Double-shell circumstellar dust shells

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Summary. Models are presented for high optical depth Type II OH-IR sources with deep silicate absorption. The models consist of a cool star at the centre of a spherically symmetric $n(r) \propto r^{-2}$ dust shell together with a second shell of cold absorbing dust. From kinematic arguments the luminosities of the sources are close to $10^5 M_\odot$. The origin of the second shell is discussed and the only plausible explanation is that it represents a previous phase of ejection by the star. The mass of gas in the shell of cold dust is estimated to be 4–15 $M_\odot$ assuming normal abundances, and it is inferred that the sources must represent the late stages of evolution of massive stars, $M \geq 30 M_\odot$. The alternative hypothesis, that the stars are giants in the last stages of planetary nebula formation, could hold only if the second shell is at least a factor of 3 closer in to the star than estimated here. This would lead to a poor fit of the long wavelength data.

1 Introduction

Searches for infrared sources at the positions of OH masers have yielded a new class of circumstellar dust shell (Evans & Beckwith 1977). The OH sources are of type II (strongest emission at 1612 MHz, double-peaked velocity structure), the dust shells are of high optical depth ($\tau_{uv} \gg 40$), and there is an absorption feature, often very deep, at 10 $\mu$m. Oxygen-rich features have been seen in OH 26.5 +0.6 and GL 2885 (Merrill & Stein 1976) and 2.3 $\mu$m CO absorption has been seen in OH 30.1−0.2 and 45.5 +0.1 (Evans & Beckwith 1977), indicating that the illuminating stars are of late type.

The 10 $\mu$m absorption distinguishes these objects from other high optical depth circumstellar dust shells modelled by Rowan-Robinson & Harris (1982a), e.g. GL 157, 585, 1274, 1977, 2350, 2514, 2650. Werner et al. (1980) have proposed that a $n(r) \propto r^{-1.5}$ density distribution could account for this. Rowan-Robinson & Harris (1982a) propose a two-component model for GL 2205 (OH 26.5 +0.6) and 2885, in which a normal $n(r) \propto r^{-2}$ dust shell is surrounded by an additional shell of cold dust, and in this paper this model is applied to other objects in the class and discussed in further detail.

The objects modelled in the present paper are listed in Table 1. In addition to the six sources found by Evans & Beckwith (1977), a further five AFGL sources identified with OH sources have similar spectra (GL 230, 1882, 1992, 2290, 2885).
Table 1. Parameters for double-shell CDS.

<table>
<thead>
<tr>
<th>Source</th>
<th>Refs for IR and OH data</th>
<th>C in Fig. 2</th>
<th>$\tau_{uv}$ (arcsec)</th>
<th>$\tau_{f_{\nu}}$ (arcsec)</th>
<th>$\log \theta_{f}$ (arcsec)</th>
<th>Kinematic distances $a$ (kpc)</th>
<th>$\log (L/L_{\odot})$, luminosity at max. near far</th>
<th>Adopted distance hot cold</th>
<th>$\log (M_d/M_{\odot})$</th>
<th>$\log (\dot{M}<em>d)$ ($M</em>{\odot}$/yr)</th>
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<tr>
<td>OH 21.5 + 0.5</td>
<td>1, 2</td>
<td>3.5 s</td>
<td>200</td>
<td>-2.25</td>
<td>3</td>
<td>0.27</td>
<td>7.5 10.9</td>
<td>5.08 5.41 7.5 -1.84 0.46</td>
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<tr>
<td>(GL 2205)</td>
<td></td>
<td>w 300</td>
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<td>40</td>
<td>-2.31</td>
<td>1</td>
<td>0.20</td>
<td>3.1 14.0</td>
<td>4.19 5.60 (7.9) -2.62 -0.10</td>
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<td>(GL 2290)</td>
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<td>w 50</td>
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<td>-2.475</td>
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<td>75</td>
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<td>1.1</td>
<td>14.3 6.44</td>
<td>(2.7) -2.09 0.20 -5.66</td>
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<td>w 40</td>
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<tr>
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<td>0.36</td>
<td>2.1 11.7</td>
<td>3.57 5.07 11.7 -1.85 -0.03</td>
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<td>19.0 6.09</td>
<td>(5.4) -2.22 -0.10 -5.89</td>
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<tr>
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<td>20</td>
<td>-1.775</td>
<td>2</td>
<td>-</td>
<td>-</td>
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<td>-2.05</td>
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</table>

References for Table 1.

Notes
The masses of hot and cold dust are calculated assuming $r_{s} \sim r_{w} \sim r_{f} = 10^{3} r_{f}$. The final column of the table gives the rate of outflow of hot dust. $s$ and $w$ denote the strongest and weakest phases at which observations are available.
Double-shell models

The models consist of a spherically symmetric dirty silicate dust shell with an $n(r) \propto r^{-2}$ density distribution, illuminated by a $T_s = 2500$ K blackbody. As in Rowan-Robinson & Harris (1982a) the temperature the hottest grains would have if heated only by the star is set to $T_1 = 1000$ K: the actual temperature achieved by the hottest grains is somewhat higher due to the absorption of light emitted or scattered by dust. The parameters of the shell are therefore the total extinction optical depth in the ultraviolet, $\tau_{uv} (= \tau(0.5 \mu m) \times 1.31 = \tau(10 \mu m) \times 13.4)$, and the extent of the shell, characterized by $r_1/r_2$, where $r_1$ and $r_2$ are the inner and outer radii of the CDS. As the parameter $r_1/r_2$ is not very well determined by the infrared observations, it has been set to 0.001 for the models shown. The infrared emission from this CDS is then subjected to extinction by cold dirty silicate dust, characterized by the optical depth at $10 \mu m$, $\tau_{10}^{c}$. The grain properties are as shown by the solid curve of fig. 1 of Rowan-Robinson & Harris (1982b).

Sequences of such models are illustrated in Fig. 1 and detailed fits to the observed spectra of the sources in Table 1 are shown in Fig. 2, the corresponding CDS parameters being given

![Figure 1. Sequence of double-shell models with $T_s = 2500$ K, $T_1 = 1000$ K, $r_1/r_2 = 0.001$, dirty silicate grains, and $\tau_{uv} = 20, 50, 100, 200, 400$. In each case models with, from the top, $\tau_{10}^{c} = 0, 1, 2, 3$, are shown. The constant $C$ is, reading from the top, $2.45 - 2 \log \theta_{\circ\text{arcsec}} + 4, 3, 1, -1, -3$, where the units of flux are erg s$^{-1}$ cm$^{-2}$.](image-url)
in Table 1. The CDS responsible for the emission has $\tau_{\text{uv}}$ ranging from 40 to 300, while the second shells of cold dust have $\tau_{\text{OH}}^* = 1-3$ ($\tau_{\text{uv}} = 13-40$). As the sources vary, the optical depth in hot emitting dust predicted by the models varies, but the optical depth in cold dust does not. Forrest et al. (1978) noted that the depth of the 10 $\mu$m feature in OH 26.5 + 0.6 varies with phase. The models proposed here for this object at the two best-studied phase (Fig. 2c) show that this effect can be interpreted as due to variation in the optical depth in the hot emitting dust, the optical depth in the second shell of cold dust remaining the same at both phases. Inclusion of the effect of molecular bands would have virtually no effect on the spectra of Figs 1 and 2 (Rowan-Robinson & Harris 1982a) and the choice of stellar temperature is also not critical in such high optical depth dust shells. Almost identical spectra would result if $T_\star = 2000$ K, for example.

Models in which the density distribution is changed to $n(r) \propto r^{-\beta}$, with $\beta = 0$ or 1, are shown in Fig. 3. These can not adequately represent the observed spectra of Fig. 2.
3 Luminosities and distances

Evans & Beckwith (1977) calculate kinematic distances for six of the sources of Table 1. These lead to the luminosities, corrected for the effect of extinction by cold dust, given in Table 1. Two of these entries stand out as implausible. The far kinematic distance for OH 26.5 + 0.6 leads to a luminosity of $5.1 \times 10^6 L_\odot$, which would make it one of the most luminous stars in our Galaxy. The near distance for OH 45.5 + 0.1 leads to a luminosity of $3.7 \times 10^3 L_\odot$, a factor of more than 20 below the minimum luminosities implied for OH 21.5 + 0.5, 26.5 + 0.6 and 32.8 - 0.3. If the near distance is adopted for OH 26.5 + 0.6 and the far distance for 45.5 + 0.1, their luminosities are 6.4 and $12 \times 10^4 L_\odot$, similar to those derived from the unambiguous kinematic distances for GL 230 and 2885, 1.3 and $1.25 \times 10^5 L_\odot$. These can be compared with the maximum luminosity for stable red giant stars with degenerate cores of $6 \times 10^5 L_\odot$ (Paczyński & Ziolkowski 1968; Wood 1979) and with the range of luminosity for early M supergiants with CDS, $2 - 36 \times 10^4 L_\odot$ (Rowan-Robinson & Harris 1982b). These stars are therefore at the very highest luminosity end of the red giant range or are in the middle of the luminosity range for supergiants with CDS.

If the near distances are adopted for OH 21.5 + 0.5, 30.1 - 0.7 and 32.8 - 0.3, their luminosities are 12, 7 and $9 \times 10^4 L_\odot$, so that for seven of the stars a luminosity close to $10^5 L_\odot$ is plausible. We therefore adopt this luminosity for the remaining stars in Table 1.
The objects then fit very nicely on the luminosity—expansion velocity relation found by Rowan-Robinson (1982) for M giants and supergiants and carbon stars. The source 345.0 + 15.7 (GL 1822) poses a problem since a luminosity of $10^5 L_\odot$ implies a height above the Galactic plane of 1.4 kpc compared with < 100 pc for all the other sources.

4 The nature of the second shell

The possibility that the material responsible for the 10 $\mu$m absorption is simply interstellar material in the line-of-sight was discussed by Evans & Beckwith (1977) and found by them to be unlikely. They also argue that this cold material is unlikely to be a molecular cloud surrounding the star. I consider two further possibilities here: (1) that the shell is due to interstellar material swept up by the expanding dust shell, (2) that the shell represents a previous phase of ejection by the star.

4.1 Swept-up Interstellar Material

If the shell is at distance $r$ from the star and is of thickness $\Delta r$, then

$$\tau_{10 \mu m} = \pi a^2 Q_{10 \mu m} n \Delta r,$$

(1)
where \( n \) is the number-density of grains in the shell and \( a \) is the radius of the grains. The corresponding mass in dust is

\[
M_d = 4\pi (4\pi a^3 \bar{\rho}_{gr}/3) n r^2 \Delta r \\
= (16\pi a \bar{\rho}_{gr}/3 Q_{10 \mu m}) r_{10 \mu m}^2.
\]

(2)

where \( \bar{\rho}_{gr} \) is the mean density of the grain material. If the number-density of hydrogen atoms in the interstellar gas is \( n_H \), then the mass of swept-up hydrogen is

\[
M_g = 4\pi r^3 n_H m_H/3.
\]

(3)

If the dust comprises a fraction \( Z \) of the interstellar material by mass, then \( M_d = Z M_g \) and from equations (1) – (3)

\[
n_H = (4a \bar{\rho}_{gr}/Z m_H Q_{10 \mu m}) r_{10 \mu m}/r.
\]

(4)

If we take \( r = r_2 = 1000 r_1, a = 0.1 \mu m, \bar{\rho}_{gr} = 2.5 \text{ gm cm}^{-3} \), we find \( n_H \) in the range 1.2 – 3.8 \times 10^5 cm^{-3}. Such densities would only be encountered in a dense molecular cloud, but Evans & Beckwith (1977) find that no molecular cloud with \( A_V > 10 \) exists in the direction of these sources in the appropriate velocity range. Placing the shell further out leads to unreasonable values for the total mass swept up. This hypothesis is therefore implausible.

### 4.2 Previous Ejecta

If the shell of cold dust also has a \( n(r) \propto r^{-2} \) structure, for \( r_3 \leq r \leq r_4 \), then

\[
\tau_{10 \mu m}^c = \pi a^2 Q_{10 \mu m} n(r_4) r_4 (r_4/r_3 - 1)
\]

and

\[
M_d = (16\pi a \bar{\rho}_{gr}/3 Q_{10 \mu m}) r_3 r_4 \tau_{10 \mu m}^c
\]

(5)

(6)

and with \( r_3 \approx r_4 \approx r_2 = 1000 r_1 \) we find masses of cold dust in the range 0.8 – 2.9 \( M_\odot \). To get an estimate of the radial distance of the shell from the star, a lower limit is given by the angular radii measured for the OH emission from GL230 (\( \theta_{OH} = 1.55 \text{ arcsec, Booth et al. 1981} \)) and OH265 + 0.6 (\( \theta_{OH} = 1.1 \text{ arcsec, Reid, Moran & Johnston 1981} \)), i.e. \( r_3 \geq 10^2 r_1 \).

(A similar limit follows from the estimate of Schultz, Sherwood & Winnberg 1978 that the typical size of the OH sources is \( 4 \pm 2 \times 10^{16} \text{ cm} \).) For a more direct estimate we note that at longer wavelengths we may expect to observe a flux from this dust of \( 4\pi \theta^2 \tau_{10 \mu m}^c B_\nu(T_d) \), where \( T_d \) is the temperature of the cold dust and \( \theta \) is the angular radius of the shell of cold dust. The observed spectra in Fig. 2 do indeed show an excess compared with the models at wavelengths \( \gtrsim 30 \mu m \) in several cases. These observed far infrared excesses are consistent with \( T_d = 50 \text{ K} \) (the broken lines in Fig. 2) and the corresponding values of \( \theta \) are given in Table 1.

The resulting values of \( \theta/\theta_1 \), where \( \theta_1 \) is the angular radius of the inner edge of the hot dust shell, are in the range \( 10^{2.5} - 10^{2.8} \) and this agrees well with the prediction of the models that a temperature of 50 K would be achieved by the dust at distances \( r \sim 10^{2.5} r_1 \) from the star. With this latter value equation (6) then leads to masses of cold dust in the range 0.08 – 0.29 \( M_\odot \) and the corresponding mass of gas in the shell, assuming \( Z = 0.02 \), is 4 – 15 \( M_\odot \). The ejection would have occurred about 3000 years ago if it took place at the velocities of expansion inferred from the OH data. These ejected masses are clearly inconsistent with the hypothesis that the stars are giants, for which stellar masses in the range 1 – 2 \( M_\odot \) would be expected. If \( r_3 \sim r_4 \sim 10^2 r_1 \), the distances at which the OH emission is...
observed, the ejected masses would be $0.4 - 1.5 M_\odot$ and the stars could be giants in the process of forming planetary nebulae. However, at this radius the dust temperature would be 100 K and the agreement with the observed long wavelength excess would be poor. Also the low height above the Galactic plane of all the objects except GL1822 (which deserves further study) suggests the stars belong to Population I. The stars are therefore probably supergiants and represent the late stages of the evolution of massive stars ($M > 15 M_\odot$). These objects may resolve a long-standing paradox, the absence of very luminous cool stars corresponding to the late stages of the evolution of very massive stars ($30 - 100 M_\odot$) (Humphreys & Davidson 1979). An object like η Carinae might be the precursor for these double-shell sources, though the mass of dust ejected by η Carinae to date is far below that proposed here. At intermediate stages, since $\tau \propto r^{-2}$ for a fixed mass in an outward-moving shell, the dust shell may be so optically thick that the objects are visible only as luminous far-infrared sources.

References


