A spherical circumstellar dust model for IRAS 09371 + 1212

G. Robinson, R. G. Smith and A. R. Hyland
Department of Physics, University College, The University of New South Wales, Campbell, ACT 2600, Australia

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SUMMARY
We present the results of fitting a spherically symmetric circumstellar dust model to the peculiar source IRAS 09371 + 1212, a bipolar nebula with an extremely cool dust shell which exhibits clear evidence for large quantities of water ice. The entire spectrum in the wavelength range 2–100 μm can be well represented by a model employing grains with a silicate core and a water ice mantle. However, a small quantity of an additional grain species, such as graphite, is necessary to provide an extra source of opacity in the near-infrared. In particular, the 3.1-μm ice absorption feature and the two ice emission features at 44 and 62 μm can simultaneously be well fitted, showing that it is the same dust which gives rise to both features. It is found that a good fit can be obtained using crystalline ice particles, in agreement with the results of earlier simple models. Furthermore, in view of the sharply peaked nature of the observed far-infrared energy distribution, radiative transfer effects cannot compensate for a substantially incorrect opacity law, such as that appropriate to amorphous water ice. Core region limb brightening is predicted at wavelengths where the shell is optically thin. A consequence of this is that the 3.1-μm ice absorption feature should be deepest at the inner boundary of the dust shell. Thus, the location of the inner boundary of the shell could be determined by obtaining spectra of the 3.1-μm feature at an angular resolution of better than 0.3 arcsec. The evolutionary status is discussed and the possibility that IRAS 09371 + 1212 may be a weak or naked T Tauri star rather than an evolved object, as is generally believed, is examined.

Key words: radiative transfer – dust, extinction – interstellar medium: individual objects: IRAS 09371 + 1212.

1 INTRODUCTION
The object IRAS 09371 + 1212, the so-called ‘Frosty Leo Nebula’, has a most unusual infrared energy distribution with a sharp peak in the 60-μm IRAS band. Although originally identified by Condon & Broderick (1986) as a peculiar galaxy, Forveille et al. (1987) proposed that the 60-μm IRAS flux may be due to emission in the 46-μm water ice band. Furthermore, they noted that the optical spectrum is consistent with that of a late-type giant or supergiant star, which led them to suggest that IRAS 09371 + 1212 is a post-AGB star with a circumstellar envelope. The presence of a large amount of water ice has been confirmed by the detection of a very deep 3.1-μm (τ3.1μm ~ 3.5) absorption band (Rouan et al. 1988; Hodapp, Sellgren & Nagata 1988; Geballe et al. 1988). Hodapp et al. (1988) interpreted the feature as absorption by pure, primarily crystalline water ice, since it is very narrow, has no long-wavelength wing and the observed minimum does not occur at 3.08 μm as is appropriate to amorphous water ice, but at the longer wavelength of 3.11 μm (Hagen, Tielens & Greenberg 1981). Geballe et al. modelled the 3.1-μm feature using the Rayleigh approximation to compute the cross-sections for spherical core–mantle grains. The best-fitting models consisted of silicate cores and a mantle comprised of a mixture of amorphous and crystalline water ice in a ratio in the range 0.5:1 to 2:1.

Near-infrared images of IRAS 09371 + 1212 have revealed two elliptical lobes at J and H, of maximum extent ~ 5 arcsec, separated by a dark lane, which coalesces into a single maximum at K (Rouan et al. 1988; Hodapp et al. 1988). At L, the object appears almost spherical of diameter ~ 2 arcsec, being only slightly extended in the direction of the lobes, and with no evidence of the dark lane. Thus IRAS 09371 + 1212 shows the typical structure of a bipolar nebula.

Most recently Omont et al. (1990) obtained 35–68 μm spectrophotometric data of IRAS 09371 + 1212 from the KAO and found evidence for two distinct emission peaks, at about 44 and 62 μm respectively. These two peaks correspond to the maxima of the absorption coefficient of crystalline water ice (Bertie, Labbé & Whalley 1969). Since amorphous ice does not have the secondary maximum at 62...
µm, it cannot be the dominant constituent (see e.g., Léger et al. 1983). Omont et al. constructed simple models to account for the 25–100 µm spectrum using core–mantle grains and assuming optically thin emission, and found that a surprisingly good fit could be obtained with a single well-defined grain temperature (T = 47 ± 2 K) and approximately equal volumes of crystalline silicate cores and crystalline water ice mantles. They found that crystalline silicate cores with a long-wavelength emissivity varying as λ−2 (Draine & Lee 1984; Draine 1985, 1987) produced a significantly better fit than amorphous silicates whose emissivity at similar wavelengths varies as λ−µ, where 1.0 ≤ µ ≤ 1.5 (see e.g., Day 1976). They also found that a model with a range of grain temperatures, varying from Tmin = 29 K to Tmax = 53 K, gave a similarly satisfactory fit and that very little dust appreciably hotter than 60 K could be present without seriously degrading the fit to the 25–100 µm spectrum.

The aim of this paper is to extend the work of Omont et al. by theoretically fitting the far-infrared ice feature in conjunction with the rest of the infrared spectrum, taking into account the effects of radiative transfer. Since the shell is optically thick at 3.1 µm, radiative transfer effects are clearly of importance. To date there has been no attempt to simultaneously fit both the near- and far-infrared spectrum. In this paper we use a spherical circumstellar dust model with the aim of representing the entire observed infrared spectrum of IRAS 09371 + 1212 beyond about 2 µm, in particular the 3.1-µm ice absorption feature as well as the 44- and 62-µm ice emission features. We have not attempted to fit the energy distribution at shorter wavelengths because the bipolar nature of the source below 2 µm is extremely difficult to model. It is not, however, unreasonable to adopt a spherical approach as at L (3.5 µm) the lobes do not appear to contribute appreciable flux.

In recent years models have been developed which depart from spherical symmetry. Whilst these models certainly represent a first step in representing non-spherical sources, at present in general they lack the mathematical rigour and flexibility of spherical models. For example, the recent axisymmetric model of Collison & Fix (1991) treats scattering isotropically only. As may be seen from Fig. 1 and Section 3.1 below, the silicate ice grains used in this study are quite strongly forward scattering at short wavelengths (λ ≤ 1 µm) and in the vicinity of the ice features at 3.1 and 44 µm. Thus, to some extent one is forced to trade off geometrical realism against mathematical rigour.

2 THE MODEL

The model employed here is based on the quasi-diffusion method, in spherical geometry, due to Leung (1975, 1976), as implemented by Mitchell & Robinson (1978, 1980). In the particular version adopted in this paper, we have used a total of 165 wavelength points, sufficient points being chosen to accurately represent the ice features and also the, as yet undetected, 10-µm spectrum (the upper limit to the IRAS uncorrected 12-µm flux is 0.3 Jy). The model employed 50 impact parameters and 41 spatial points, and iterations were continued until the maximum percentage temperature change at any point in the shell was ≤0.05 per cent, ensuring flux constancy to better than 1 per cent. Linearly anisotropic scattering has been included, this being necessary since scattering dominates over absorption for 0.2 ≤ λ ≤ 2.5 µm (see Section 3.1 below). It has also been found necessary to use more than one grain species in the shell and hence the so-called multigrain temperature correction procedure has been employed (Leung 1976; Mitchell & Robinson 1980). In this formalism a Newton–Raphson scheme of temperature correction for each grain species is used, rather than computing an ‘average’ temperature for the grains on the basis of their averaged opacity. Furthermore, the model allows for non-uniform mixing of the different grain species throughout the shell, and this non-uniform mixing has been found to substantially improve the model fit.

The best estimate to date of the spectral type of the central source is K7 II (Mauron, Le Borgne & Picquet 1989) which we adopt in this paper, the effective temperature appropriate to this class being 3750 K (Johnson 1966). We adopt a luminosity of 250 L⊙D (kpc)² (Rouan et al. 1988), where D is the distance to the object. The currently accepted value for D is around 1 kpc (Mauron et al. 1989), and at such a distance the luminosity is rather low for the proposed luminosity class. We assume the central source radiates as a blackbody. A power-law density distribution of the grains in the shell was assumed, i.e., ρ = ρ0r^n. Because the dust shell is not very extended (Rmax/Rmin ≤ 4; see Table 1 below), the actual value of the index n does not have a strong influence on the shape of the spectrum for this particular object, and hence may not be well determined. This was verified by a number of trial runs with a range of values of n, and hence, after the initial trial runs n was fixed at −2, consistent with constant velocity outflow.

2.1 The nature of the grains and the opacity law

Although we are primarily interested in the shape of the spectrum in the wavelength range 2 ≤ λ ≤ 100 µm, it is important to have reasonable estimates of the optical characteristics of the grains over a considerably wider wavelength range, in order that the condition of radiative equilibrium be accurately formulated and hence the grain temperature reliably determined. In view of the demonstrated presence of large amounts of water ice in the envelope of IRAS 09371 + 1212, a core–mantle grain model has been used, with the core consisting of crystalline silicate material and the mantle comprised of crystalline water ice.

The silicate opacity law adopted here is based on the optical constants of ‘astronomical silicates’ given by Draine (1987), who tabulates the real and imaginary parts of the complex refractive index (n and k) in the wavelength range 0.0304 ≤ λ ≤ 2000 µm. Following Leung (1975), the water ice data was obtained from Greenberg (1968) for 0.0304 ≤ λ ≤ 0.95 µm, Irvine & Pollack (1968) for 0.95 ≤ λ ≤ 1.25 µm and Bertie et al. (1969) for 1.25 ≤ λ ≤ 333 µm. For wavelengths in the range 333 ≤ λ ≤ 2000 µm, the complex refractive index of ice was taken to be constant, with n = 1.790 and k = 0.0239. The data of Bertie et al. (1969), which is for crystalline water ice at a temperature of 100 K, in fact covers the entire spectral region of interest here; the data outside this range are not of critical importance, except in determining the equilibrium grain temperature.

The various efficiencies and the asymmetry parameter for anisotropic scattering, g, were calculated from n and k using Mie theory for spherical core–mantle grains (see, e.g.,
Bohren & Huffman (1983) with a core radius of $a_{\text{core}}$ and a total radius (i.e., core plus mantle) of $a_{\text{total}}$.

We have found that with a single core–mantle grain species with the core whose optical constants are based on the 'astronomical silicate' data of Draine (1987), the predicted continuum level in the vicinity of the 3.1-$\mu$m ice feature is too high and simply increasing the optical depth to any reasonable value does not reduce the level sufficiently. It appears that this may be due to the astronomical silicate data having insufficient opacity in the near-infrared, i.e., the grains are not 'dirty' enough. In investigating the effect of dust shell emission on the strengths of infrared spectral features in a sample of OH/IR stars Hyland & Robinson (1990) also found that the astronomical silicates did not appear to give red enough near-infrared colours, at least for the grain sizes used in that study. The only way we have found to remedy the situation is to introduce an extra source of opacity in the near-infrared; in this case graphite grains have been employed. However, this does not necessarily imply that there is graphite in the shell of IRAS 09371 + 1212. The graphite is simply an additional source of near-infrared opacity and in fact the need to include it at all may just point to a deficiency in the silicate optical constants of Draine, rather than the presence of an additional grain species. Furthermore, it has been found necessary to employ non-uniform mixing of the two grain species, with the graphite grains being located further from the central source than the silicate ice grains. In this way their temperature may be kept low enough ($T \leq 48$ K) so that they do not cause significant emission in the 44–62 $\mu$m region, which would mask the water ice signature.

We note that a disc-like structure characteristic of a bipolar nebula, and graphitic material far out in a spherical shell, although very different geometrically, have equivalent effects. The disc causes extinction but essentially no emission because of the small solid angle it subtends, whilst the graphite material causes extinction but very little emission because of its low temperature.

The graphite data, in the entire wavelength range 0.0304 $\leq \lambda \leq$ 2.000 $\mu$m was obtained from Draine (1987) who tabulates the efficiencies and the asymmetry parameter for a range of grain sizes for randomly oriented graphite spheres at a temperature of 20 K.

2.2 The free parameters of the model

Having adopted the opacity law for the grains as that appropriate to core–mantle silicate–water ice and graphite, as outlined above, there remain a number of free parameters. These are (i) the inner and outer radii of the dust shell, $R_{\text{min}}$ and $R_{\text{max}}$, (ii) the extinction optical depth of the shell, $\tau_{\text{elm}}$ (ext), (iii) the radius of the core, $a_{\text{core}}$, and the total radius of the silicate–water ice grains, $a_{\text{total}}$ and (iv) the relative amounts of silicate–water ice and graphite and their distribution through the shell.

Although the above parameters may not be treated independently in the sense that they each influence more than one aspect of the output energy distribution, their primary effects are as follows. The inner and outer radii of the dust shell dictates the maximum and minimum grain temperatures, $T_{\text{max}}$ and $T_{\text{min}}$ respectively, which in turn influence the shape of the 25–100 $\mu$m spectrum. The extinction optical depth of the shell, in conjunction with the ratio of the amount of silicate ice to graphite, are the main factors in determining the ratio of the continuum flux in the vicinity of the 60-$\mu$m maximum to that in the vicinity of the 3.1-$\mu$m ice absorption feature. The graphite grains must be far enough from the central source to give negligible emission in the 44–62 $\mu$m region and, in addition, they must be large enough to give sufficient opacity in the near-infrared in the vicinity of the 3.1-$\mu$m ice feature.

The depth of the 3.1-$\mu$m ice feature may be varied by altering the ratio of the total radius to that of the core for the silicate ice grains, $a_{\text{total}}/a_{\text{core}}$ (i.e., the ratio of the volume of ice to that of the silicate material). Finally the finer details of the shape of the 3.1-$\mu$m feature are influenced by the absolute values of $a_{\text{total}}$ and $a_{\text{core}}$.

The above procedure is far from straightforward because of the variety of competing effects of the different parameters. For example, if one attempts to reduce the depth of the 3.1-$\mu$m ice band by decreasing the amount of ice by reducing the ratio $a_{\text{total}}/a_{\text{core}}$, the sharpness of the 44- and 62-$\mu$m emission features is also reduced. Eventually the two peaks are lost and a smoothly varying spectrum is obtained. This underscores the importance of modelling as large a wavelength range as possible in objects such as this. More than 50 models were run with various combinations of the above parameters before a reasonable fit was obtained.

3 RESULTS AND DISCUSSION

3.1 The spectral characteristics of the grains

In Fig. 1 the absorption efficiency $Q_{\text{abs}}$, the scattering efficiency $Q_{\text{scat}}$ and the asymmetry parameter $g$, are shown plotted as a function of wavelength for the core–mantle and graphite grains used in the best fitting model. Note that $g = 0$ corresponds to isotropic scattering, $0 < g < 1$ corresponds to forward scattering and $-1 < g < 0$ corresponds to backward scattering. For the core–mantle silicate–water ice grains $a_{\text{core}} = 0.20$ $\mu$m and $a_{\text{total}} = 0.32$ $\mu$m [i.e., an ice to silicate volume ratio of approximately $3:1$ which may be compared with the ratio of approximately $1:1$ obtained by Omont et al. (1990) for their isothermal model] whilst for the graphite grains $a_{\text{graphite}} = 0.50$ $\mu$m. It may be noted that both of these grain species are relatively large. There is growing evidence for large grains existing in both reflection nebulae and in circumstellar shells. For example Pendleton, Tieles & Werner (1990) in their theoretical studies of dust grains associated with reflection nebulae found that large grains ($a \approx 0.5$ $\mu$m) are prevalent in the Orion molecular clouds 1 and 2. McGregor et al. (1988) and Hyland & Robinson (1991) found that the infrared spectrum of AG Carinae could best be represented if the grains in the circumstellar dust shell were of radius $a \approx 1.0$ $\mu$m.

From Fig. 1 it may be seen that the most important characteristics of the grains, from the point of view of this study, are:

(i) the well-known maxima of $Q_{\text{abs}}$, $Q_{\text{scat}}$ and $g$ at 3.1, 12, 44 and 62 $\mu$m due to the crystalline ice mantle;
(ii) the 9.7- and 20-$\mu$m features due to the silicate cores;
(iii) for the silicate–water ice grains, $Q_{\text{scat}}$ completely dominates $Q_{\text{abs}}$ for $0.2 \leq \lambda \leq 2.5$ $\mu$m; and
(iv) the relatively featureless characteristics of $Q_{\text{abs}}$ for the
graphite grains with $Q_{abs}$ being approximately constant out to $\lambda \sim 2.1 \mu m = 3.1 \mu m$, and thereafter decreasing approximately as $\lambda^{-2}$.

Point (iii) alone suggests that, if these grains are in fact similar to those existing in the environs of IRAS 09371 + 1212, at all wavelengths out to K we are seeing scattered radiation from the central source rather than thermal emission from the grains. The additional fact that the shell temperature is so low (\(< 70 K\)) also means there is negligible emission for $\lambda \lesssim 12 \mu m$.

3.2 The overall spectrum

The best-fitting model is shown in Fig. 2, where it is compared with the observational results and the parameters of this model are shown in Table 1. The overall flux level of the model has been arbitrarily shifted for best agreement with the 25–100 \mu m observations.

From Table 1 it may be seen that the maximum and minimum temperatures of the silicate ice grains are 69.0 and 35.5 K respectively, which may be compared with the values obtained by Omont et al. (1990) from their fit to the 25–100 \mu m spectrum of 53 and 29 K. The graphite grains, although further from the central source, have a relatively high temperature, in the range 47.7 to 41.4 K. The total (i.e., silicate ice plus graphite) extinction optical depth of the shell at 1 \mu m is relatively high, $\tau_{1\mu m (ext)} = 8.00$, almost exclusively due to scattering by the silicate ice grains. The total angular diameter of the shell is \(~ 6.7\) arcsec, although most of the energy arises from a region of size (FWHM) \(~ 3\) arcsec (see Section 3.5), which may be compared with the estimate of Omont et al. of \(~ 2\) arcsec.

It may be seen from Fig. 2 that the agreement with the overall spectrum, and in particular the far-infrared, is excellent. However, while the fit to the 3.1-\mu m ice feature is reasonable, there is a disparity in that the level and slope of the observed continuum in the vicinity of 2.0–2.5 \mu m is not well represented by the model. Increasing the total extinction optical depth significantly further than $\tau_{1\mu m (ext)} \sim 10$ results in only a marginal decrease of the level of the 2–4 \mu m con-
Figure 2. The complete flux distribution as a function of wavelength for the best-fitting model is shown as a continuous curve, whilst the flux from the central star is shown as a dotted curve. The observational results were obtained from Mauron et al. (1989) and Rouan et al. (1988), who employed beam sizes which include essentially all the radiation, (shown as filled triangles), Geballe et al. (1988), who employed a 5-arcsec beam, (shown as filled small circles with error bars) and Omont et al. (1990) from the KAO, who employed a 30-arcsec beam, (shown as filled squares with error bars). The three open circles and the upper limit at 12 μm are the IRAS colour-corrected observations. The model results and the stellar energy distribution have been arbitrarily shifted for best agreement with the observations in the 25–100 μm region.

The continuum at the expense of reducing the contrast of the sharp features in the 44- and 62-μm region, and hence loss of agreement in this region.

We note also that the model results lie significantly below the observations for λ ≤ 1.25 μm. This is no doubt due to the fact that, with the beam sizes used at these wavelengths (40 arcsec at V, R and I, 11 arcsec at J) most of the observed energy is scattered radiation from the lobes. Whilst the treatment of the radiation from the lobes is beyond the scope of the present work, the fact that the V, R, I and J observations lie below the unattenuated stellar flux is reassuring from the energy conservation viewpoint.

The fact that it is possible to obtain a reasonable fit to the entire spectrum indicates that the adopted opacity law for the crystalline water ice mantles, at least, is substantially correct. We have found that radiative transfer effects cannot compensate for a widely incorrect opacity law, such as that appropriate to amorphous ice. Thus the agreement of the model with the observations provides strong support for the crystalline water ice hypothesis of Hodapp, Selligren & Nagata (1988), Geballe et al. (1988) and Omont et al. (1990). Furthermore, the fact that it is possible to fit both the 3.1-μm absorption band and the 44- and 62-μm emission features implies that it is the same dust which gives rise to both features.

In the 10–20 μm region the model results predict that there should be a deep minimum, due to the rapid fall-off of the stellar continuum and the dust shell emission not being significant because of the low grain temperature. The 12-μm model result is in good agreement with the upper limit to the corrected IRAS 12-μm flux. It is only at wavelengths longer than about 20 μm that the thermal emission from the shell dominates the attenuated stellar component. Consequently the silicate feature at 9.7 μm and the water ice feature at 12 μm are both predicted to be in absorption, with the 12-μm ice feature being the more prominent, and the 20-μm silicate feature is very weakly in emission.

3.3 The 3.1-μm ice absorption feature

In Fig. 3, the model results are compared with the observations in the vicinity of the 3.1-μm water ice absorption band.

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Table 1. Central source and dust shell parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_\ast$ (K)</td>
<td>3750</td>
</tr>
<tr>
<td>$L_\ast/L_\odot$</td>
<td>$250D(kpc)^2$</td>
</tr>
<tr>
<td>$R_\ast/R_\odot$</td>
<td>38 $D(kpc)$</td>
</tr>
<tr>
<td>$a_{\text{core}}$ ($\mu$m)</td>
<td>0.20</td>
</tr>
<tr>
<td>$a_{\text{total}}$ ($\mu$m)</td>
<td>0.32</td>
</tr>
<tr>
<td>$a_{\text{graphite}}$ ($\mu$m)</td>
<td>0.50</td>
</tr>
<tr>
<td>$R_{\text{min}}/R_\ast$</td>
<td>$4.80 \times 10^3$ [0.84 arc sec]</td>
</tr>
<tr>
<td>$R_{\text{bound}}/R_\ast$</td>
<td>$1.63 \times 10^4$ [2.86 arc sec]</td>
</tr>
<tr>
<td>$R_{\text{max}}/R_\ast$</td>
<td>$1.90 \times 10^4$ [3.34 arc sec]</td>
</tr>
<tr>
<td>Density distribution $\rho = \rho_\odot n$, $n = -2$</td>
<td>69.0, 47.7</td>
</tr>
<tr>
<td>$T_{\text{max}}$ (K)</td>
<td>35.5, 41.4</td>
</tr>
<tr>
<td>$T_{\text{min}}$ (K) #</td>
<td>7.24, 0.76, 8.00</td>
</tr>
<tr>
<td>$\tau_{\text{1\mu m}}(\text{ext})$ ‡‡</td>
<td>0.42, 0.32, 0.74</td>
</tr>
<tr>
<td>$\tau_{\text{1\mu m}}(\text{abs})$ ‡‡</td>
<td>6.82, 0.44, 7.26</td>
</tr>
</tbody>
</table>

†D is the assumed distance to IRAS 09371 + 1212 in kpc.
‡R_{\text{bound}} denotes the boundary between the core mantle silicate ice grains and the graphite grains.
* Temperatures of silicate ice core mantle grains (species 1) and graphite grains (species 2) at the inner and outer boundaries of the two grain species respectively.
‡‡Optical depths at 1 $\mu$m of species 1, species 2 and the total optical depth respectively.

Also shown plotted in Fig. 3 is the model stellar atmosphere flux distribution for a 3800 K giant, as obtained by Bessell et al. (1989).

As noted in Section 3.2 the observed continuum in the vicinity of 2.0–2.5 $\mu$m lies considerably below, and is marginally steeper than the model results. Whilst we have employed a blackbody central source only in the models, it may be seen that the model stellar atmosphere continuum closely follows a blackbody in the vicinity of the 3.1-$\mu$m ice band. The photospheric CO band at $\Delta > 2.3$ $\mu$m is clearly too weak to substantively effect the short-wavelength wing of the 3.1-$\mu$m circumstellar water ice band although the band head at 2.29 $\mu$m may possibly be present in IRAS 09371 + 1212. Thus it appears that the disagreement between the model and the observations in this region is not primarily due to a photospheric effect. One possible explanation of this discrepancy is that it may be the result of both scattering and extinction effects in a non-spherical shell. Pendleton et al. (1990), in their models of reflection nebulae, used a plane parallel slab which scatters incident starlight, which then in turn passes through an absorbing molecular cloud. Their models demonstrate a wide range of ice band shapes, with the shape depending on the scattering angle. Some of their models for large grains ($a > 0.5$ $\mu$m) show the level and slope of the short- and long-wavelength wing of the 3.1-$\mu$m ice feature to differ considerably, which does not occur in our models. This approach does offer some hope for the explanation of the shape of the wings of the ice band and would be a worthwhile area for further study.

In comparison to the 3.1-$\mu$m absorption feature seen towards massive protostars embedded in molecular clouds (e.g., Smith, Sellgren & Tokunaga 1989) and towards stars lying behind the Taurus dark cloud (e.g., Whittet et al. 1988), IRAS 09371 + 1212 has quite an unusual 3.1-$\mu$m absorption profile. The former sources show a very distinct additional absorption, i.e., additional to that of pure H$_2$O ice, in the 3.2–3.6 $\mu$m region (sometimes referred to as the 'long-wavelength wing'). Common suggestions for the source of this wing are a mixture of NH$_3$ or some form of hydrocarbon with the H$_2$O ice, and recent arguments tend to support the hydrocarbon hypothesis (see discussion in Smith et al. 1989). As may be seen from the spectra in Fig. 3, this wing is completely absent in IRAS 09371 + 1212. There are, however, a small number of other sources where this wing is not seen. These are exclusively AGB (OH/IR) stars, well-evolved objects with high mass-loss rates and thick oxygen-rich circumstellar envelopes, the best studied example being OH 231.8 + 4.2 (Smith, Sellgren & Tokunaga 1988). The absence of a wing in these objects is consistent with the hydrocarbon (or possibly NH$_3$) origin for the wing in that the dominant molecule in these oxygen-rich envelopes is OH and, condensed onto the grains, H$_2$O. Thus the lack of a wing in IRAS 09371 + 1212 is an argument in support of its being a well-evolved, oxygen-rich star.

Nevertheless, a comparison of the 3.2–3.4 $\mu$m region in, for example, OH 231.8 + 4.2 and IRAS 09371 + 1212 still shows a distinct difference, not in the presence of additional absorption, but in the sharpness of the turnover or inflection near 3.3 $\mu$m where the 3.1-$\mu$m H$_2$O ice absorption meets the continuum. This inflection is much sharper in IRAS 09371 + 1212. In fact, although the 3.1-$\mu$m absorption in OH 231.8 + 4.2 can be modelled using Mie theory for small, H$_2$O ice-coated silicate grains, producing a good fit near 3.3 $\mu$m, this is not possible for IRAS 09371 + 1212. Geballe et al. (1988) have attempted to model the H$_2$O ice band in IRAS 09371 + 1212 using a crystalline-amorphous ice mantle. However, their best-fitting model still fell far short of fitting the sharp turnover near 3.3 $\mu$m. We had hoped that by taking the full radiative transfer effects into account, we would be able to obtain a better fit to this region of the spectrum. But, as Fig. 3 shows, the fit is more or less the same as that of Geballe et al. (1988). In fact, after exploring a wide range of theoretical 3.1-$\mu$m H$_2$O ice band profiles using our model, we do not see how any combination of optical constants and scattering effects can fit the sharp turnover in IRAS 09371 + 1212 near 3.3 $\mu$m, at least using the currently available optical constants of H$_2$O ice. Crystalline H$_2$O comes closest, which is consistent with our modelling of the overall spectrum of IRAS 09371 + 1212, particularly near 44–62 $\mu$m, but this is still inadequate.

The fact that none of the models fits well raises some interesting questions when we search for an explanation. For example, could this be a grain size effect? Van de Bult, Greenberg & Whittet (1985) certainly see some variation in the H$_2$O ice band profile when they use Mie theory to compare the extinction efficiency of thin cylindrical grains to

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spherical ones, although it is not obvious that the turnover near 3.3 μm is significantly modified. The models of Pendleton et al. (1990) for reflection nebulae may offer a possible explanation in that one of their models for large grains and a scattering angle of 30° does reveal a relatively sharp turnover near 3.3 μm.

One other, somewhat more speculative explanation is that there is some additional emission from the dust around IRAS 09371 + 1212, similar to that responsible for the 3.3-μm emission feature seen in a wide variety of sources, including young stellar objects, H II regions, the Orion nebula, and even galaxies. A large range of substances containing aromatic CH bonds, including polycyclic aromatic hydrocarbons (PAHs) and amorphous carbonaceous materials, are thought to give rise to this feature (see e.g., Sakata et al. 1990; Tokunaga et al. 1991). However, in what appears to be an oxygen-rich environment, this would require a source of carbon-rich dust, most likely in the form of small hydrocarbon grains, and a strong UV source to excite these grains into emission. While one could imagine carbon-rich material being dredged up in one of the thermal pulses if IRAS 09371 + 1212 is an AGB star, there is at present no evidence to support this. No carbon lines appear in the visible spectrum (Mauron et al. 1989), nor is there any strong evidence for a major UV component in the spectrum of the central star; only weak Paschen line emission is seen. It is nevertheless noteworthy that we found it necessary to include a second grain species with characteristics similar to graphite to improve the overall fit in the short-wavelength region. However, we are still left with a puzzling question concerning the 3.1-μm ice band in IRAS 09371 + 1212; it is clear that it is largely due to crystalline H₂O ice, but it has at least one feature, the sharpness of the inflection near 3.3 μm, that has not previously been identified in any astronomical H₂O ice band so far observed.

3.4 The 44- and 62-μm ice emission features

In Fig. 4, the model results are compared with the observations in the 10–200 μm region. It may be seen that the agreement is good at all wavelengths. The fit of Omont et al. (1990) in the 25–100 μm region is, however, equally as good, for the fundamental reasons that at ~50 μm scattering is negligible and the shell is optically thin, and in addition it is also physically thin (R_{max}/R_{min} = 4; see Table 1) and hence essentially isothermal. Thus in considering the 25–100 μm spectrum alone, radiative transfer effects are not likely to be of major importance and hence it is not surprising that the simple model of Omont et al. produces a satisfactory fit, given that the opacity law is essentially correct.

The model results show that there cannot be a significant amount of dust with T ≥ 70 K, otherwise the quality of the fit in the 12–40 μm region would be adversely affected, in particular the 12-μm IRAS upper limit would be exceeded. Similarly, if there is a significant amount of dust with T ≤ 35 K, the 100-μm model flux exceeds the 100-μm IRAS...
Figure 4. As for Fig. 2, showing the 10–200 $\mu$m region on a larger scale. The filled squares with error bars represent the KAO observations of Omont et al. (1990) whilst the open circles and the upper limit at 12 $\mu$m are the IRAS colour-corrected observations.

Observation. Thus the maximum and minimum dust shell temperatures are fairly well established, primarily as a result of the IRAS observations.

At the peak of the two ice features the model estimates of the optical depth of the shell are $\tau_{a,9.7}$ (ext) = 0.55, and $\tau_{a,3.3}$ (ext) = 0.14; essentially all of this extinction is due to absorption. These values may be compared with the estimates of Omont et al. (1990) of $<0.3$ at the 44-$\mu$m peak and $\sim0.1$ in 'most of the far infrared'.

It should be noted that the two peaks at 44 and 62 $\mu$m do not tell us exactly 'how crystalline' the ice is. In the model, we have used the optical constants of Bertie et al. (1969), which are for crystalline ice at 100 K. The only amorphous ice data available in the far-infrared are those of Léger et al. (1983), measured at 77 K. These data do not have the second maximum at 62 K. However, the laboratory work of Hagen et al. (1981) shows that as $\mathrm{H}_2\mathrm{O}$ is deposited at increasingly higher temperatures, the resulting ice structure takes on more of a crystalline form, characterized at 3.1 $\mu$m by a narrowing and increased substructure of the absorption feature. By the time the temperature reaches 130–140 K the ice is completely crystalline, although the substructure in the 3.1-$\mu$m feature begins to appear before this temperature (Fink & Sill 1982). Thus, somewhere between 77 K and 130–140 K the structure of the ice changes such that the 62-$\mu$m peak appears. This means that the current observations can really only place a lower limit $\sim80$ K on the temperature at which the $\mathrm{H}_2\mathrm{O}$ ice formed on the grains around IRAS 09371 + 1212 and that the ice may not necessarily be completely crystal-

line. It is clear that further laboratory work to determine at what temperature the 62-$\mu$m peak appears would be extremely useful in providing a better lower limit to the grain temperature at which $\mathrm{H}_2\mathrm{O}$ ice formed around IRAS 09371 + 1212.

3.5 The angular distribution of radiation

Fig. 5 shows, for a number of representative wavelengths, the model predictions of the forward directed specific intensity at the outer boundary of the shell, $I^+ (R_{\text{max}})$, as a function of angular distance measured from the centre of the star, and the flux integrated out to a given angular distance.

The most important feature of Fig. 5 is the prediction of significant limb brightening from the limb of the central source to the inner edge of the dust shell (which occurs at an angular distance of about 0.84 arcsec) at four of the six wavelengths shown plotted. The primary reason for this core-region limb brightening is that the geometrical and optical thickness of the shell is a maximum along the line of sight to the inner boundary of the shell. In the optically thin case, and in the absence of scattering, one would therefore expect the observed specific intensity to increase from the limb of the star to a maximum at the inner boundary of the dust shell and thereafter to decrease to zero at the outer boundary of the shell. In the general case the degree of limb brightening will be influenced by factors such as the optical depth of the shell, the temperature and density distributions through the shell and the proportion of the observed intensity which is due to

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scattering. In particular, at wavelengths where the shell is optically thick, limb brightening should not occur, since one does not see far into the shell and hence the large geometrical path length is not important.

At 1 μm (see Fig. 5a), no limb brightening is predicted. At this wavelength the shell is optically thick and the observed intensity is almost exclusively due to scattered light from the silicate ice core mantle grains \( \tau_{\text{core mantle}} = 6.82 \), \( \tau_{\text{abs}} = 0.42 \); see Table 1. For these grains the asymmetry parameter, \( g = 0.3 \) (see Fig. 1), corresponding to weak forward scattering, and this leads to limb brightening being suppressed, in spite of the competing geometrical effect giving rise to maximum optical thickness at the edge of the core.

At 9.7 and 62.5 μm (Figs 5b and c respectively) the shell has become optically thin, scattering is negligible, and core region limb brightening is predicted.

For 2.5 ≤ \( \lambda \) ≤ 4.0 μm, absorption and scattering are comparable. In the short- and long-wavelength wings of the 3.1-μm ice feature, at 2.86 and 3.33 μm respectively, the shell is optically thin and core region limb brightening is again predicted (see Figs 5d and f). However, in the centre of the ice feature at 3.11 μm (Fig. 5e), the shell becomes optically thick and core region limb brightening does not occur. This leads to the important model prediction that if one could measure the shape of the ice feature as a function of angular position with a resolution of ≤ 0.3 arcsec, the feature should vary significantly in depth with position, and should be deepest at the inner boundary of the dust shell. Observations of this kind could place constraints on the true distribution of the grains responsible for the ice band feature.

Another feature of the model results of Fig. 5, which we mention only in passing since it is an artefact of the presence of graphite in the model, is the local maximum of intensity at an angular distance of about 2.9 arcsec from the central source for all wavelengths other than 1 μm, including the centre of the ice band at 3.11 μm. This angular distance corresponds to the boundary between the silicate ice core mantle grains and the graphite grains, and the maximum results from the graphite geometrical and optical thickness being maximum along this line of sight. It is suppressed at 1 μm because for graphite the asymmetry parameter \( g = 0.6 \) at 1 μm (see Fig. 1) which results in there being little radiation scattered sideways into the line of sight.

The flux integrated out to a given angular distance provides an interesting insight into the variation of the size of the source with wavelength. At 1 μm there is considerable emission from the central star, virtually no thermal emission from the dust shell but a significant amount of stellar radiation is scattered by the dust shell into the line of sight. Thus, the integrated flux increases substantially with angular distance. At 9.7 μm the stellar radiation completely dominates both the thermal emission from the shell and the radiation scattered by the shell and hence the integrated flux is essentially constant with increase in angular distance out to the outer boundary of the shell. At 62.5 μm the flux from the central star is very small, and there is essentially no scattering, almost all the radiation being thermal emission from the shell. Thus once again the integrated flux increases with angular distance. The implications of this is that the predicted angular size (FWHM) of the source should be smaller.
3.6 The mass of the shell and the mass-loss rate

The parameters of the model shown in Table 1 lead to an estimate of the mass of the dust in the shell around IRAS 09371 + 1212 of $M_{\text{dust}} \approx 1.5 \times 10^{-3} \, D \, (\text{kpc})^2 \, M_\odot$. This refined determination of the mass of the dust component is some 50 per cent larger than the largest value estimated by Forveille et al. (1987) from the far-infrared emissivity and the assumption of an isothermal envelope. More than 70 per cent of the mass of the dust component is due to the silicate ice grains. Assuming a gas-to-dust ratio of 100 leads to a total shell mass of $M_{\text{shell}} = 0.15 \, D \, (\text{kpc})^2 \, M_\odot$. This estimate is unlikely to be inaccurate by more than a factor of two, the major uncertainty being the fraction of gas which is tied up in the ice mantles.

In order to derive the mass-loss rate it is necessary to make some assumptions regarding the time-scale over which the shell material was ejected. From the structure of the shell and the lack of hot dust grains we assume that significant mass loss occurred over a period of time, $t$, and then subsided. A crude estimate of $t$ may be obtained by assuming that the grains condensed from the outflowing gas and then moved outwards with a constant velocity of $v$, where $v$, based on the 115.3-GHz CO line width, is taken to be $\sim 20 \, \text{km s}^{-1}$ (Forveille et al. 1987). In this way the time taken to produce a shell with the physical size determined by the model can be estimated from the time it would take a silicate ice grain to move from the inner boundary of the shell, $R_{\text{shell}}$, to the outer boundary of the silicate ice grains, $R_{\text{bound}}$, i.e.,

$$t = (R_{\text{bound}} - R_{\text{shell}}) \, D \, (\text{kpc}) / v = 4.6 \times 10^2 \, D \, (\text{kpc}) \, \text{yr}^{-1},$$

which is 1000 times higher than can be sustained by the present luminosity of the star, $L_\star / c^2 = 2.5 \times 10^{-7} \, D \, (\text{kpc}) \, M_\odot \, \text{yr}^{-1}$ (Castor, Abbott & Klein 1975). This is also significantly higher than the rate of $2 \times 10^{-6} \, D \, (\text{kpc}) \, M_\odot \, \text{yr}^{-1}$ determined from CO emission by Forveille et al. (1987), which however depends critically on the number of free oxygen atoms not bound up in water ice. Since the ice mantles comprise around 30 per cent of the total mass of dust, a significant fraction of the oxygen is bound up in ice leading to a large uncertainty in the value of $[\text{CO}] / [\text{H}_2]$ used in their calculations. The large mass-loss rate is not consistent with the low luminosity as suggested by its spectral type at its proposed distance of 1 kpc. This supports the suggestion of Dougados et al. (1990) that the mass-loss rate may have been the result of a short-term event in the life of the star when its luminosity increased by an order of magnitude. Nevertheless such a short-term increase in luminosity (e.g., via a thermal pulse, or the helium shell flash) is unlikely to occur in an object with a luminosity no greater than $\sim 250 \, L_\odot$. This proposed mechanism therefore creates difficulties for the hypothesis that IRAS 09371 + 1212 is an evolved late-type star.

4 THE EVOLUTIONARY STATUS OF IRAS 09371 + 1212

In any discussion of the physical nature of such an unusual object as IRAS 09371 + 1212, a knowledge of its evolutionary status is crucial.

The currently accepted view that IRAS 09371 + 1212 is a post asymptotic giant branch (AGB) star in the process of shedding material through for example, thermal pulses, on its way to becoming a planetary nebula (Forveille et al. 1987; Dougados et al. 1990), is predicated on the evidence that one very well-studied object, OH 238.1 + 4.2 shows that bipolar outflows may be found around AGB stars (see, e.g., Cohen et al. 1985). The observational similarity between this source and IRAS 09371 + 1212 and the late spectral type of the latter (K7 II) have been used as evidence in favour of this hypothesis. However, the currently accepted luminosity and distance of the source determined from its spectrum (250 $L_\odot$, 1 kpc) are not consistent with the above scenario (Omont et al. 1990). Lattanzio (1986) has shown that weak thermal pulses are first experienced only when a star ascending the AGB reaches a luminosity $\sim 1500 \, L_\odot$ at a temperature significantly hotter than that exhibited by IRAS 09371 + 1212. For large thermal pulses to occur at temperatures similar to that of IRAS 09371 + 1212, the luminosity needs to be significantly greater still. For the source luminosity to be consistent with this hypothesis, the distance would need to be increased to at least 2.5 kpc. This presents another problem, in that at the high galactic latitude of $b = 42.7^\circ$, the source would lie at a distance of 1.7 kpc from the galactic plane. It would therefore be expected to show low metallicity and be unlikely to have produced such an extensive circumstellar shell. In the light of this problem, therefore, other alternatives should be investigated.

The majority of bipolar outflow sources have been classified as pre-main-sequence objects (Lada 1985). Adams & Shu (1986) predict that one step in pre-main-sequence evolution is a star with a thick dust shell, and consequently if the shell is sufficiently thick, H$_2$O condensation onto grains would be expected to occur. Examples of this phase of evolution are HL Tau and probably PV Cep. Hence, a possible alternative which does not appear to have been considered so far is that the star is a weak or naked T Tauri star in the final throes of ejecting the remains of its embryonic dust shell. The spectral type is certainly within the correct temperature range (see, e.g., Cohen & Kuhi 1979) although its luminosity classification is rather high. Emission lines in the Paschen series have been seen although other emission features do not seem to be present. Another argument in favour of the young object hypothesis is that large amounts of ice are far more common in protostellar sources than they are in the outflows from evolved objects (see, e.g., Jura & Morris 1985). The possibility that IRAS 09371 + 1212 is very young rather than evolved would necessarily imply a luminosity for the object $\sim 10$–100 $L_\odot$, implying that its distance must be less than 1 kpc.

It would appear that both interpretations can explain the presence of significant quantities of water ice in the cool dust
shell. However, the present temperature of the dust shell around IRAS 09371 + 1212, 35–70 K (see Table 1) is lower than that at which crystalline water ice is expected to form on grains. Under laboratory conditions water ice formed at temperatures below 130–140 K is in the amorphous form, whilst higher temperatures are required for the formation of crystalline water ice (see, e.g., Hagen et al. 1981). In circumstellar environments, because of the much longer time-scales involved, the transition temperature may be somewhat lower, in the range 100–110 K (Omont et al. 1990). Thus one would expect crystalline water ice to be found preferentially in the known warm ($T \approx 100$ K) envelopes surrounding evolved objects and amorphous water ice to be found in extremely young objects whose protostellar dust shell has yet to be heated by local stellar radiation. Another difficulty with the crystalline ice hypothesis is that H$_2$O ice should sublime above $T \approx 100$ K unless the density is extremely high ($n \approx 10^6$ cm$^{-3}$; Léger et al. 1983). This suggests that the crystalline ice clearly seen in IRAS 09371 + 1212 must have been formed in the very dense ejecta from the star at $T \approx 130$–140 K, and has since cooled as the dust shell expanded and the density decreased.

In the pre-main-sequence objects studied by Smith et al. (1989), the observed 3.1-$\mu$m ice feature was identified as being due to amorphous ice. The question arises as to whether the ice particles in these objects are located within the individual dust clouds surrounding the sources, or in the intervening cold dark cloud. Elias 16, a source considered to be behind the Taurus dark cloud and without a circumstellar shell (Elias 1978), clearly shows the presence of ice particles within the Taurus cloud itself (Whittet et al. 1983, 1988; Smith et al. 1989), suggesting that the features in the other sources may also be due to the intervening cloud. Unlike the pre-main-sequence objects studied by Smith et al. (1989), IRAS 09371 + 1212 is an isolated source at high galactic latitude with no apparent intervening dark cloud other than its own compact dust shell. In addition, the fact that the 44- and 62-$\mu$m features are seen in emission (which requires $T_{\text{exc}} \approx 40$ K) further strengthens the case for the ice being associated with IRAS 09371 + 1212 itself. If it is in fact a young pre-main-sequence object it would require that the dust in the shell had been heated in a disc earlier in its evolution, and this disc is now being expelled from the source (i.e., the material cannot merely be the cool remnant of the protostellar cloud).

A possible observational test to distinguish between the above two alternatives would be to determine the $^{12}$C/$^{13}$C ratio in the object; in highly evolved objects this ratio is $\sim 5$, while in young objects the ratio is similar to that found in the Sun, i.e., $\sim 90$. This could be determined by high-resolution measurements of the first overtone bands of CO at around 2.3 $\mu$m.

5 SUMMARY AND CONCLUSIONS

In this paper we have attempted to fit the entire infrared flux distribution from IRAS 09371 + 1212, in particular the 3.1-$\mu$m ice absorption band and the 44- and 62-$\mu$m emission bands, with a spherical circumstellar dust model using core–mantle grains with the core consisting of crystalline silicate material and the mantle consisting of crystalline water ice. The principal conclusions of this work are as follows.

(i) In order to simultaneously match both the far-infrared spectrum and the near-infrared continuum using a spherically symmetric model, it has been found necessary to introduce an extra source of opacity in the near-infrared, in addition to the 'astronomical silicates' coated with a crystalline water ice mantle. Graphite grains are one possible source of this extra opacity. In the best fitting model both grain species are relatively large ($a \sim 0.3$–$0.5$ $\mu$m). The need for a second grain species may simply be a result of using a spherical model, but it may also be due to the 'astronomical silicate' data of Draine (1987) having insufficient opacity in the near-infrared.

(ii) Although we have been able to fit the general shape of the 3.1-$\mu$m ice feature, there are difficulties in reproducing the slope and level of the short-wavelength wing (2.0–2.5 $\mu$m), and the sharpness of the turnover in the long-wavelength wing (3.2–3.4 $\mu$m). Possible explanations for these discrepancies include a combination of scattering and extinction effects by coated grains in a non-spherical shell and, in the case of the long-wavelength wing, departure of the grains from a spherical shape, or an additional source of emission near 3.3 $\mu$m perhaps due to small hydrocarbon grains.

(iii) The maximum and minimum temperatures of the grains in the shell are fairly well established at approximately 70 and 35 K respectively.

(iv) Core region limb brightening is predicted from the limb of the central source to the inner boundary of the dust shell at all wavelengths where the shell is optically thin. As a consequence, the 3.1-$\mu$m water ice feature should be deepest at the inner boundary of the dust shell. Spectra of the ice feature at resolutions of $\approx 0.3$ arcsec would be useful in investigating this phenomenon and placing constraints on the angular distribution of the grains.

(v) At 9.7 $\mu$m the angular diameter of the source should be essentially that of the star ($\approx 3.5 \times 10^{-4}$ arcsec) whereas at 1 and 62.5 $\mu$m the FWHM is $\sim 3$ arcsec. At 1 $\mu$m the extended nature of the source is due to scattering whilst at 62.5 $\mu$m it is due to thermal emission by the grains in the shell.

(vi) The evolutionary status of IRAS 09371 + 1212 is not clear and high-resolution measurements of the first overtone bands of CO at around 2.3 $\mu$m could be used to determine the $^{12}$C/$^{13}$C ratio, which may cast some light on this status.

Finally it may be noted that the interpretation of the far-infrared emission from IRAS 09371 + 1212 is critically dependent on a knowledge of the optical constants of water ice, in particular crystalline water ice. The most complete currently available laboratory data for crystalline water ice is now more than two decades old. There is an urgent need for more up-to-date data particularly in the far-infrared, if the source of far-infrared radiation in objects with very cool dust shells, the known number of which is likely to increase dramatically in the near future with the coming of ISO, is to be more positively identified.

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