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On the relations between infrared colors and mass loss rates for Mira stars*

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Abstract. A relation between the near-infrared color K-L' and the mass loss rate, $\dot{M}$, is found for nearby ($d < 2$ kpc) oxygen-rich Mira stars. This relation is qualitatively similar to the one for carbon stars, but quantitatively different.

Red supergiants, and maybe long-period OH/IR stars, do not follow this relation. This could point to a different process for mass loss in these more luminous sources.

Relations between the J-K and K-12 indices and $\dot{M}$ are also found, but present more scatter. Nevertheless, they could be useful in the context of the near-infrared surveys, DENIS and 2MASS, which are in progress. Correlations between the IRAS colors and $\dot{M}$ are found to be loose.

These relations are investigated on the basis of hydrodynamical wind models. For carbon-rich Miras, there is a partial agreement (within a factor 2) between the time dependent models and the observations. For the same infrared color, the stationary models require a much higher luminosity (typically a factor 3) and give larger mass loss rates. Although no oxygen-rich consistent model is presently available, it seems that the stationary case could apply to M supergiants.

Our results support the idea that the mass loss from Mira stars results from the combined actions of i) dissipation of shock wave momentum leading to a density enhancement in the atmosphere and triggering the onset of dust condensation, and ii) radiation pressure on the dust grains which actually initiates the outflow and accelerates the wind to its terminal velocity. We suggest that some supergiant winds, by contrast, could be purely dust-driven.

Key words: stars: carbon – stars: circumstellar matter – stars: late-type – stars: mass loss – stars: AGB and post-AGB – infrared: stars

1. Introduction

Cool stars are sometimes surrounded by a circumstellar shell made of gas and dust. Most of these mass losing stars are Red Giants on the Asymptotic Giant Branch (AGB), but some are Red Supergiants (RSG). Depending on the value of the carbon-to-oxygen (C/O) abundance ratio they fall into 2 classes: carbon-rich (C/O > 1) or oxygen-rich (C/O < 1). They are generally variable. Those which present a well defined period and a relatively large amplitude (at least 2.5 mag. in the visual range) are catalogued as Miras. The others are classified as Semi-Regular variables or as Irregular. These distinctions are somewhat artificial, and sometimes the classification is arbitrary. For the Miras, there is a relation between the period and the luminosity (Whitelock et al. 1991).

The carbon-rich mass losing stars are on the AGB and the Miras have periods in the range 150-700 days. The oxygen-rich stars are on the AGB or on the RSG branch. The Miras have in general periods in the same range as carbon stars, but some extreme sources (OH/IR) have periods up to 2000 days. The evolutionary status of OH/IR sources is unclear: they may be AGB stars or RSGs.

AGB stars contribute probably to more than 70 % of the replenishment of the Interstellar Medium (ISM) in the Solar Neighborhood (Sedlmayr 1994). It would be important to strengthen this result and to investigate the impact of AGB stars in other galactic environments such as the Bulge or the Halo, and in other galaxies. Recently, it has been shown that there is a good correlation between near-infrared color indices and mass loss rates for carbon stars (Le Bertre 1997, Paper I). This relation is important because, as it is distance-independent, it provides an easy-to-use tool to measure directly mass loss rates. On the other hand, for O-rich stars the prospects are not as good. Le Sidaner & Le Bertre (1996) find correlations, but with large scatter (their Figs. 3 & 4).

The goal of the present work is to reanalyse the correlations between infrared colors and mass loss rates for O-rich stars and to investigate the significance of such relations on the mass loss processes in cool stars.

2. Mass loss rates of O-rich Miras

Le Sidaner & Le Bertre (1996, Paper II) have studied a sample of 27 O-rich sources which have been well observed with ground-based photometry (Le Bertre 1993) and for which IRAS data are also available (IRAS Science Team 1988). Their sample contains Miras and supergiants with optical counterparts, and type II OH/IR sources. The spectra were interpreted in terms

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* Based on observations obtained at ESO, La Silla, Chile

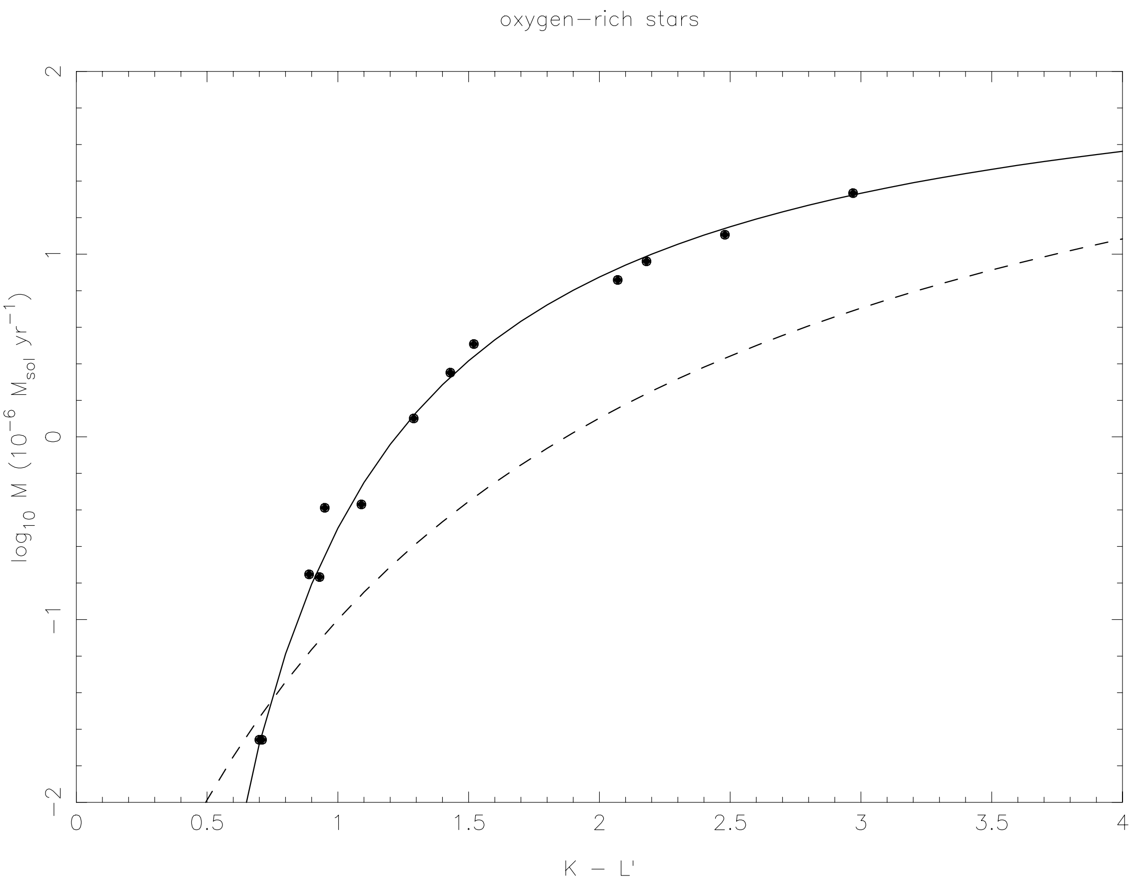

Fig. 1. K-L' versus $\dot{M}$ for O-rich Miras. The solid line represents Eq. (1) in Sect. 3.1. The dashed line is the fit obtained for carbon Miras (Paper I)

Table 1. Distances and mass loss rates

name	distance parsecs	mass loss rate 10^{-6} $M_\odot$ yr^{-1}
SY Scl	1450	0.18
IRAS 00193	1680	9.10
IRC +10011	650	21.50
IRC -30023	610	0.41
NML Tau	245	3.20
S Col	695	0.02
IRC -30050	1000	0.02
IRC -20197	1200	7.20
IRC -20540	1300	2.25
IRC -10529	800	12.80
IRAS 22231	1650	1.25
IRC +10523	780	0.43
R Aqr	215	0.17

of a radiative transfer model applied for each object at several different phases of the variability (Le Sidaner & Le Bertre, 1993, Paper III). Several physical quantities were derived from this modeling and among them the mass loss rates, $\dot{M}$. This approach requires the knowledge of parameters such as the distance and the outflow velocity (relation 2 in Paper III). A fair estimate of the distance can be obtained for the Miras on the basis of the Period-Luminosity relationship followed by these objects. The estimates for supergiants and OH/IR sources were derived from the stellar radial velocity and assuming that these objects follow the galactic rotation. They are probably more uncertain. The outflow velocities were estimated from the separation of the OH maser peaks or from the width of the CO (J = 2-1/1-0) molecular lines.

Le Sidaner & Le Bertre (1996) find correlations between color indices and $\dot{M}$ which appear loose as compared to those found for carbon-rich sources (Paper I). Several reasons can be suggested: their sample is not homogeneous with a mixture of AGB stars and RSGs, there are large uncertainties on the distances, the interstellar extinction may affect the colors, their modeling is inadequate for mass loss evaluation, the effect is real and O-rich and C-rich sources behave differently, etc.

We have considered the 3 first possibilities and extracted from the sample the genuine AGB stars which show a Mira-type variability. For these sources, a good estimation of the distances can be derived using the Period-Luminosity relation for O-rich Miras of Feast (1996):

$$M_{bol} = -3.00 \log_{10} P + 2.78$$

Recently, van Leeuwen et al. (1997) have discussed the zero-point of the Period-Luminosity relation for O-rich Miras on the basis of HIPPARCOS data. They found for the LMC mean

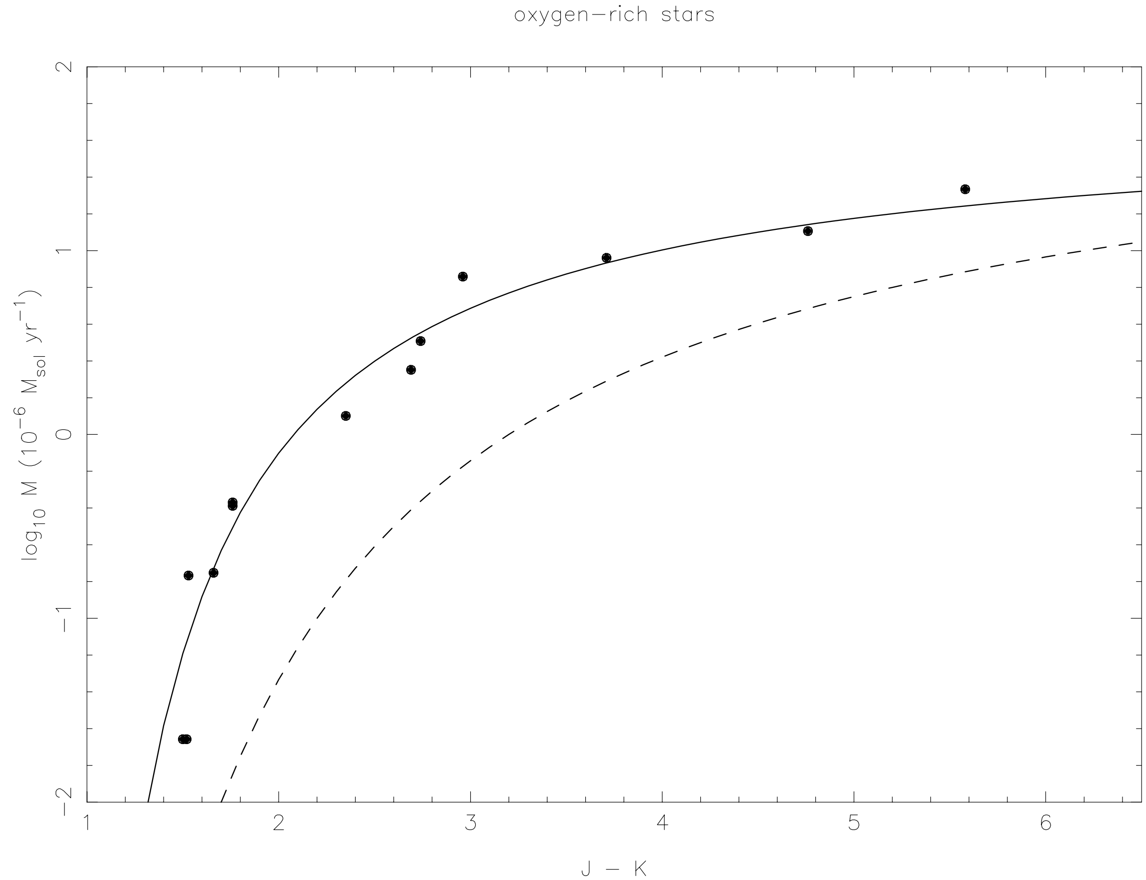

Fig. 2. J-K versus $\dot{\rm M}$ for O-rich Miras. The solid line represents Eq. (2) in Sect. 3.2. The dashed line is the fit obtained for carbon Miras (Paper I)

distance modulus a most likely value of 18.54, instead of 18.57 used by Feast (1996). The two values agree quite well and, at this level, the difference is not meaningful. Also, the OH/IR sources which are found at large distances in the Galactic Plane have been eliminated from the sample.

The resulting set of bona-fide O-rich Miras is given in Table 1. The distances have been revised using the Period-Luminosity relation of Feast (1996) and the bolometric luminosities derived in Paper II. The mass loss rates have also been revised in function of these newly determined distances. As for carbon-rich Miras (Paper I, Fig. 15), we find only a coarse correlation between period and mass loss rate.

These evaluations can be compared with those obtained using CO data. From Loup et al. (1993), IRC +10011, NML Tau and IRC -10529 have mass loss rates of, resp., 29.0, 3.5 and 21.0 10^{-6} $M_\odot$ yr^{-1}. Both types of evaluations compare well and there is no reason to suspect some inadequacy in the Paper II modeling.

3. Relation between infrared colors and mass loss rate

3.1. K-L' versus $\dot{\rm M}$ for O-rich stars

The K-L' color as a function of mass loss rate is presented in Fig. 1. There is a clear correlation which can be represented by the relation:

$$\log_{10} \dot{\rm M} = -2.75/(\text{K-L'}) + 2.25 \qquad (1)$$

with $\dot{\rm M}$ in 10^{-6} $M_\odot$ yr^{-1} and $0.7 \leq$ K-L' ≤ 3.0. The relation has the same shape as the one for carbon stars (dashed line in Fig. 1), but is numerically different.

The correlation was not seen so well in Paper II because it was confused by RSGs and OH/IR stars. It is clear that the RSGs with optical counterparts do not follow it. The situation for OH/IR stars is less clear. Their distances are uncertain and, also, their spectra may be affected by interstellar extinction in an amount which is difficult to estimate. Furthermore, some of these sources could be supergiants (Le Bertre 1991; Heger et al. 1997). Lépine et al. (1995) find a correlation between K-L' and $\dot{\rm M}$ for OH/IR stars, but, in the range of K-L' explored by us, their relation is much flatter than the one we find for O-rich Miras.

3.2. J-K versus $\dot{\rm M}$ for O-rich stars

The J-K color is linked similarly to $\dot{\rm M}$ (Fig. 2). The correlation can also be represented by a relation analogous to the one for carbon stars:

$$\log_{10} \dot{\rm M} = -2.5/(\text{J-K} - 0.65) + 1.75 \qquad (2)$$

with $1.6 \leq$ J-K ≤ 6.0.

The correlation is not as good as with K-L'. Nevertheless it presents some interest because there are 2 surveys of the sky

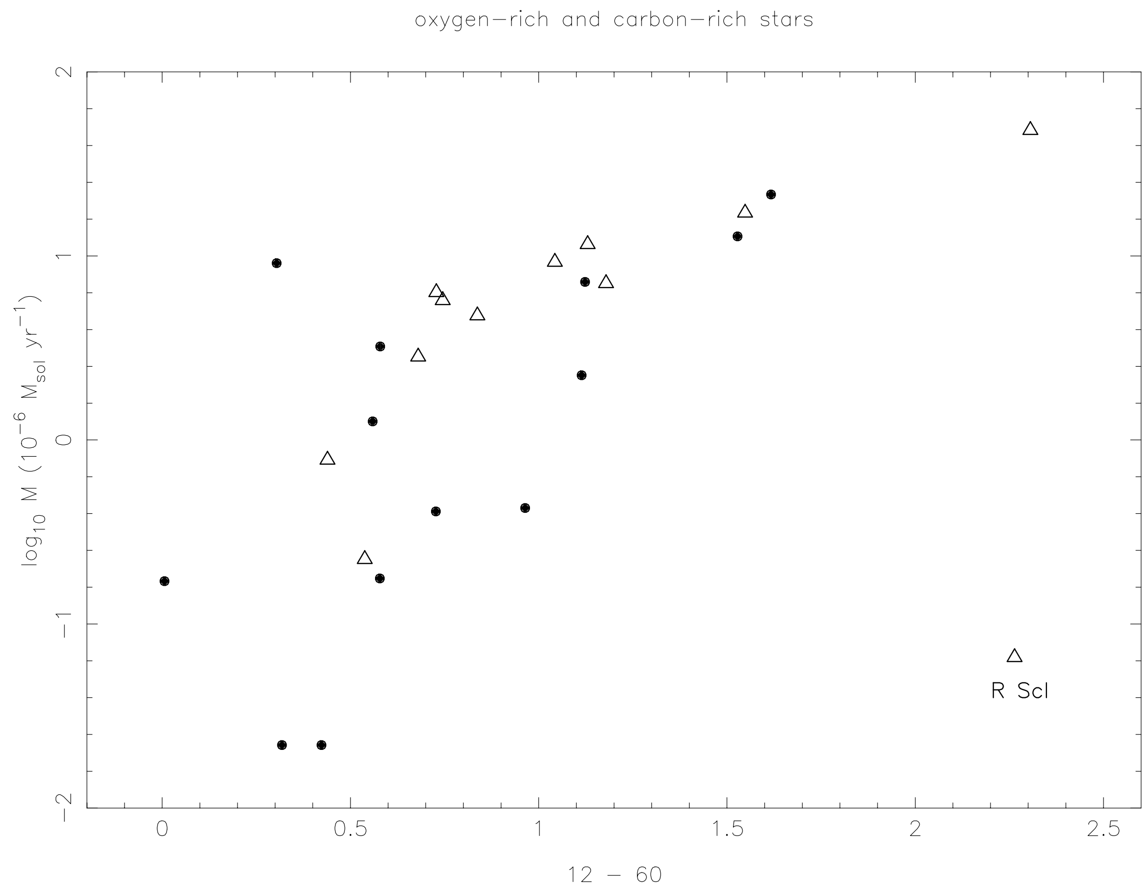

Fig. 3. 12-60 versus $\dot{M}$ for O-rich Miras (dots) and for C-rich Miras (triangles)

at near-infrared wavelengths ($\lambda \leq 2.5\,\mu$m) which are presently in progress. The DENIS programme is covering the Southern Sky in the bands I (0.8 μm), J (1.25 μm) and K_s (2.15 μm). The 2MASS programme is covering the whole sky in J, H (1.65 μm) and K_s. Both are sensitive enough to detect all AGB stars in the Galaxy and most in the Magellanic Clouds. The J-K_s index which is common to both projects is therefore of practical interest. It should not behave very differently from the J-K index.

3.3. Combinations with IRAS data

Most of the mass losing AGB stars in the Galaxy, up to the distance of the Galactic Center, should have been detected by the IRAS satellite. Unfortunately, there is no clear trend between any IRAS color and mass loss rate. As an example, the IRAS 12-60 color is presented as a function of mass loss rate in Fig. 3. No correlation can be seen, neither for O-rich stars (dots) nor for C-rich ones (triangles).

On the other hand, combining near-infrared data with IRAS data appears more promising. The K-12 index is presented as a function of $\dot{M}$ for oxygen-rich Miras in Fig. 4 and for carbon Miras in Fig. 5. The IRAS magnitudes are taken directly from IRAS Science Team (1988) and have not been color-corrected. For both categories of objects, there is a clear trend which can be represented for O-rich stars by:

$$\log_{10} \dot{M} = -55./(\mathrm{K}\text{-}12 + 5.) + 6. \qquad (3)$$

with 2. $\leq$ K-12 $\leq$ 7., and for C-rich stars by:

$$\log_{10} \dot{M} = -24./(\mathrm{K}\text{-}12 + 4.) + 3. \qquad (4)$$

with 2. $\leq$ K-12 $\leq$ 14.

Again in the context of the on-going near-infrared surveys, these relations can be useful for evaluating the mass loss rates of AGB stars which have been detected by IRAS in at least one band. The correlation between K-12 and $\dot{M}$ for O-rich stars was first noted by Whitelock et al. (1994). Their results are consistent with Eq. (3).

4. Comments

The infrared colors of mass losing Miras are clearly correlated with the mass loss rates $\dot{M}$. As the colors are distance independent, the color-$\dot{M}$ relations can be very useful for evaluating mass loss rates. However these relations depend on spectral type (O-rich/C-rich) and it is necessary to separate the 2 kinds of sources. Fortunately this can be done easily by using infrared color diagrams (Epchtein et al. 1987). In the context of the on-going near-infrared surveys, DENIS and 2MASS, Le Bertre et al. (1994) note that O-rich and C-rich stars separate clearly in a (J-K, 12-25) diagram.

This separation has been shown to be the effect of the different optical properties of the dust condensing in O-rich (siliceous grain) and C-rich (carbonaceous grain) environments. It is rea-

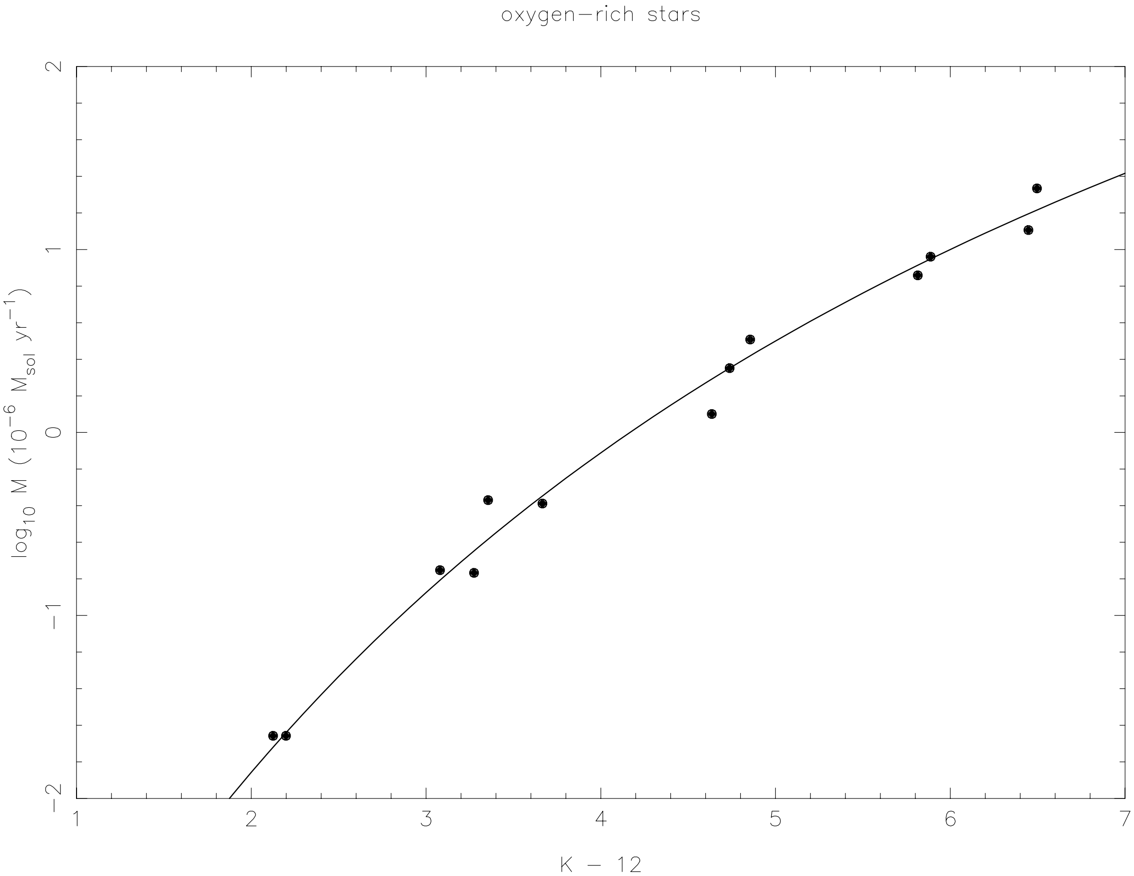

Fig. 4. K-12 versus $\dot{M}$ for O-rich Miras. The solid line represents Eq. (3) in Sect. 3.3

sonable to assume that this effect is also at the origin of the difference in the color-$\dot{M}$ relations for C-rich and O-rich Miras.

However, Habing et al. (1994) argue that the metallicity affects the dust to gas ratio and the outflow velocity from evolved stars. The mass loss rate is related to the optical depth (hence the $\sim$ colors) through these two quantities (see, e.g. relation 2 in Paper III). Therefore, it is possible that the color-$\dot{M}$ relations depend also on metallicity and are different in other environments such as the Galactic Bulge or the Magellanic Clouds. Also in this context, it is worth noting that Alvarez et al. (1997) argue that nearby O-rich Miras ($d < 2$ kpc) separate into at least 2 groups of different initial mass, age and metallicity with stars belonging either to the disk (their Group 1) or to the halo (their Group 3). From their analysis of the period distributions, it seems that our sample contains mainly stars of Group 1.

Relations between colors and circumstellar shell optical depth have been found for O-rich sources (Bedijn 1987, Paper II) as well as for C-rich sources (Le Bertre 1988). There are also relations between the period and the luminosity for Miras. However, we do not find a clear relation between periods and $\dot{M}$ (Sect. 2 & Fig. 15 in Paper I) so that the relations between colors and $\dot{M}$ are not easy to understand. In this context, it appears necessary to resort to models connecting the properties of the stellar atmospheres and of the circumstellar shells.

The absence of correlation between $\dot{M}$ and IRAS colors is puzzling. It is not well understood in the framework of circumstellar shell models such as those of Bedijn (1987). Perhaps the distributions of matter at larger distances from the central stars are no longer spherically symmetric or the mass loss rates are variable on timescale $\leq 10^4$ years. Indeed, in the case of R Scl (see Fig. 3), it is well established that the mass loss rate has undergone strong variations during the last 10^4 years (Olofsson et al. 1996). However, we will see further below that the absence of correlation between $\dot{M}$ and IRAS colors has a more profound signification.

The correlations between infrared colors and $\dot{M}$ for Miras in the Solar Neighborhood bring new constraints on the models of mass loss from cool giants. Furthermore, these models should help to investigate the effects of parameters such as metallicity, age, or initial mass. Models including a consistent treatment of hydrodynamics, chemistry, dust formation, and radiative transfer are becoming available for carbon-rich sources (Sedlmayr & Winters 1997).

Stationary models have been developed by Winters et al. (1994). In these models, radiation pressure on dust is the dominant force producing the wind (dust-driven wind models). These models require a minimum luminosity ($\sim$ Eddington luminosity) to initiate the outflow. This translates to the existence of a minimum mass loss rate, typically $\sim 10^{-7}\,M_\odot\,yr^{-1}$, to be sur-

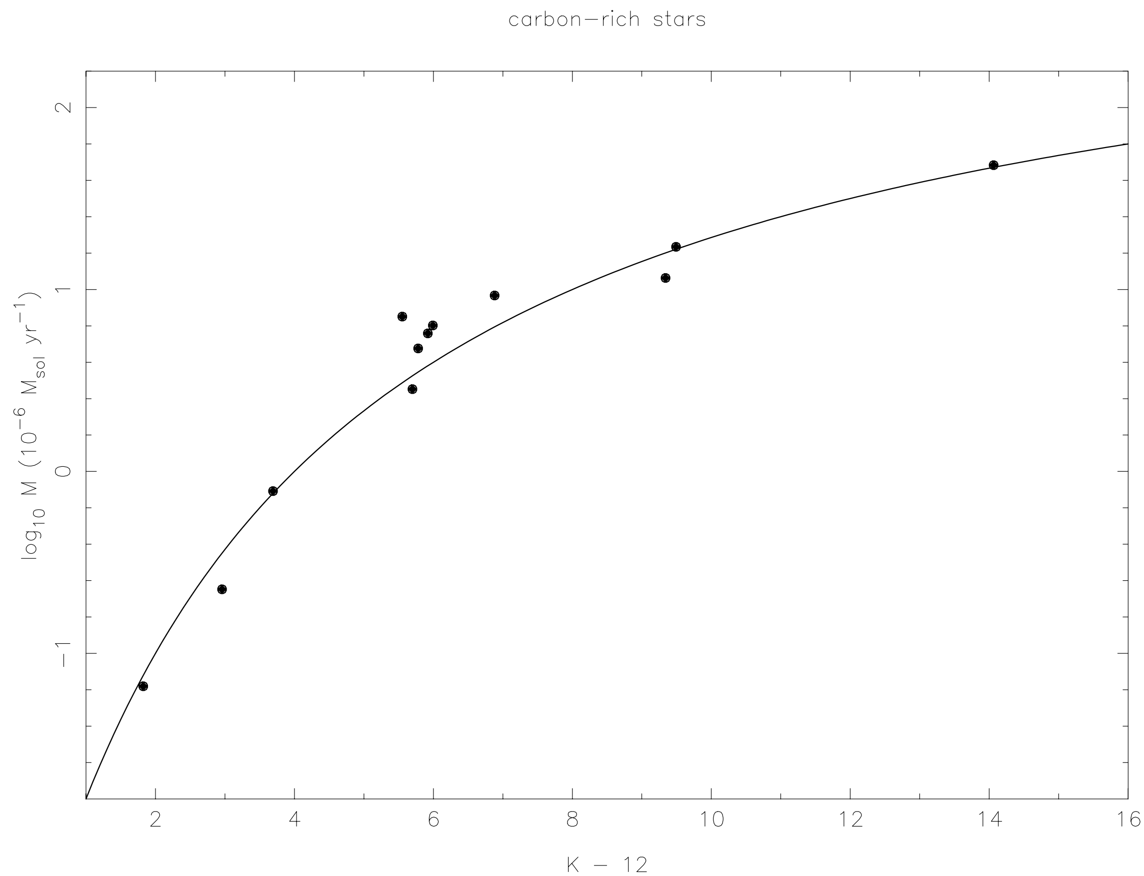

Fig. 5. K-12 versus $\dot{\mathrm{M}}$ for C-rich Miras. The solid line represents Eq. (4) in Sect. 3.3

mounted in order for the wind to be dust driven (Gail & Sedlmayr 1987, Sedlmayr & Dominik 1995). Due to this limitation, the stationary models (open triangles in Fig. 6) do not account for the Mira observations. The parameters of the stationary models shown in Fig. 6 are listed in Tab. 2.

In the case of the time-dependent models (Fleischer et al. 1992), the upper layers of the atmospheres are lifted by the stellar pulsations (pulsation-supported winds) and shock waves are travelling outwards generating density increases where dust can form. Then, the winds are accelerated by radiation pressure on dust as in the stationary case. In both cases, the mass loss rate is determined by the local density in the dust formation region, where the outflow velocity of the wind is of the order of the sound speed. The results of the time-dependent models are shown in Fig. 6 (filled triangles) and the corresponding parameters are listed in Tab. 3. The agreement with observations is much better. The trend of $\dot{\mathrm{M}}$ in function of the near-infrared color is well reproduced. One notes still a systematic shift by a factor $\sim$ 2. This may be the effect of the calibration of the observations, of parameters such as the metallicity, or of some remaining uncertainties in the models. The two high mass loss rate models at K-L = 4.65 and 5.27 have luminosities of $L_0 = 2.4 \cdot 10^4 L_\odot$ and $L_0 = 3.0 \cdot 10^4 L_\odot$, respectively.

From the time-dependent calculations, we also find clear correlations between the mass loss rate and the J-K and the K-12 color indices. At given J-K, the models produce mass loss rates typically a factor 1.6 higher than derived in Sect. 3.2, whereas at a given K-12 the models give mass loss rates about a factor 3 higher than derived in Sect. 3.3. Also from the models, there is no clear correlation between the mass loss rate and the IRAS colors. In this context it should be stressed that the models are spherically symmetric and do not include long-term variations of the mass loss rate (i.e. on a timescale of $\approx 10^3$yr). One would expect a correlation if the color index is sensitive to the physical conditions in the shell region where the driving mechanism determines the mass loss rate by supplying the energy and momentum necessary to lift the atmosphere out of the gravitational field. This occurs only in the sub-sonic wind regime, i.e. close

Table 2. Range of parameters for 90 stationary wind models (open symbols in Fig. 6). $\epsilon_{\mathrm{C}}/\epsilon_{\mathrm{O}}$ is the carbon to oxygen abundance ratio

$M_\star/M_\odot$	$L_\star/10^4 L_\odot$	T_*/K	$\epsilon_{\mathrm{C}}/\epsilon_{\mathrm{O}}$
0.5	3.0	2190	1.4
0.6	$2.0-3.0$	$1980-2380$	1.4
0.7	$2.0-5.0$	$1970-2600$	$1.2-3.0$
0.8	$3.0-5.0$	$1990-2400$	1.4
0.9	$4.0-5.0$	$2040-2340$	1.4
1.0	$3.5-6.0$	$2030-2520$	$1.3-3.0$
1.1	5.0	2250	1.4

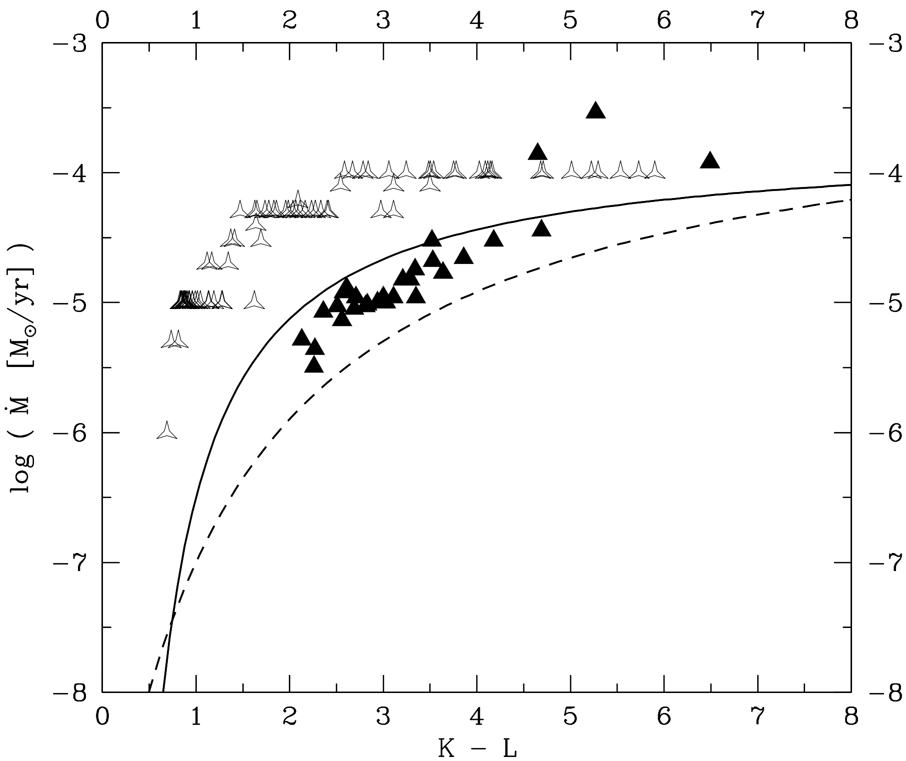

Fig. 6. K-L versus $\dot{\rm M}$ diagram for carbon-rich sources. The open triangles represent the results of the stationary hydrodynamical models of Winters et al. (1994). The filled triangles represent the results of time-dependent hydrodynamical models as described in Fleischer et al. (1992). The broken line is the relation obtained from observations of carbon stars (Paper I), the solid line represents the fit obtained for the oxygen-rich Miras in Sect. 3.1

Table 3. Range of parameters for 30 time-dependent models (filled symbols in Fig. 6). The subscript "0" indicates the values of the hydrostatic initial models. P is the period and Δu is the velocity amplitude at the inner boundary

$M_*/M_\odot$	$L_0/10^4 L_\odot$	T_0/K	$\epsilon_{\rm C}/\epsilon_{\rm O}$	P/d	Δu/kms^{-1}
0.6	1.0	2600	1.8	650	2
0.8	$0.6-0.8$	3000	$1.3-1.4$	650	$7-8$
1.0	$0.5-3.0$	$2200-2800$	$1.2-2.2$	$325-975$	$1-8$
1.5	1.0	2600	1.8	650	2

to the star. The near-infrared colors resulting from the model calculations are sensitive to the conditions in the dust formation region where the wind is initiated by radiation pressure on dust. On the other hand, the flux in the IRAS bands is dominated by thermal emission of dust located in the outer parts of the shell where the flow is highly supersonic. In this region, the input of momentum by radiation results in an increase of the outflow velocity, but does not affect the mass loss rate. This is a general feature of stellar winds (e.g. Holzer & MacGregor 1985, Lamers 1997) and was also found by Habing et al. (1994).

There are presently no suitable hydrodynamical models for O-rich sources. Nevertheless, we can expect the same qualitative behavior for O-rich Miras as for C-rich ones. As radiation pressure on dust is the dominating driving force in the models, one would expect to find different relations for O-rich and C-rich Miras because of the different optical properties of their respective condensates. On the other hand, the facts that RSGs do not follow the same relations as O-rich Miras and that they are much more luminous with higher mass loss rates suggest that the mass loss mechanism at work in these objects is somewhat different from that in the Mira stars. For these objects, the stationary case (purely dust-driven) may apply. It is worth noting that some RSGs do not exhibit a clear variability while still undergoing mass loss at a large rate (e.g. α Ori, Guilain & Mauron 1996).

5. Conclusion

As for carbon Miras, there is a good correlation between K-L' and $\dot{\rm M}$ for O-rich Miras. However, the relations are not the same. This is probably an effect of the different properties of the condensates in the 2 types of stars. The J-K and K-12 colors are also correlated with $\dot{\rm M}$. These relations will be useful in the context of the on-going infrared surveys that will produce color indices for large quantities of AGB stars. However, before applying them in environments other than the Solar Neighborhood, one should be careful to investigate the effect of metallicity on these relations.

The correlations between colors and $\dot{\rm M}$ bring new constraints on the process responsible for mass loss in Miras. The agreement between the time-dependent hydrodynamical models and the observations for Miras supports that the wind from these stars is the result of a 2 step process: (i) pulsations levitate the atmosphere and trigger the onset of dust formation, (ii) radiation pressure on dust initiates and accelerates the wind. As Red Supergiants do not follow these relations, the mass loss process in these stars might be different. In these high luminosity objects, the first mechanism may not be needed.

There is obviously a critical need of consistent wind models for O-rich Miras and for M supergiants.

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