DUST SHELLS AROUND CARBON MIRA VARIABLES

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Abstract.

The spectral energy distributions and mid-infrared spectra of 44 carbon Mira variables are fitted using a dust radiative transfer model. The periods cover the entire range observed for carbon Miras. The luminosities are calculated from a period-luminosity relation. Parameters derived are the distance, the dust mass loss rate and the ratio of silicon carbide to amorphous carbon dust. The total mass loss rate is derived from a modified relation between the photon momentum (L/c) and the momentum in the wind ($\dot{M}$ v_∞). Mass loss rates between 1×10^{-8} and 4×10^{-5} $M_\odot yr^{-1}$ are found. We find good correlations between mass loss rate and pulsation period, and mass loss rate and luminosity. The dust-to-gas ratio appears to be almost constant up to periods of about 500 days, corresponding to about 7900 $L_\odot$, and then to increase by a factor of 5 towards longer periods and higher luminosities. A comparison is made with radiation-hydrodynamical calculations including dust formation. The mass loss rates predicted by these models are consistent with those derived in this paper. The main discrepanacy is in the predicted expansion velocities for models with luminosities below ~5000 $L_\odot$. The radiation-hydrodynamical calculations predict expansion velocities which are significantly too large. This is related to the fact that these models need to be calculated with a large C/O ratio to get an outflow

in the first place. This is contrary to observations. It indicates that a principle physical ingredient in these radiation-hydrodynamical calculations is still missing. Possibly the winds are 'clumpy' which may lead to dust formation on a local scale, or there is an additional outwards directed force, possibly radiation pressure on molecules.

1. Introduction

One of the main characteristics of AGB stars is their large mass-loss rate. Dust grains form in the cool expanding circumstellar envelope, absorb optical radiation and re-emit it in the infrared.

In Groenewegen (1995, hereafter G95) the spectral energy distributions (SEDs) and mir-IR spectra of 21 carbon stars were fitted, concentrating on "infrared" carbon stars, i.e. those with thick dust shells. In the present paper we concentrate on carbon-rich Mira variables. The main advantage of using Miras is that the period-luminosity relation provides reasonable accurate distances for such stars, largely eliminating the uncertainty of some of the fit parameters on distance. Secondly, using Miras enables a study to be made of the relation between mass-loss rate and pulsation period, c.q. mass-loss rate and luminosity, which is important from an evolutionary point of view. To this end we took the 10 stars from G95 with measured pulsation periods and selected 34 other stars from the literature to cover the entire known range of periods for Miras.

This contribution is a summary of a paper by the same authors submitted to MNRAS (GWSK97).

2. The model and fitting procedure

The radiative transfer model of Groenewegen (1993) is used. This model was developed to handle non-r^{-2} density distributions in spherically symmetric dust shells. It simultaneously solves the radiative transfer equation and the thermal balance equation for the dust. The central star is represented by a blackbody modified to allow for the characteristic absorption feature in carbon stars at 3.1 μm due to HCN and C_2H_2 For the dust composition a combination of amorphous carbon (AMC) and silicon carbide (SiC) grains is assumed. For simplicity a single condensation temperature is used. The absorption coefficient for AMC is calculated from the optical constants listed in Rouleau & Martin (1991) for their AC1-species. It was shown in G95 that most of the silicon carbide features can be fitted with α-SiC (Pégourié 1988). The optical constants from that paper are therefore adopted. To estimate the luminosity from the pulsation periods the period-luminosity relation for carbon Miras from Groenewegen & Whitelock (1996) is used.

The models are fitted to the observed SEDs and mid-IR spectra. Most of these data come from the literature. However, some new or previously unpublished data are also used as constraints (see GWSK97 for details). The fits to the SEDs and mid-IR spectra are generally of good quality and are shown in GWSK97.

From the radiative transfer modelling the dust mass-loss rate is derived. The total mass-loss rate is derived from equations similar to those in Netzer & Elitzur (1995) and Ivezić & Elitzur (1995), which are valid if radiation pressure is the force that drives the outflow:

$$\dot{M} = 2.02 \times 10^{-8}\ \tau_{\mathrm{F}}\ \frac{L}{v_\infty - v_0} \left(1 - \frac{1}{\Gamma}\right) \quad (M_\odot/yr), \tag{1}$$

with τ_{F} the flux-weighted optical depth at infinity (derived from the radiative transfer modelling), L the luminosity in solar units, v_∞ the terminal gas velocity, v_0 the gas velocity at the dust condensation radius (both in km s^{-1}), and Γ is the ratio of radiation pressure to gravitational pull (see GWSK97 for details).

3. Results

3.1. MASS-LOSS RATE AND DUST-TO-GAS RATIO

In Fig. 1 the mass-loss rates and dust-to-gas ratios are plotted against pulsation period and luminosity (the filled squares). There is a good correlation between log $\dot{M}$ and $\log L$ and $\log P$ over the entire range. Least-squares fitting on the 36 data points give the following results:

$$\log \dot{M} = (4.08 \pm 0.41)\ \log P - (16.54 \pm 1.10)\, (\sigma = 0.27), \tag{2}$$

and

$$\log \dot{M} = (3.94 \pm 0.28)\ \log L - (20.79 \pm 1.10)\, (\sigma = 0.28). \tag{3}$$

As we assumed a $P - L$-relation from the start, these relations are not independent. If we had assumed a constant luminosity for all stars, we still would have found a significant relation between mass loss rate and pulsation period.

Whitelock (1990, 1994) derived the mass-loss rates for oxygen-rich Miras in the Galactic Bulge and at high galactic latitude, respectively. The dashed polygon in Fig. 1 indicates the region wherein most of the former sample is located while the dotted polygon indicates the region wherein most of the later sample is located. The relations for oxygen-rich and carbon Miras appear to be similar. There are some caveats however. The mass-loss rates for the oxygen-rich Miras were not derived from model fits to the SEDs, but from Jura's (1987) formula which relates mass-loss rate to the IRAS

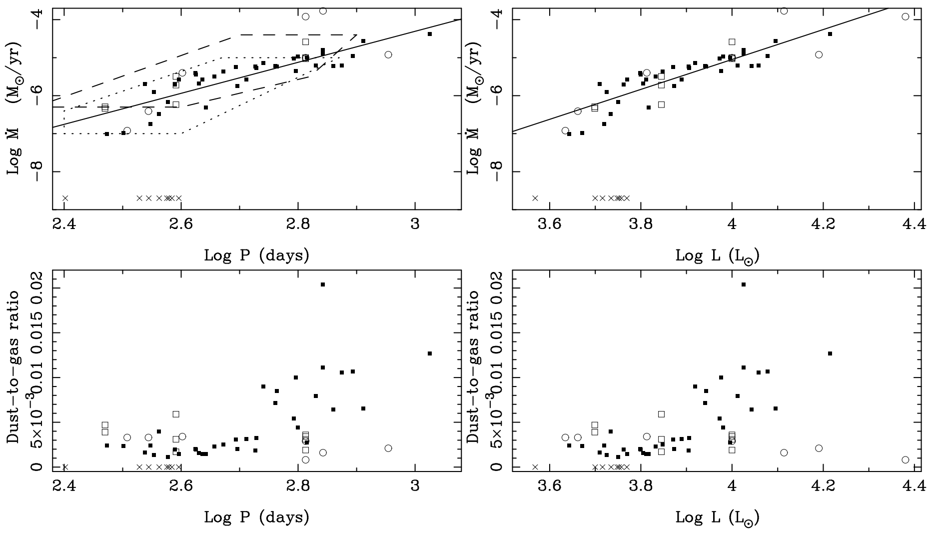

Figure 1. Mass-loss rate and dust-to-gas ratio, versus pulsation period and luminosity (filled squares). The crosses plotted at a mass-loss rate of 2 10^{-9} $M_{\odot}yr^{-1}$ and $\Psi = 0$ are stars without measured expansion velocity or for which no dust mass-loss rate could be derived. The solid lines are least-squares fits. The dashed and dotted polygons indicate regions occupied by different samples of oxygen-rich Miras (see text). The open squares and circles represent selected models from radiation-hydrodynamical calculations including dust formation from the Vienna and Berlin groups, respectively (see text).

flux, luminosity, mean wavelength of the emergent light, dust-to-gas ratio and expansion velocity. Whitelock assumed a constant dust-to-gas ratio and a constant expansion velocity for all of the stars in a given sample. As we show below, the dust-to-gas ratio for carbon stars appears to be a function of period, and there is a large spread in expansion velocity at a given period. If the same holds for oxygen-rich stars then there will be systematic uncertainties in the derived mass-loss rates of the two samples of O-rich Miras.

The dust-to-gas ratio appears to be rather constant at a value of 0.0025 up to $P \approx 500$ days, or $L \approx 7900$ $L_{\odot}$, and then increase markedly to values up to 0.015. AFGL 3068 appears to have an extremely high dust-to-gas ratio of about 0.02.

3.2. EXPANSION VELOCITY

Figure 2 shows the observed expansion velocity plotted against luminosity and pulsation period. The correlations are poor. In order to make a more general comparison between oxygen-rich and carbon-rich Miras, we selected from the literature data on the CO and/or OH expansion velocities of O-rich Miras and OH/IR stars with known periods. More details on the selection procedure can be found in GWSK97. The results are plotted as the dots in the bottom panel of Fig. 2.

There is a good deal of overlap between the regions occupied by O-rich and C-rich stars, although for periods below 600 days the carbon stars appear to lie systematically above the oxygen-rich Miras. For large periods the expansion velocities seem to level off. For both oxygen- and carbon-rich stars there is a scatter of up to a factor of 2 in velocity at a given period.

3.3. COMPARISON WITH THEORETICAL MODELS

Two groups (Berlin and Vienna) calculate radiation-hydrodynamical models of the atmospheres and circumstellar shells of carbon-rich long-period variables which include dust formation (see Höfner et al. 1996 for details and a comparison between the two groups). In this section we compare selected models with our derived parameters.

From the Vienna group we take the models of Höfner & Dorfi (1997), from the Berlin group the models from Fleischer et al. (1992), Winters et al. (1997) and Fleischer et al. (1997). In all buth two cases only those models with luminosities in accordance with our adopted $P-L$ relation are taken. All of the models provide mass-loss rates, time averaged dust-to-gas ratios and expansion velocities. The model results are plotted as the open squares (Vienna models) and open circles (Berlin models) in Figs. 1 and 2.

In general, the mass-loss rates these models predict are in good agreement with observed values derived in the present paper (Fig. 1). The exception being the models specifically designed to fit IRC +10 216 (Winters et al. 1997) and AFGL 3068 (Fleischer et al. 1997). Apart from having a luminosity inconsistent with the $P-L$ relation, their proposed mass-loss rate of 1.2×10^{-4} $M_{\odot}yr^{-1}$ for IRC +10 216 is larger than the upper limit of 4×10^{-5} $M_{\odot}yr^{-1}$ derived by Keady & Ridgway (1993) from the non-detection of the H_2 S(1) rotation line at 17.0 μm. We find a mass-loss rate of 1.1-1.3 $\times 10^{-5}$ $M_{\odot}yr^{-1}$.

Regarding the dust-to-gas ratio there is good agreement for short periods and low luminosities, in particular if one considers that there may be systematic uncertainties due to the uncertainty in the absolute values of the dust opacity. For longer periods and higher luminosity there is a systematic difference in the sense that the theoretical models predict similar, and observations suggest higher, dust-to-gas ratios than at shorter periods.

Regarding the expansion velocities (Fig. 2) one notices that the theoretical models predict velocities for short period/low luminosity Miras which are too large compared to observations. This could be partly because the theoretical models neglect the drift velocity and thus predict the dust velocity, while the velocity which is observed is that of the gas. On the other hand it is also clear that the C/O ratio predominantly determines the final velocity in the theoretical models. This is nicely demonstrated by the Vienna models at 7000 $L_\odot$, or 390 days. As the C/O ratio goes up from 1.8 to 2.0 to 2.5, the expansion velocity goes up from 7 to 21 to 33 km s^{-1}, with all other parameters remaining the same. The observations suggest therefore a C/O ratio between 1.8 and 2.0 for stars of these luminosities. The Vienna models at 295 days and the Berlin models at 322 and 350 days are calculated with C/O ratios of 2.0, 3.0 and 2.8, respectively. The observations imply therefore C/O ratios smaller than 2. This is consistent with the C/O ratios determined in 30 carbon-rich semi-regular and irregular variables with little or no dust by Lambert et al. (1986) who find that the largest C/O ratio is 1.6, and 50% of the stars in their sample have C/O < 1.1. An increase of the C/O ratio with luminosity is also consistent with an evolutionary picture in which stars with higher luminosity evolve from stars of higher initial mass; these have experienced more thermal pulses and thus dredged-up more carbon (see the scenario by Groenewegen et al. 1995).

The reason why the Berlin and Vienna groups calculate models with low luminosity only for large C/O ratios is that only under these conditions do their models predict outflows. This reveals a limitation of the current state of modelling. It could imply there is an additional outward directed force besides radiation pressure on dust, possibly radiation pressure on molecules (Jørgensen & Johnson 1992), acoustic waves (Pijpers & Habing 1989), or Alfvén waves (Hartmann & MacGregor 1980). Alternatively, the flow may not be homogeneous, but clumpy, which could lead to localised dust formation. Clumpy structures are seen in the CO emission around the carbon stars with detached shells (e.g. Bergman et al. 1993, Olofsson et al. 1996).

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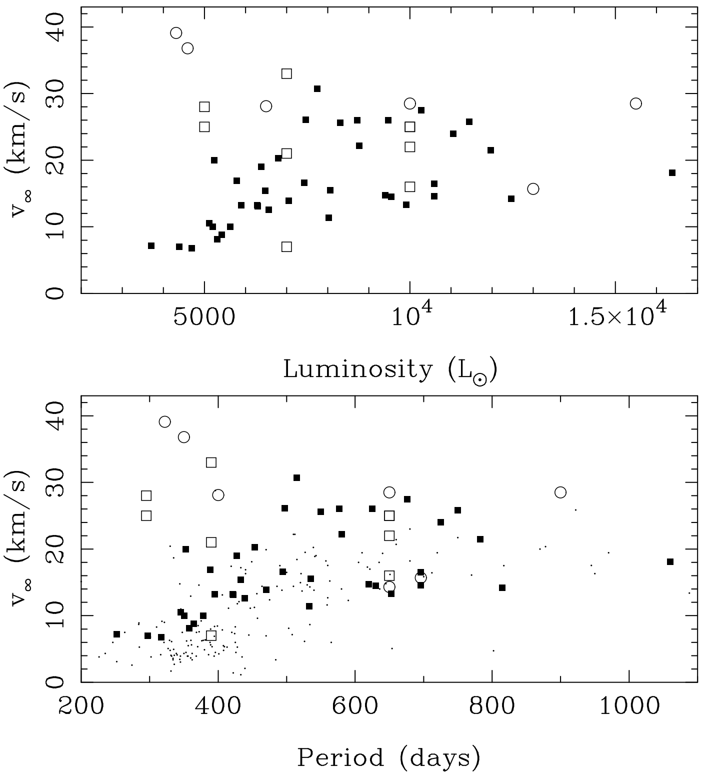

Figure 2. Observed expansion velocity luminosity and pulsation period. The open squares and circles represent radiation-hydrodynamical model calculations (see text). The dots represent observed values of expansion velocities based on CO or OH observations for O-rich Miras and OH/IR stars (see text).

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