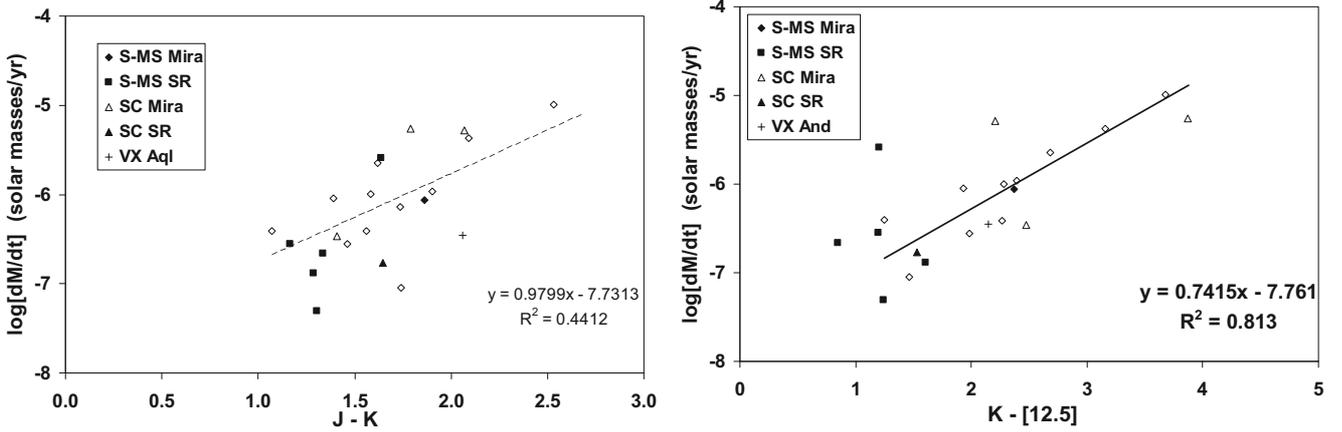


Fig. 2. Relations linking the mass loss rates of S-type AGB sources to the IR colors. The photometric data have been taken from Paper II (where a detailed analysis can be found) and come respectively from 2MASS for the J and K bands and from ISO-SWS, MSX and IRAS-LRS for the $[12.5]$ band. Here and elsewhere “ K ” is a compact notation for the 2MASS filter K_s (K -short). More details about the two plots can be found in the text.

distances derived from period-luminosity relations. The crucial thing that should be pointed out here is that for S-MS Mira stars there are signs of a correlation between mass loss rates and periods of variability. One could wonder if the same thing happens also for Semiregular sources at shorter periods, but in our case the sample is too small and scattered to give reliable indications.

2) *The color.* Near-to-mid infrared colors are crucial to study the main parameters of AGB stars: for both C-rich (Paper I) and S-type (Paper II) stars our best bolometric corrections were obtained with these colors. Therefore, the bolometric magnitudes depend on them. We examine now Fig. 2. It shows two plots in which the mass loss rates are compared with two different colors: a near-IR color ($J - K$) in the left panel and a near-to-mid IR one ($K - [12.5]$) in the right panel. This figure can give us important informations: it confirms the argument made until now and offers us indications about which wavelengths are more useful in the search for relations between the stellar winds and the photometric colors (and the temperature).

The $K - [12.5]$ color adopted in the right panel of Fig. 2 was also one of the baselines used to derive bolometric corrections for S stars in Paper II. Therefore this color is as important as the variability period to infer absolute luminosities (and distances). S-MS Mira stars show a well-defined relation between mass loss rates and both mentioned parameters. In the right panel of Fig. 2 we have added a least-square fit based on these sources. The results are indicated in the plot. The tendency to have stronger mass loss rates for redder sources is clear, and the linear relation has a good reliability ($R^2 = 0.813$). Mass loss rates for S-MS Miras show again a clear correlation with another parameter (the near-to-mid IR color) calculated in an independent way. We caution the reader again that Mira sources show some variability also in the $10 \mu\text{m}$ region (Busso et al. 2007), and this could affect our results.

We can also examine the different results that we obtained in Fig. 2 if we use a near-IR color ($J - K$) in the left panel or a near-to-mid infrared color ($K - [12.5]$) in the right panel) as a function of the mass loss rates. In the left panel ($J - K$ color), the Miras seem to show a relation, but the data are quite scattered; instead, in the right panel ($K - [12.5]$ color) the least-square line that we computed for the Mira S-MS sources has a much better coefficient of correlation than in the previous case. On the other hand, Semiregulars are very scattered in both plots,

without signs of clear patterns in their behavior. In Paper I we pointed out that the entity of the overlapping region between Miras and Semiregulars could vary with the colors in abscissa. In this case Miras and Semiregulars are again quite well separated in both plots, but this effect is best enhanced if a near-to-mid infrared color is adopted.

The pattern between mass loss rates and luminosities shown in Fig. 1 originates from the relations with two independent parameters: periods of variability and near-to-mid infrared colors (Fig. 2, right panel). This pattern should not be contaminated by errors in the selection criteria. Moreover, we can examine the plots in Fig. 3 where these two parameters (the colors $J - K$ and $K - [12.5]$ and the periods of variability) are compared. In this figure, as these parameters are all independent from the distance of the sources, we consider all the sources from Paper II that have both an estimate of the period and reliable mid-IR observations (see Paper II). From the plots we see that, if associated with a well-chosen color, the period of variability separates the Miras population in the best way from the Semiregulars. Moreover (left panel), when we use a near-to-mid infrared color the Mira subgroup seems to show a correlation between $K - [12.5]$ and the period of variability. Unfortunately, in this case the data for Miras are more scattered (the coefficient of correlation of a linear least-square fit for full rhombs and squares is $R^2 = 0.346$), nonetheless, there is the hint of a pattern, because sources with longer periods are on average redder. We have to remember that the classification of variables between Miras and Semiregulars does not have a physical basis: there are lot of sources in a “grey zone” that could be (and have been) classified in both ways depending on the light-curves used. Looking at the right panel of Fig. 3, we see that again a plot with pure near-IR colors has the data more scattered than a similar plot with near-to-mid infrared colors. This underlines the importance of considering both the cool, dusty, circumstellar envelope (mid-IR) and the warmer regions near the central star (near-IR) in a photometric analysis for these sources. Colors derived only from near-infrared fluxes are not sensitive enough (and do not have a long enough baseline) to give a good description of the relations between colors and other crucial physical parameters like periods and mass loss rates.

Until now we have considered only the mass loss rates from the gaseous part of the circumstellar envelopes. Completing this

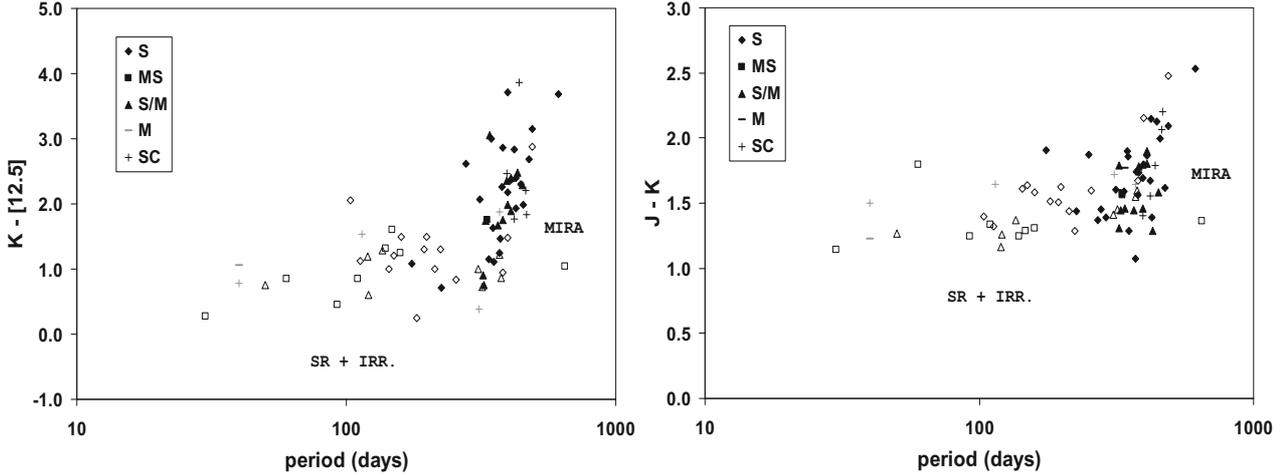


Fig. 3. A near-to-mid infrared color (*left panel*) and a near-infrared one (*right panel*) plotted as a function of period of variability. In this case full dots are Miras, while empty dots are Semiregulars and Irregulars. Sources are from the Paper II sample. In both panels the regions of the Miras and of the Semiregulars/Irregulars are indicated. Photometric data have been taken from Paper II, periods come from the GCVS catalogue (Samus et al. 2004).

analysis requires a similar study on the mass loss rates for the dust component and an estimate of the dust-to-gas ratios. We have checked the dust mass loss rates from Ramstedt et al. (2009) and Groenewegen & de Jong (1998) and have calculated the dust-to-gas ratios from them and from our estimates of gas mass loss rates. The ratios are reported in the last column of Table 1. They are on average lower than the ones observed in the interstellar medium. This raises doubts on their reliability (and particularly on the dust mass loss rates), because AGB envelopes should be among the sites where dust is created. Further researches should be performed on this topic.

Outflow velocities have also been included in Table 1. They can be measured from the CO profiles used to estimate the mass loss rates for gas. Zuckerman & Dick (1989) in their Fig. 3 observed a correlation between outflow velocities and absolute values of the galactic latitude $|b|$ for a sample of C-rich sources: the ones with a higher outflow velocity ($>20 \text{ km s}^{-1}$) have a low value of $|b|$ (<20 degrees), while the ones with a high value of $|b|$ have a low outflow velocity. This property, if confirmed, could be linked to the age and mass of the stars, giving us interesting hints on their evolutionary properties. In Fig. 4 we present a similar plot made with our sample of S-type stars. The same relation between outflow velocity and galactic latitude $|b|$ appears also in this case. Moreover, the data in Fig. 4 suggest that the absence of really high-mass-loss stars in our sample seems to be linked with the absence of sources with a high outflow velocity. This finding, if linked with their quite high values of luminosity and mass loss rate (even if the highest values of the C-rich stars of Paper I are not reached), confirms that S-type stars in our Galaxy have masses slightly lower than those of carbon sources. A good fraction of them could evolve along the AGB phase without becoming C-rich (see Paper II for more details).

4. Conclusions

We integrated the analysis of MS-S-SC galactic AGB stars, started in Paper II, by examining the mass loss rates for a sample of sources with reliable estimates of the distance. Selection criteria for the estimates of the stellar winds were discussed and the chosen rates were updated according to new measurements of distances.

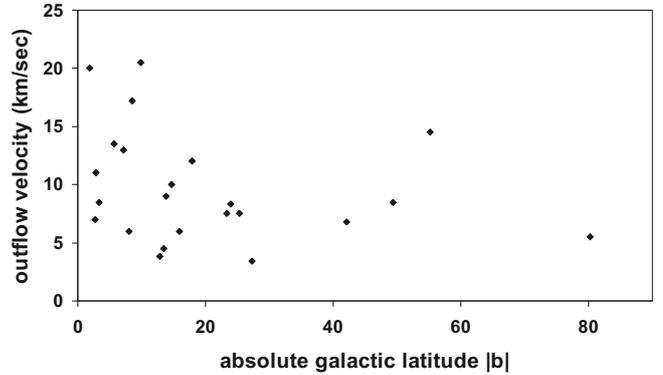


Fig. 4. Plot of the circumstellar outflow velocity v_e compared with the absolute value of the galactic latitude $|b|$.

The figures shown in our analysis suggest the existence of a correlation between mass loss rates and absolute bolometric magnitudes for Mira variables (Fig. 1). In the past the existence of such a correlation was doubtful (see e.g. van Loon et al. 1999a,b, 2005, and references therein) but an accurate selection of the sample seems to provide enough evidence (for Mira-type sources). It appears to be linked with and to be originated from relations that the rates of the stellar winds have with two physical parameters that are independent from the distance: the period of variability and the $K - [12.5]$ color (Fig. 2, right panel).

These two parameters are fundamental tools for the two methods adopted to estimate the absolute bolometric luminosities in Paper II: the period-luminosity relations and the bolometric corrections.

Figure 2 shows a strong linear relation between the mass loss rates and the $K - [12.5]$ color for Mira sources. This relation could become of the utmost importance in the future, because, through its application, we could obtain reliable estimates of the mass loss rates directly from a photometric color. In this way the rates of the stellar winds for Mira sources could be estimated without the need of radio observations of the CO lines (or other independent observations) and/or estimates of the distance. Near-infrared colors (i.e. $J - K$) seem to be less useful than the near-to-mid infrared ones.

Finally, if we directly compare the period of variability with the near-to-mid infrared color $K - [12.5]$, we find that this is the best color index to separate Miras and Semiregulars. Moreover, a relation might exist between these two parameters for Miras, but the scatter in our sample is too large to draw final conclusions on it.

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