Dirty silicate models for hot-centred clouds

M. Rowan-Robinson Department of Applied Mathematics,
Queen Mary College, Mile End Road, London E1

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Summary. Models for spherically symmetric clouds of dirty silicate dust grains illuminated by a young hot OB star are presented and compared with the average infrared spectrum for hot-centred clouds. An excellent fit is found with a uniform density distribution across the cloud: one as steep as \( n(r) \propto r^{-2} \) is ruled out. From the infrared spectra alone it is impossible to infer much about the visible and ultraviolet properties of the grains.

Models are given for a number of individual sources, selected on the basis of their compact size and isolated nature. For a class of source whose infrared spectra resemble that of the BN object in Orion (GL490, 989, 4176, 2591 and probably S140) a double-shell model is required to fit the infrared spectra: an outflowing shell of hot dust with an \( n(r) \propto r^{-2} \) density distribution is surrounded by a second shell of cold dust, presumably associated with the ambient cloud of dust and molecules from which the OB star has formed. The outflow could be spherically symmetric or, as suggested by recent molecular line observations, bi-polar. For an expansion velocity of 25 km s\(^{-1}\), the total mass loss rates (in gas) are estimated to be in the range \( 0.6-10 \times 10^{-7} M_\odot \text{yr}^{-1} \) and could be driven by radiation pressure. However, the masses of gas inferred are a factor of 10\(^3\) below those estimated from CO observations. If the latter are correct they imply that a substantial fraction of the ambient cloud has been accelerated to high velocity and that the acceleration mechanism cannot be radiation pressure acting on dust.

For the remaining sources modelled (W3OH, GL961, GL4182, W75N) a uniform density distribution gives a good fit to the observed spectra, which suggests that the clouds from which the stars have formed are not in a state of collapse. W3OH seems to have evolved slightly further than the others since the dust has been cleared from a zone ten times larger than the grain melting radius.

The idea that the 3.1 \( \mu \) 'ice' feature could be due to organic molecules which are also responsible for the 10 \( \mu \) feature is untenable for the BN-type sources.
1 Introduction

In an earlier paper (Rowan-Robinson 1980) I discussed radiative transfer in dust clouds illuminated by a newly-formed hot star and found that amorphous silicate grains gave a reasonable fit to the typical hot-centred dust cloud spectrum. Studies of radiative transfer in circumstellar dust shells (CDS) around M stars (Rowan-Robinson & Harris 1982a, b) show that the dirty silicate grain models of Jones & Merrill (1976) give an excellent fit to the spectra of these CDS (except that in the case of early M supergiants there is evidence that the grain absorption efficiency in the range 8–10 μm needs to be reduced compared to the Jones & Merrill values). In this note I investigate the suitability of dirty silicate grain models for hot-centred dust clouds, applying them both to the mean spectrum for hot-centred clouds (Rowan-Robinson 1979) and to a number of individual clouds.

2 Grain properties

For modelling infrared emission from CDS around M stars, the behaviour of the grains at visual and ultraviolet wavelengths is of great importance (Rowan-Robinson & Harris (1982a, b) assumed $Q_{\nu,\text{abs}} = 0.472$ and $Q_{\nu,\text{sc}} = 0.708$ for $\lambda < 0.4 \mu$m). For a dust cloud illuminated by a hot star the visual and ultraviolet properties of the grains could be more important. In this note I have adopted an empirical approach and used the observed total extinction and albedo found in interstellar extinction studies (Savage & Mathis 1979) for $\lambda < 0.8 \mu$m. With this assumption $\tau_{\text{uv}} \equiv \tau(\lambda < 0.1 \mu$m) can be related to the monochromatic optical depths at 0.5 and 10 μm by $\tau_{\text{uv}} = 4.17 \tau(0.5 \mu$m) = 26.4 $\tau(10 \mu$m).

Rowan-Robinson (1979) found that at long wavelengths ($> 350 \mu$m) the absorption efficiency in hot-centred clouds behaves as $Q_{\nu,\text{abs}} \propto \nu$. I have therefore extrapolated the Jones & Merrill (1976) absorption efficiency as $Q_{\nu,\text{abs}} \propto \nu$ for $\lambda > 50 \mu$m (case a) and for $\lambda > 100 \mu$m (case b), both of which give absorption efficiencies at 350 μm and 1 mm within a factor of two of the estimates of Rowan-Robinson (1979). Grains in the interstellar medium can presumably be thought of as a mixture of grains formed in the atmospheres of oxygen-rich and carbon-rich stars, so this long wavelength extrapolation may be the contribution of amorphous carbon grains, for which $Q_{\nu,\text{abs}} \propto \nu$ for $\lambda > 1 \mu$m (Koike, Hasegawa & Manabe 1980).

![Figure 1](https://academic.oup.com/mnras/article-abstract/201/2/289/1024226)  

Figure 1. Grain properties used in the present paper. Solid line: absorption efficiency, dotted line: scattering efficiency. The broken curve shows the case (b) absorption efficiency at long wavelengths.
and which are found to give a good fit to the infrared emission from CDS around carbon stars (Rowan-Robinson & Harris 1982c). The grain properties are shown in Fig. 1. The contribution of H$_2$O ice mantles has not been included in the grain properties: this is discussed further below in Section 6. The grains are assumed to scatter isotropically, in the absence of observational evidence on the grain phase function in these clouds.

3 Model parameters

The basic models consist of a spherically symmetric dust cloud illuminated by a star at the centre. Although many examples are known where the geometry is far from spherically symmetric, this may be a reasonable assumption during the early stages in the evolution of a hot-centred cloud. Possible departures from spherical symmetry are discussed in Section 5.

Rowan-Robinson (1980) showed that the temperature of the illuminating star, $T_\text{s}$, has little effect on the emergent infrared spectrum if $T_\text{s} > 10000 \text{ K}$, so I take $T_\text{s} = 40000 \text{ K}$, corresponding to an O5 star. Rowan-Robinson & Harris (1982b) found that the temperature of the hottest grains, $T_\text{1}$, was 1000 K for most CDS in which the optical depth across the shell at high frequencies, $\tau_\text{uv} > 1$. I have therefore adopted this value here. The remaining parameters are then the density distribution, which I take as $n(r) \propto r^{-\beta}$, $\tau_\text{uv}$, and the extent of the cloud, characterized by $r_1/r_2$, where $r_1$ and $r_2$ are the inner and outer radii of the cloud.

4 Mean spectrum for hot-centred clouds

Infrared spectra for a series of models with $\beta = 0, 1, 2$ are shown in Fig. 2. Unless otherwise specified they correspond to case (a) grain properties at long wavelengths and $r_1/r_2$ has been taken as 0.001 in order to give far infrared surface brightneses in the range found for hot-centred clouds (cf. Rowan-Robinson 1980). The average spectrum for hot-centred clouds (Rowan-Robinson 1979) is shown as vertical bars, together with the $\pm 1$-sigma range. It should be noted that this average includes sources where the assumption of spherical symmetry is certainly not a good one. The effect of replacing the absorption and scattering efficiencies in the visible and ultraviolet by those assumed by Jones & Merrill (1976) is also illustrated. From this comparison of theory and observation a number of general conclusions can be drawn.

(i) Dirty silicate grains provide an excellent fit to the infrared spectra of hot-centred clouds.

(ii) The properties of the grains at visible and ultraviolet wavelengths cannot be inferred from infrared spectra alone.

(iii) If the assumption of spherically symmetric illumination by a single source (or small cluster of sources) at the centre is correct for the majority of these clouds, a density distribution as steep as $n(r) \propto r^{-2}$ is ruled out, $n(r) \propto r^{-1}$ is acceptable, and $n(r) = \text{constant}$, is the best fit. This suggests that the clouds have not collapsed very far and that the theoretically predicted $n(r) \propto r^{-1.5}$ or $r^{-2}$ regimes (e.g. Black & Bodenheimer 1978) can apply only near the newly formed star.

(iv) $r_1/r_2$ lies within a factor of 3 of 0.001 for most of the clouds in Table 1 of Rowan-Robinson (1979). Since the characteristic size of these clouds is in the range $\sim 1-20$ arcsec (diameter $\sim 1-20$ pc), the main emission at short wavelengths ($\lambda < 10 \mu$) should come from regions 0.05-1.0 arcmin in extent. The H II regions associated with the illuminating star(s) would not be much larger than this. In many cases a substantial part of the illumination is...
Figure 2. Emergent spectra for dirty silicate models with $T_s = 40\,000\,K$, $T_1 = 1000\,K$ and, unless otherwise specified, $r_i/r_j = 0.001$ and case (a) long wavelength grain properties. (a) $\beta = 0$, $\tau_{uv} = 40, 100, 200, 500$. (b) $\beta = 0$. Solid curves: $\tau_{uv} = 200$ and, from the top, $r_i/r_j = 0.00316, 0.001, 0.000316$. The broken curve shows the effect of using case (b) long wavelength grain properties in the $r_i/r_j = 0.001$ model. The dotted curve is for grain properties used in Rowan-Robinson & Harris (1981a, b), with $\tau_{uv} = 100, r_i/r_j = 0.001$. The vertical bars are the mean spectrum for hot-centred clouds calculated by Rowan-Robinson (1979), with $\pm 1\sigma$ range. (c) $\beta = 1$, $\tau_{uv} = 50, 100, 200, 500$. (d) $\beta = 2$, $\tau_{uv} = 50, 100, 200, 500$.

provided by a star with an H II region much more evolved and extended that this, and in these cases the assumption of spherical symmetry is certainly not satisfied.

(v) $\tau_{uv}$ lies in the range $50-200$, the corresponding visual extinction is $A_v \sim 12-50$ and the $10\mu$ optical depth is $2-8$. These are in good agreement with the range of values found in studies of infrared hydrogen lines (Thompson & Tokunaga 1978, 1980; Tokunaga & Thompson 1979a, b) and of the $10\mu$ feature (Gillett et al. 1975; Willner 1976, 1977; Merrill, Russell & Soifer 1976; Beckwith et al. 1976).
5 Models for individual clouds

Fig. 3 shows model fits to the infrared spectra of a number of individual sources, selected for their compact size and isolated nature, so that they are the most likely to satisfy the assumption of spherically symmetric illumination by a single star. For a number of sources with infrared spectra similar to the BN object in Orion, which I shall refer to as BN-type objects, the spectrum does not appear to be consistent with a single power-law density distribution. For these a double-shell model, similar to that discussed for OH–IR II sources by Rowan-Robinson (1982), except that the illuminating star is here assumed to be hot (40 000 K), is fitted. Fig. 4 shows predicted spectra for different optical depths in the hot emitting ($n(r) \propto r^{-2}$) dust and for a range of 10$\mu$ optical depths, $r_{10}\psi$ in the second shell of cold absorbing dust, which we may identify with the ambient cloud in which the new massive star has formed.

Table 1 gives the parameters for these models, the columns giving: (1) AFGL number, (2) source name, (3) the vertical scaling constant $C$ in Fig. 3, (4) references for infrared data, (5) $r_{10}\psi$, (6) $r_{10}\mu$, the optical depth at 10$\mu$ in the second shell of cold dust, (7) $r_{1}/r_{2}$, (8) the predicted overall angular radius of the dust cloud, (9) $\log_{10}$ of the distance in kpc, (10) reference for distance, (11) $\log_{10}$ of the total luminosity implied by the model, in solar
Figure 4. Double-shell models with $T_\infty = 40\,000\,\text{K}$, $T_1 = 1000\,\text{K}$, $\beta = 2$ and, from the top, $\tau_{uv} = 500$, 200, 100, 50. In each case models are shown with $\tau_{10\mu} = 0, 1, 2, 3$.

units, (12) $\log_{10}$ of the overall radius of the dust cloud, in cm, (13) $\log_{10}$ of the mass in dust, in solar units. Columns (14) and (15) are discussed in Section 6 below.

I now discuss the sources modelled in Fig. 3 individually:

**W3OH**

The uniform density ($\beta = 0$) distribution gives a reasonably good overall fit to the spectrum, although the predicted $10\mu$ feature is rather deeper than observed and the $T_1 = 1000\,\text{K}$ model predicts higher fluxes than observed at $3-5\mu$. The angular radius of the inner edge of the cloud, $0.045\,\text{arcsec}$, would lie well within the shell of ionized gas seen by Dreher & Welch (1981) and Scott (1981) at $\theta = 0.5-0.8\,\text{arcsec}$. A model with $r_1/r_2 = 0.01$, $T_1 = 300\,\text{K}$, has therefore been plotted. The inner edge of the dust cloud would then have angular radius $\theta_1 = 0.45\,\text{arcsec}$ and would lie at the edge of the HII region. This model fits the observations well for $\lambda > 3\mu$. The fluxes observed at 1.6 and 2.2$\mu$ are about a factor of 20 too high compared with the predicted fluxes, which are due entirely to transmitted (and scattered) light from the star. This could be due to an overestimate of the grain absorption efficiency by a factor of about 2 at these wavelengths. Alternatively there may be some...
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<th>(\log d) (kpc)</th>
<th>(\log L/L_\odot)</th>
<th>(\log r_2) (cm)</th>
<th>(\log M_\Delta/M_\odot)</th>
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**Notes**

- \( T_1 = 300 \text{ K.} \)
- \( T_S = 2500 \text{ K.} \)
- Mass in hot dust only.
- \( T_S = 600 \text{ K}, T_1 = 200 \text{ K.} \)
- \( T_S = 600 \text{ K}, T_1 = 150 \text{ K.} \)
- For biconical model, \( L, \theta_2^2, r_2^2 \), and \( r_2^2 \) have to be scaled by \((1 - \cos \alpha)\).
- Biconical model: \( L, \theta_2^2, r_2^2 \), have to be scaled by \( \cos \alpha \).

19. Cas OB6, distance for this and other OB associations from Alter et al. 1966.
20. Cam OB1.
22. Mon OB1.
emission from hot dust within the H II region. Predicted intensity profiles are shown for the $T_1 = 300\,\text{K}$ model in Fig. 5(a) for several wavelengths.

**GL490**

The double-shell model gives a good fit to the observations at $\lambda < 10\mu$ of this BN-type object, in which a high-velocity outflow has been observed (Lada & Harvey 1981). The spectrum would be almost unchanged if the illuminating star were cool, but this would be inconsistent with the observed Bo emission (Thompson & Tokunaga 1979; Simon, Simon & Joyce 1979), assuming this is due to photoionization, and with the lack of molecular bands in the

![Figure 5(a). Intensity profile, relative to intensity at rim of cavity, at different wavelengths for $T_1 = 300\,\text{K}$ model for W3OH.](image1)

![Figure 5(b). Intensity profile at different wavelengths for W75N model.](image2)
visible spectrum (Cohen & Kuhi 1977). The circumstellar extinction implied by the model, $A_V = 9.6$, agrees well with the direct estimate by Cohen & Kuhi (1977), $A_V = 10.5$ for a heavily extinguished O or B star (allowing $\sim 1$ mag for interstellar extinction, plausible for $d = 0.9$ kpc).

To explain the excess radiation observed at $\lambda > 10\mu$ in GL490, there are two simple possibilities. If the assumption of spherical symmetry is broadly correct then the far infrared radiation could simply be re-emission of the radiation absorbed by the cold ambient dust shell from the hot outflowing dust. To model this emission we consider a uniform density cloud illuminated by a $T_s = 600$ K blackbody, a reasonable approximation to the emission from the hot outflowing $n(r) \propto r^{-2}$ shell. A good fit to the far infrared observations is obtained with $\tau_{uv} = 50$, $r_1/r_2 = 0.01$, $T_1 = 200$ K (this would result in $r_{10\mu}^C \sim 2$, but the star may not be exactly at the centre of the ambient cloud).

Figure 6. Sketch of possible configuration for a bipolar outflow from a star embedded in an ambient molecular cloud.
Since CO observations of the high velocity outflow in GL490 suggest a bipolar structure (Lada & Harvey 1981), a second possibility for this source is that the hot outflowing \( n(r) \propto r^{-2} \) dust is confined to a biconical region of semi-angle \( \alpha \), absorbing a fraction \( 1 - \cos \alpha \) of the star’s output. The remainder would be absorbed directly by the ambient cloud and be re-emitted in the far infrared. A reasonable fit to the far infrared spectrum is obtained with \( \beta = 0 \), \( \tau_{uv} = 40 \), \( r_1/r_2 = 0.001 \) and a comparison of the luminosities in the two components yields \( \alpha = 62^\circ.5 \). Here I am assuming that the temperature structure in a biconical shell, or in a spherical shell with a biconical section removed, is identical to that of a spherical shell, which will not be strictly valid particularly near the conical boundary between the shells. I am also neglecting the heating effect of radiation from the hot outflowing dust on the cold ambient cloud. Clearly a more accurate solution of this problem, which correctly accounts for the radiation crossing the conical boundary, is desirable.

A natural explanation of a biconical structure for the outflow could arise if the star was strongly magnetic: a sketch of the model is given in Fig. 6.

**GL961 (N2244, Rosette)**

A uniform density model with \( T_1 = 1000 \) K is a reasonable fit to the spectrum. The cloud is predicted to extend from angular radius \( \theta_1 = 0.025 \) arcsec to \( \theta_2 = 25 \) arcsec and the 50 \( \mu \) intensity falls to 10 per cent of the value at \( \theta = \theta_1 \) at \( \theta = 3.6 \) arcsec, consistent with the 20 arcsec upper limit set by Harvey, Campbell & Hoffmann (1977a).

**GL989**

Although a \( \beta = 1 \) density distribution gives a reasonable overall fit to the spectrum, the predicted 10 \( \mu \) absorption is too deep. A double-shell model is a good fit to the \( \lambda < 10 \mu \) observations. As with GL490, the longer wavelength radiation could then come from a more extended uniform density cloud, illuminated either by the outflowing \( n(r) \propto r^{-2} \) shell of hot dust or directly by the star if the latter shell has a biconical structure. The inferred value of the cone semi-angle for the latter model is \( \alpha = 55^\circ.2 \).

**GL4176 (OH 308.9 + 0.1)**

This appears to be another BN-type object and is fitted reasonably well by a double-shell model.

**GL4182 (OH 309.8 + 0.5)**

None of our models fits the spectrum observed by Epchtein et al. (1982) particularly well: a uniform density model is shown which extends from angular radius 0.042 to 42 arcsec. Further observations are desirable, particularly at longer wavelengths.

**GL2591**

The double-shell model is an excellent fit to this BN-type object. Almost as good a fit is obtained if the temperature of the illuminating star is taken as 2500 K. Although Ba has not been detected in this source (Thompson & Tokunaga 1979; Simon et al. 1979) the upper limit does not rule out the presence of a hot main-sequence star.

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W75N

A uniform density model is a good fit to the spectrum. The predicted intensity profiles at several wavelengths are shown in Fig. 5(b) for this model. At 50 μ the intensity falls to 50 per cent of the peak value seen at the rim of the cavity at an angular radius of 0.63 arcsec and to 10 per cent of the peak value at 8.5 arcsec. This can be compared with the map of Harvey et al. (1977b), which shows the source to be essentially unresolved with a 17 arcsec beam.

S140

The uniform density model gives a reasonable overall fit to the spectrum, although it predicts too little radiation at λ < 2 μ (cf. W3OH), too shallow a 10 μ feature and too much radiation at λ > 50 μ (this could be improved by using case (b) grain properties). A β = 1 density distribution is also shown, which is a better fit at long wavelengths and gives the correct 10 μ depth, but does not give a good fit to the shape of the spectrum in the range 1.25—5 μ.

The spectrum of S140 can also be interpreted in terms of two-component models similar to those used for GL490 and 989. For the biconical model the cone semi-angle α = 52°.4. Solomon, Hugeni & Scoville (1981) report that high velocity molecular gas has also been seen in this source.

The intensity profiles at several wavelengths for the uniform density model are shown in Fig. 5(c). At 50 μ the intensity falls to 50 per cent of the peak value at the rim of the cavity at an angular radius of 1.35 arcsec and to 10 per cent of the peak value at 10 arcsec, consistent with the observation of Harvey et al. (1978) that the source is probably marginally resolved with a diameter of 20 arcsec.

The 10 μ profile observed by Blair et al. (1978) is narrower than that observed in any other astronomical source: this deserves further investigation.

6 Discussion

The sources chosen are reasonably well fitted by two types of model.

6.1 GL490, 989, 4176 and 2591

For the BN-type sources a double-shell model fits well. The inner shell of hot dust with an \( n(r) \propto r^{-3} \) density distribution is presumably associated with the high velocity outflow which has been seen in several sources (Rodriguez, Ho & Moran 1980; Snell, Loren & Plambeck 1980; Solomon et al. 1981; Lada & Harvey 1981; Beckwith 1981). For an outflow velocity of 25 km s\(^{-1}\), the rates of loss of mass in dust lie in the range 0.6—9.5 \times 10^{-7}M_\odot per year (column 14 of Table 1). To test whether this outflow could be driven by radiation pressure acting on the dust, I calculate what Zuckerman (1981) calls the ‘overpressure’, \( \xi = M_g v c / L \), assuming \( v = 25 \text{ km s}^{-1} \) (the value found in GL490 by Lada & Harvey 1981) and that the mass of gas \( M_g = 50M_d \), and compare it with the value predicted by our models (see Appendix A). The ratio of observed to predicted values ranges (column 15 of Table 1) from \(~ 0.1\) for GL4176 to 1.0 for GL490 and 1.2 for GL989, < 1 to within the uncertainties of the model parameters. The actual mass of gas \( M_g \) (but not the rate of loss of mass) depends on the value of \( r_2 \), a parameter poorly determined in our models. However, if we use the extent of the high-velocity CO emission observed in GL490, \( r_2 = 0.29 \text{ pc} \) (Lada & Harvey 1981), we obtain a mass \( M_g = 0.034M_\odot \) in hot outflowing gas, an estimate which would not
be greatly altered by a biconical structure for the shell. This represents a huge discrepancy with the estimate from CO observations, $M_\text{g} = 16-45 M_\odot$. Assuming the interpretation of the CO line profiles is correct, the only conclusion must be that a substantial fraction of the ambient cloud has been accelerated to high velocity and that the acceleration mechanism is not radiation pressure.

Several of these sources (GL490, BN, GL989) show excess line radiation compared with a zero-age main-sequence star, which may require mass-accretion to explain it. This has been indicated schematically in Fig. 6.

S140 can also probably be best understood as a BN-type object, since a $\beta = 1$ density distribution does not have a natural interpretation.

6.2 W3OH, GL961, GL4182, W75N

For W3OH, GL961, GL4182, W75N, a uniform density cloud illuminated by an early-type star gives a reasonable fit to the observed spectra. This suggests that the molecular clouds from which the stars have formed are not in a state of collapse. Assuming a dust-to-gas ratio of 0.02, the masses of these clouds range from $27 M_\odot$ for GL961 to $1.6 \times 10^{5} M_\odot$ for W3OH and $1.9 \times 10^{5} M_\odot$ for GL4182 (assuming $d = 4$ kpc). W3OH seems to have evolved slightly further than the others since the dust has been largely cleared from a zone ten times larger than the grain melting radius. This is consistent with the higher position of W3OH in the log$L - \log(N_\text{H}_2 \cdot \nu)$ diagram of Thompson (1981), between the zero-age main-sequence and supergiant loci.

The 3.1 $\mu$m features seen in the spectra of GL490, GL989 and 2591 can be compared with that in BN to obtain the optical depths, relative to BN, 0.15, 0.84, 0.59. The lack of correlation of this 3.1 $\mu$m optical depth with the depth of the 10 $\mu$m feature is well-known. From the model parameters given here, it can be seen that 3.1 $\mu$m optical depth is correlated neither with the optical depths in the hot outflowing dust ($\tau_{\text{uv}} = 40, 50, 100$) nor in cold absorbing dust ($\tau_{\text{e}} = 1, 0.5, 2$), so it appears that the formation of ice mantles depends strongly on local conditions. The idea that this feature is due to organic molecules which are also responsible for the 10 $\mu$m feature (Hoyle & Wickramasinghe 1977a, b, c, d, 1978, 1979) is clearly untenable.

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References

Appendix A

It can be shown (Rowan-Robinson 1982, in preparation) that the radial momentum absorbed by dust from radiation flowing through a spherically symmetric dust cloud is

\[
\frac{16\pi^3 a^2}{c} \int_0^\infty \left[ Q_{\gamma,\text{abs}} + Q_{\gamma,\text{sc}} (1 - \langle \cos \phi \rangle) \right] \, dv \int_{r_s}^{r_1} n(r) r^2 H_\gamma(r) \, dr
\]
where \( \langle \cos \phi \rangle \) is the anisotropy factor for scattering, and \( H_\gamma (r) \) is the net outward flux across \( r \).

This can be written \( \tau_H L/c \), where \( \tau_H \) is the effective optical depth at the peak frequency of the outward flux averaged over the different zones of the cloud.

Equating the radial momentum absorbed by the dust to the total outward momentum of the cloud, we have

\[
\tau_H L/c = \dot{M}_g v_g + \dot{M}_d v_d = \dot{M}_g v_g
\]

since \( v_d = v_g = v \) if the gas and dust are well-coupled. Thus the 'overpressure' factor \( \xi = \dot{M}_g uc/L = \tau_H \). This has been evaluated for each of the double-shell models used in the present paper, and the ratio of the observed to the predicted value is given in column 15 of Table 1.

Note that for \( \tau_{uv} \gg 1 \), \( \xi \) can be \( \gg 1 \), and this is because the photons are absorbed and re-emitted many times, always with velocity \( c \). Scattering can make a contribution to the momentum transfer, provided \( \langle \cos \phi \rangle < 1 \), (cf. Phillips & Beckman 1980) but does not do so significantly for the grains used in the present paper.