On the evolution and properties of AGB stars

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Chapter 5

A new dust radiative transfer program

Abstract

A numerical code is presented to calculate the radiation transfer in a spherically symmetric dust shell around a central star. The dust temperature is derived from the condition of radiative equilibrium. The program allows for an arbitrary mass loss history. The model is tested and applied to the case of a mass loss rate increasing with time on the AGB following the mass loss law of Bedijn (1987). The far-infrared and sub-mm fluxes are especially sensitive to the effect of an increasing mass loss rate.

Given the uncertainty in the IRAS fluxes at 60 and 100 μm, which are usually used to constrain radiative transfer models, only increases in the mass loss rate of more than a factor of 2 over a time scale of $10^4$ years are detectable. The sub-mm region is a more sensitive tracer of the mass loss history, but one has to take into account that sub-mm fluxes are usually measured with an instrument with a beam smaller than the region where the sub-mm emission originates. Another problem is that the far-infrared and sub-mm fluxes are also sensitive to the adopted absorption coefficient ($Q_\lambda \sim \lambda^{-\alpha}$). It is found that a change from $\alpha = 2.1$ to 2.7 for $\lambda > 20$ μm has the same effect as the change from a constant mass loss rate to one which has increased by a factor of 10 over the past $10^4$ years.

1 Introduction

The numerical problem of radiative transfer in circumstellar dust shells has been treated by many authors, e.g. Hummer & Rybicki (1971), Leung (1976), Tsam & Schwarts (1976), Bedijn et al. (1978), Haisch (1979), Yorke (1980), Martin & Rogers (1984), Rogers & Martin (1984, 1986). The study of the dust shells around AGB stars based on these models are even more numerous, e.g. Jones & Merrill (1976), Rowan-Robinson (1980), Rowan-Robinson & Harris (1983a, b), Rowan-Robinson et al. (1986), Bedijn (1987), Martin & Rogers (1987), Schutte & Tielens (1989), Orofino et al. (1990), Griffin (1990), Justtanont & Tielens (1992) or Griffin (1993). The need for yet another radiative transfer code seems therefore hardly warranted. However, most, if not all, of the codes mentioned above allow only for a $1/r^2$ density distribution, at best a $1/r^{\alpha}$ distribution. In contrast, the mass loss rate of AGB stars is probably a function of time. This can be a graduate increase during the evolution on the AGB (see e.g. Bedijn 1987), or a more erratic behaviour related to thermal pulses (e.g. the carbon and M stars with a 60 μm excess, Willems & de Jong 1988, Zijlstra et al. 1992). The transition from the AGB to the post-AGB phase is yet another example of temporal behaviour of the mass loss rate that is not easily described by a $1/r^{\alpha}$ density distribution. The study of such phenomena requires a radiative transfer code where an explicit $\dot{M}(t)$ function may be specified.

In many numerical codes the inner radius of the dust shell is specified and then the corresponding dust temperature is calculated in the program. In the present model a more realistic approach is
adopted to specify the dust (condensation) temperature at the inner radius, and let the program determine the location of the inner radius.

The essence of the present radiative transfer code is not computational speed but rather flexibility in the choice of mass loss histories combined with a straightforward solution of the radiative transfer and the radiative equilibrium equation.

After developing the equations in Sect. 2, and testing the model in Sect. 3, an example of the influence of a non-constant mass loss rate on the spectral energy distribution is given in Sect. 4. The results are discussed in Sect. 5.

![Figure 1: The geometry of the problem. Indicated are the radial coordinate, r, the impact parameter, p, the distance along the line of sight, z, and the angle \( \theta \). The angle the central star subtends from the inner dust radius is \( \theta'' \).](image)

### 2 Basic equations

Consider the geometry in Fig. 1, with the radial coordinate, \( r \), the impact parameter, \( p \), and the distance along the line of sight, \( z \), with the observer at \( z = +\infty \). As usual we define \( \mu = -\cos \theta \).

The time-independent, non-relativistic radiative transfer equation along the line-of-sight may be written as:

\[
\frac{dI_\lambda}{dz} = -\sigma_e I_\lambda + j_\lambda
\]  

where \( I \) is the specific intensity, \( \sigma_a, \sigma_s, \sigma_e (\equiv \sigma_a + \sigma_s) \) are the absorption, scattering and extinction coefficients and \( j_\lambda \) is the emissivity given by (in the case of isotropic and coherent scattering):

\[
j_\lambda = \sigma_a B_\lambda + \sigma_s \frac{1}{2} \int_{-1}^{1} I_\lambda d\mu
\]  

where \( B_\lambda \) is the Planck function. The solution of Eq. (1) is:

\[
I(z) = I_0 e^{-\int_0^z \sigma_e dz'} + \int_{z_0}^z j(z') e^{-\int_{z'}^z \sigma_e dz''} dz'
\]
2. Basic equations

When a grid in the \( z \)-direction exists \( (z_{i+1} > z_i) \), which is spaced closely enough to perform the integrations accurately by the trapezium-rule, Eq. (3) can be written as:

\[
I(z_{i+1}) = I(z_i) e^{-\Delta z_{i+1}^+} + \frac{1}{2} (z_{i+1} - z_i) (j(z_{i+1}) + j(z_i) e^{-\Delta z_{i+1}^+})
\]  

(4)

with

\[
\Delta z_{i+1}^+ = \frac{1}{2} (z_{i+1} - z_i) (\sigma_{i+1}^2 + \sigma_i^2)
\]  

(5)

The intensity is solved in the inward (minus-\( z \)) direction, \( I^- \), and the outward direction \( I^+ \). The boundary conditions are \( I^- = 0 \) at the outer radius \( (z = +\infty) \) and

\[
I^+ = I^-
\]  

(6)

\[ p > R_\star \]

\[
I^+ = B_\lambda(T_{\text{eff}})G_\lambda
\]  

\[ p \leq R_\star \]

at \( z = 0 \). The central star is represented by a blackbody modified to allow for absorption features. For example, in Groenewegen et al. (1993) we consider the well known 3.1 \( \mu m \) feature observed in carbon stars and correspondingly chose the function \( G_\lambda \) to be:

\[
G_\lambda = e^{-\lambda_0} e^{-\left(\frac{1}{2} \lambda_0^2 \lambda_0 \right)}
\]  

(7)

with \( \lambda_0 = 3.1 \mu m \). The emissivity depends on the dust temperature profile, which is determined from the condition of radiative equilibrium:

\[
\int_0^\infty \sigma_\lambda^2 B_\lambda(T_{\text{dust}}) d\lambda = \int_0^\infty \sigma_\lambda^2 J_\lambda d\lambda
\]  

(8)

In the numerical code, Eqs. (1), (2) and (8) are solved by an iterative method. To this end Eq. (8) is used in the following form (using \( \sigma_\lambda^2 = n(r) \pi a^2 Q_\lambda \), where \( a \) is the grain size and \( Q_\lambda \) the absorption coefficient):

\[
T_{\text{dust}}^4 \frac{2k^4}{\hbar^3 c^2} \int_0^\infty Q_\lambda \frac{z^3}{e^{z} - 1} \, dz = \int_0^\infty Q_\lambda \frac{1}{2} \int_{-1}^{1} I(\mu) \, d\mu \, d\lambda
\]  

(9)

\[ + \frac{1 - \mu_\star^{i+1}}{1 - \mu_\star^i} \int_{-1}^{1} Q_\lambda \frac{1}{2} \int_{-1}^{1} I(\mu) \, d\mu \, d\lambda
\]

where \( \mu_\star^i \) is the cosine of the angle to the central star in the \( i \)-th iteration. This choice is convenient since it separates the integral over \( \mu \) in two physically different regimes, namely rays that intersect the central star and rays that do not. In the absence of a dust shell, \( \int_{-1}^{1} I(\mu) \, d\mu = 0 \) and \( \int_{-1}^{1} I(\mu) \, d\mu = (1 - \mu_\star^i) B_\lambda(T_{\text{eff}}) \). When the iterative process has converged, \( \mu_\star^i \) is equal to \( \mu_\star^{i+1} \) and Eqs. (9) and (8) are identical.

When the intensity \( I_\lambda(z, p) \) is determined, the flux at Earth is calculated from:

\[
F_\lambda = \frac{2}{D^2} \int_0^\infty I_\lambda(z = +\infty, p) \, p \, e^{-\left(\frac{z - r_{\text{Earth}}}{\Delta r}\right)^2} \int_0^\pi e^{-2r_{\text{Earth}}(1 - \cos \phi)/\Delta \phi^2} \, d\phi \, dp
\]  

(10)

where \( D \) is the distance between the central star and the observer and where we assume that the flux at Earth is measured with an instrument with a Gaussian beam (FWHM = 1.6651\( \Delta p \)) centered at an offset \( p_0 \) from the central star.

In the code, grids in \( r, p, z, \mu \) and \( \lambda \) need to be specified. These are not independent since \( p^2 = r^2 - z^2 = r^2(1 - \mu^2) \). The main grid is in \( r \). From the condition that the error using the
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The trapezium-rule in Eq. (3) is small and from the fact that $\sigma \approx 1/r^2$, one may derive the following estimate for the step size in the radial grid ($h = r_{i+1} - r_i$):

$$h \sim \sqrt{\frac{r^3}{r(2 + r/r)}}$$

(11)

where $\tau$ is the optical depth at some reference wavelength. In general the optical depth is given by:

$$\tau_{\lambda} = \int_{r_{\text{inner}}}^{r_{\text{outer}}} \pi a^2 Q_{\lambda}(r) n(r) \, dr = 5.405 \times 10^8 \frac{\dot{M} \Psi}{R_\star \rho_d r_c} \int_{r_{\text{min}}}^{r_{\text{max}}} \frac{R(z)}{z^2 w(z)} \, dz$$

(12)

where $x = r/r_c$, $\dot{M}(r) = \dot{M} R(x)$ and $v(r) = v_\infty w(x)$. The units are: the (present-day) mass loss rate at the inner radius $\dot{M}$ in $M_\odot/yr$, $\Psi$ the dust-to-gas mass ratio, $Q_{\lambda}/a$ in $\text{cm}^{-1}$, $R_\star$ in solar radii, $v_\infty$ the terminal velocity of the circumstellar envelope in $\text{km s}^{-1}$, $\rho_d$ the dust grain density in $\text{gr cm}^{-3}$, $r_c$ the inner dust radius in stellar radii and $r_{\text{max}}$ the outer radius in units of $r_c$. The normalised mass loss rate profile $R(x)$ and the normalised velocity law $w(x)$ should obey $R(1) = 1$ and $w(\infty) = 1$, respectively.

In Eq. (12) the radial coordinate $r$ and the time $t$ are related through:

$$t = \int_{R_\star}^{r} \frac{dr'}{v(r')}$$

(13)

With the grid in $r$ determined, the grid in impact parameters is calculated. The grid points in $p$ are the grid points in $r$ with additional points in between chosen to give, approximately, an equidistant grid in $\mu$. The number of impact parameters at $p < r_{\text{inner}}$, is a certain fraction (usually 20%) of the number of $r$-points between $r_{\text{inner}}$ and $r_{\text{outer}}$ and are chosen equidistant. The grid in wavelength consists of $\sim 80$ points between 0.1 and 1100 $\mu$m. In general there is no clear cut prescription how the various grids have to be chosen. From a computational point of view, the number of grid points should be as small as possible. On the other hand, the model results (dust condensation radius, dust temperature profile, spectral energy distribution) should not be dependent on the grid sizes.

In the code the following mass loss histories are considered. A mass loss rate increasing with time following Bedijn (1987):

$$\dot{M}(t) = \frac{\dot{M}_0}{(1 - t/t_0)^\alpha} \quad (t < t_0)$$

(14)

and a decreasing mass loss rate:

$$\dot{M}(t) = \dot{M}_0 e^{-t/t_0} + \dot{M}_\infty$$

(15)

Parameters to be specified are $\dot{M}_0$, $\dot{M}_\infty$, $t_0$, $\alpha$ and the time $t$ at which the model has to be calculated.

In the program we allow for a velocity law of the form:

$$\frac{v(r)}{v_\infty} = w_0 + (1 - w_0) \left(1 - \frac{R_\star}{r}\right)^\beta$$

(16)

The following parameters are to be specified: stellar luminosity, effective temperature, grain size and density, dust-to-gas mass ratio and dust temperature at the inner radius ($T_c$), absorption and scattering efficiencies and the parameters in the mass loss history and the velocity law.
The solution of the radiative transfer and radiative equilibrium equations proceeds as follows. Suppose we have an initial estimate for the inner dust radius, \( r_{c}^{(1)} \) and the dust temperature profile \( (T_{d}^{(1)}(r)) \). The initial guess for the intensity is \( I^{(1)} \equiv 0 \). For every wavelength point and impact parameter the radiative transfer equation is solved. In Eq. (3) the intensity enters at two locations: on the left hand side and in the scattering contribution to the emissivity. We use the estimate of \( I \) from the previous iteration \( (I^{(i)}) \) in the emissivity-term to calculate the new value of \( I^{(i+1)} \). With \( I^{(i+1)} \) determined we calculate \( \int_{-1}^{1} I^{(i+1)} d\mu \) and \( \int_{\mu_{a}}^{1} I^{(i+1)} d\mu \). We then calculate updated values for \( r_{c}^{(i+1)} \) and \( T_{d}^{(i+1)}(r) \) using Eq. (9). For the first radial grid point, which by definition is the inner dust radius, the temperature is fixed \( (T_{\text{dust}} = T_{c}) \). We solve Eq. (9) for \( \mu_{c}^{(i+1)} \) and obtain an improved estimate for the inner radius \( r_{c}^{(i+1)} \). For all other \( r \)-points we put \( \mu_{c}^{(i+1)} = \mu_{c}^{(i)} \) in Eq. (9) and solve for \( T_{\text{dust}}(r) \). The iteration on \( r_{c} \) and \( T_{\text{dust}}(r) \) is continued until they are determined with a relative accuracy of \( 10^{-4} \). An optically thin model requires typically less than 5 iterations, the most optically thick models calculated in this paper require about 30 iterations. An additional verification on the model results is the conservation of total luminosity. Mathematically, this is equivalent to the condition of radiative equilibrium, but in practice it is an independent check.

Table 1: A comparison between the two radiative transfer codes

<table>
<thead>
<tr>
<th>( \tau_{9.5} = 0.1 )</th>
<th>( \tau_{9.5} = 1.0 )</th>
<th>( \tau_{9.5} = 1.0 )</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>this work</td>
<td>RM this work</td>
</tr>
<tr>
<td>Inner radius (R_{c})</td>
<td>5.230</td>
<td>5.232</td>
</tr>
<tr>
<td>Flux convergence (%)</td>
<td>0.26</td>
<td>0.21</td>
</tr>
<tr>
<td>12 ( \mu )m flux (Jy)</td>
<td>22.4</td>
<td>22.3</td>
</tr>
<tr>
<td>25 ( \mu )m flux (Jy)</td>
<td>8.3</td>
<td>8.0</td>
</tr>
<tr>
<td>60 ( \mu )m flux (Jy)</td>
<td>1.26</td>
<td>1.20</td>
</tr>
<tr>
<td>100 ( \mu )m flux (Jy)</td>
<td>0.33</td>
<td>0.33</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>( \tau_{9.5} = 10.0 )</th>
<th>( \tau_{9.5} = 50.0 )</th>
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<tr>
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<td>this work</td>
</tr>
<tr>
<td>Inner radius (R_{c})</td>
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<tr>
<td>Flux convergence (%)</td>
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<tr>
<td>12 ( \mu )m flux (Jy)</td>
<td>205</td>
</tr>
<tr>
<td>25 ( \mu )m flux (Jy)</td>
<td>409</td>
</tr>
<tr>
<td>60 ( \mu )m flux (Jy)</td>
<td>119</td>
</tr>
<tr>
<td>100 ( \mu )m flux (Jy)</td>
<td>32.3</td>
</tr>
</tbody>
</table>

Note. (a) Including isotropic scattering. Dust particle size is 0.1 \( \mu \)m and the mass loss rate is \( 7.08 \times 10^{-7} \) \( M_{\odot} \) yr^{-1}.

3 Results

An an example, models are calculated assuming the following typical parameters for an AGB star: luminosity \( L = 6000 \, L_{\odot} \), \( T_{\text{eff}} = 3000 \) K. The star is set at an arbitrary distance of 1 kpc. We assume astronomical silicate (Draine & Lee 1984, Draine 1987) grains of radius \( a = 0.1 \, \mu \)m and density \( \rho_{d} = 2 \, \text{g cm}^{-3} \) and a dust-to-gas ratio of 0.01. We assume a constant expansion
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Figure 2: The spectral energy distribution (top panel), the LRS spectrum (middle panel) and dust temperature profile (bottom panel) for the model with $\tau_{9.5} = 50$.

velocity of 15 km s$^{-1}$ and constant mass loss rates of $\dot{M} = 6.33 \times 10^{-8}$, $6.81 \times 10^{-7}$, $9.43 \times 10^{-6}$, $7.13 \times 10^{-5}$ M$\odot$/yr corresponding to optical depths at the reference wavelength of 9.5 $\mu$m of 0.1, 1, 10 and 50. For the time being scattering is neglected. The dust temperature at the inner radius is assumed to be 1000 K and the outer radius is determined in the model by the condition that the dust temperature has dropped to 20 K. Beam effects are neglected. In Fig. 2 the spectral energy distribution, the LRS spectrum and the dust temperature profile are shown for the $\tau_{9.5}$
= 50 case.
We have tested our model against the code of Rogers & Martin (1984, 1986, hereafter RM-code). The results are listed in Table 1, where we compare the inner dust radius, the flux convergence and the IRAS fluxes for the 4 optical depths. The differences are a few percent at most. The differences in the spectral energy distribution, LRS spectrum and dust temperature profile are unnoticeably small.
To check our code and investigate the influence of scattering we included this effect in the $\tau_{9.5} = 1$ model. It proved necessary to increase the mass loss rate to $7.08 \times 10^{-7} M_\odot/yr$ to obtain $\tau_{9.5} = 1$. The agreement between the two codes is again good. The cases with and without scattering are virtually identical (see Table 1). This implies that the influence of scattering introduces a negligible uncertainty ($\sim 4\%$) in the derived mass loss rate.

Figure 3: The influence of an increasing mass loss rate with time. The mass loss rate increases by a factor of $f$ in $10^4$ years, according to the mass loss history proposed by Bedijn (1987; see Eq. 17). The spectral energy distributions are for $\tau_{9.5} = 0.1$ (upper left), 1 (upper right), 10, (lower left), 50 (lower right). Within each panel the four curves indicate $f = 1, 2, 5, 10$ from top to bottom.

4 Increasing mass loss rates on the AGB: observable or not?
Our model has already been used extensively (Groenewegen & de Jong 1991, Slijkhuis & Groenewegen 1992, Groenewegen & de Jong 1992, Oudmaijer et al. 1993). In this section we predict the changes in the spectral energy distribution (SED) when the mass loss rate is continuously increasing on the AGB compared to the constant mass loss rate case. The case of a decreasing
mass loss rate, when the star moves from the AGB to the post-AGB phase, was considered by Slijkhuis & Groenewegen (1992).

We consider the mass loss rate of Eq. (14). The relevant time scales are the flow time scale through the envelope and the time scale on which the mass loss rate changes. For the models in the previous section the time for a dust particle to travel from the inner to the outer radius is \( \sim 3.5 \times 10^4 \) yrs. The time scale on which the mass loss rate must change to give appreciable changes in the SED is therefore shorter than this and is in the present calculations adopted to be \( \Delta t = 10^4 \) yrs.

Suppose we want to calculate our model at time \( t_1 \), and to have the mass loss rate to increase by a factor of \( f \) over the past \( \Delta t \) years. The present-day mass loss rate is \( \dot{M}_1 \). Using Eq. (14) this gives:

\[
\dot{M}_1 = \frac{M_0}{(1-t_1/t_0)^\alpha}
\]

from which follows:

\[
t_0 = t_1 + \frac{\Delta t}{f^\alpha - 1}
\]

\[
\dot{M}_0 = \dot{M}_1 t_0^{-\alpha} \left( \frac{\Delta t}{f^\alpha - 1} \right)^\alpha
\]

Values for \( \alpha \) between 0.5 and 1 have been proposed in the literature (Baud & Habing 1983, Bedijn 1987, van der Veen 1989). In the following examples \( \alpha = 0.75 \) is used, expecting that the
4. Increasing mass loss rates on the AGB: observable or not?

In Fig. 5 the quantity \( Y = \frac{(S_{\lambda}(\tau, f) - S_{\lambda}(\tau = 0))}{(S_{\lambda}(\tau, f = 1) - S_{\lambda}(\tau = 0))} \) is plotted against \( f \), for \( \lambda = 60 \) an 100 \( \mu m \) for the models in Table 2. There is a good correlation between the two quantities, independent of \( \tau \). This means that it is possible to estimate \( f \) even in the case a star has been modelled with a \( 1/r^2 \)-density law. Suppose the spectrum up to \( \sim 10 \mu m \) has been modelled to determine the mass loss rate and one notices that the predicted flux at 60 and 100 \( \mu m \) (corresponding to \( S_{\lambda}(\tau, f = 1) \)) is larger than the observed flux (corresponding to \( S_{\lambda}(\tau, f) \)). Estimate \( S_{\lambda}(\tau = 0) \) from the model and calculate \( Y \). One can then immediately find \( f \) from Fig. 5.

The observed spectrum longward of \( \sim 10 \mu m \) is not only determined by the mass loss history, but also by beam effects of the instrument and the absorption coefficient in the far-infrared. Usually, beam effects are neglected when a comparison is made with observations. In Chapter 6 we show that this is not justified in the case of detached shells. In Fig. 6 we show the \( \tau_{9.5} = 10, f = 1 \) model with and without beam effects. At \( \lambda < 7 \mu m \) a Gaussian beam with a FWHM value of 20'' (typical for near-IR observations) is assumed. Between 7 and 140 \( \mu m \) we use the spatial response of the IRAS detectors taken from the Explanatory Supplement (see Chapter 6 for details) and for longer wavelengths the beam of the JCMT telescope is assumed (typically 14'' at 800 \( \mu m \)). The effects are important in the sub-mm region.

In previous studies (e.g. Rowan-Robinson et al. 1986, Justtanont & Tielens 1992) one usually adopted an absorption coefficient \( Q_{\lambda} \sim \lambda^{-\alpha} \) for \( \lambda \) larger than some value (typically 20-30 \( \mu m \)) and determined \( \alpha \) by fitting the IRAS 60 and 100 \( \mu m \) fluxes. Astronomical silicate has \( \alpha \approx 2.06 \).
for $\lambda > 20\mu m$. In Fig. 6 we show the $\tau_{9.5} = 10, f = 1$ model for astronomical silicate and for astronomical silicate with $\alpha = 2.2, 2.5, 2.7$ for $\lambda > 20\mu m$. Comparing Figs. 3 and 6 shows that a steepening of the absorption coefficient has the same effect as an increasing mass loss rate.

5 Discussion

It was shown that an increase with time of the mass loss rate in an oxygen-rich AGB star produces observable signatures in its infrared energy distribution. For the typical case of $M \approx 10^{-5}$ $M_\odot/yr$ ($\tau_{9.5} = 10$) the 100 $\mu m$ flux density for a mass loss rate increasing by a factor of 10 over $10^4$ years is a factor of 2 lower than that for a constant mass loss rate. The difference at longer wavelengths is even larger (a factor of 5). The question is if these signatures would be recognised and attributed to a non-constant mass loss rate when a model is compared to real observations. Consider a comparison based on IRAS fluxes. Even for strong sources ($S_{12} > 100$ Jy) far from the galactic plane the flux uncertainty at 60 and 100 $\mu m$ is seldom better than 15%. This means that mass loss increases of less than a factor of 2 over $10^4$ years would be hard to detect based

Figure 5: The ratio of fluxes Y (defined in the text) as a function of $f$ for $\lambda = 60$ (top panel) and 100 $\mu m$ (bottom panel). Indicated are $\tau_{9.5} = 0.1$ (solid), 1 (dot-dash), 10 (dotted), 50 (dashed).
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Figure 6: Top panel: the influence of beam effects on the SED for the $\tau_{0.5} = 10$ model. The solid curve indicates the standard model without beam effects. The dashed curve represents the model where we assumed a Gaussian beam with a FWHM of 20'' up to 7 $\mu m$, the spatial response of the IRAS detectors between 7 and 140 $\mu m$ and for longer wavelengths the response of the JCMT telescope. The 'instrument' is centered on-source. The dotted curve represent the model where the beam widths of the JCMT telescope are decreased by 1'' and the 'instrument' is centered at 2'' from the central position.

Bottom panel: the influence of different absorption coefficients in the far-IR. Indicated are astronomical silicate (solid) and astronomical silicate with $Q_\lambda \sim \lambda^{-\alpha}$ (for $\lambda > 20 \mu m$) with $\alpha = 2.2$ (dashed), 2.5 (dotted), 2.7 (dashed-dotted).

on IRAS data.

The use of sub-mm observations is limited because of the sensitivity to beam effects. Furthermore, the flux measured may be an overestimate due to CO line emission at 867 and 1300 $\mu m$. In the case of IRC 10 216, Walmsley et al. (1991) estimate that the contribution of molecular line emission to the flux at 1.3 mm is 30%.

Most AGB sources are variables (Miras, Semi-regulars or Irregular). Periods are relatively well known from optical lightcurves for AGB stars that do not lose a lot of mass, but infrared
lightcurves for mass losing OH/IR and infrared carbon stars are less well known. Since the photometric data are usually taken at different epochs, and in the case of the IRAS data is simply an average over all observations, differences between the data and a model prediction can at least partly be attributed to variability.

It was shown that a steeper slope in the far-infrared absorption coefficient has the same effect as an increasing mass loss rate. Although the absorption and scattering properties of dust around AGB stars are uncertain one has to remember that the optical constants should obey the Kramers-Kronig relation.

It will prove difficult to discriminate between an increasing mass loss rate and a change in the far-IR dust properties. A pre-requisite would be simultaneous photometry from the optical to the mm region, preferably of a star with a thick shell, so as to minimize the influence of the underlying central star on the emerging spectrum and the effects of interstellar extinction. The far-IR and mm-observations should preferably be done with a relative small telescope to minimize the influence of beam effects. To investigate the influence of variability one would need to perform these measurements at different phases of the lightcurve. It might be worthwhile to perform such observations for a well chosen sample of stars.

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