Superwind models for the dust shells around infrared carbon stars

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ABSTRACT
We investigate the observational effect of a superwind mass-loss phase driven by a thermal pulse in the interior of infrared carbon stars. We modify the dust density distribution by adding dust to form a region of enhanced density which proceeds outward. Depending on the position and the degree of the enhancement, the emergent model spectral energy distributions can be significantly different from those with conventional power-law density distributions. These new results fit the observations of some infrared carbon stars better. In particular, the deficiency in 30–100 μm observed fluxes of many infrared carbon stars, compared with conventional model results, can be explained by the superwind models with standard dust grains. Our superwind models also cover a much wider range in observed IRAS 12-, 25- and 60-μm colours than is possible with conventional models. The time evolution of the spectral energy distribution after a superwind can explain some observations of infrared carbon stars. We find that most of the observed infrared carbon stars are in the early history of our superwind model. This may be due to a gradual increase in the mass-loss rate on the AGB or to the selection effect of infrared carbon stars identified by the 11-μm SiC feature.

Key words: stars: carbon – circumstellar matter – infrared: stars.

1 INTRODUCTION
Carbon stars are generally believed to be the evolutionary successors of M-type Mira variables that have thin oxygen-rich dust envelopes. When asymptotic giant branch (AGB) stars of intermediate mass range go through the carbon dredge-up process and thus the abundance of carbon is larger than that of oxygen, oxygen-rich dust grain formation ceases, and the stars become visual carbon stars. After that phase, carbon-rich dust grains start forming and the stars evolve into infrared carbon stars with thick carbon-rich dust envelopes and very high mass-loss rates (Iben 1981; Chan & Kwok 1990). Infrared carbon stars are generally considered to be the final phase of a carbon-rich AGB star before it leaves the red giant branch. As AGB stars evolve, thermal pulses due to internal helium shell flashes have been hypothesized as a major cause of the episodes of greatly enhanced mass loss, commonly referred to as the superwind phase (Renzini 1981; Wood 1990). Radio observations reveal detached multiple envelopes around carbon stars (Olofsson et al. 1990; Bujarrabal & Cernicharo 1994; Olofsson et al. 1996). These may be due to abrupt changes in the mass-loss rate back when the star was a younger AGB star, each corresponding to a thermal pulse of the helium-burning shell.

Planetary nebulae often show two, sometimes three, shell-like structures around them (e.g. Balick et al. 1992). The presence of distinct shells of material around planetary nebulae suggests that thermal pulse episodes strongly modulate the mass-loss rate from the star. In order to explain the very thick dust shells and high mass-loss rates seen in the more extreme infrared carbon stars, the mass-loss rate from an AGB star must increase by a factor of at least 10 for the duration of the superwind. We expect one thermal pulse per $10^4$–$10^5$ yr, and the pulse lasts for a few hundred years (Iben 1975; Vassiladis & Wood 1993). Although the superwind is not expected to be exactly in phase with the thermal pulse, the duration is predicted to be comparable (Vassiladis & Wood 1993).

In this paper, we investigate the effect of a superwind on the emergent spectral energy distributions (SEDs) of infrared carbon stars. We modify the dust density distribution by adding dust to form a region of enhanced density. We then compare our model results with previous model results and the observed SEDs of several infrared carbon stars. This is a very different approach from previous modelling of carbon stars, which is limited to the description of the radial density distribution either as power laws with a rather unphysical range in exponents or as a simple detached shell.

2 MODEL CALCULATIONS
Dust grains in the outer envelopes of infrared carbon stars absorb and scatter the stellar radiation and re-emit the radiation at longer wavelengths. For given characteristics of the central star and the dust shell around it, the emergent SED can be found by analysing the radiative transport processes. Comparison of these results with
observations can be used to make adjustments and improvements in the model input parameters.

In our computation, we use Leung’s radiative transfer code (Egan, Leung & Spagna 1988) for spherically symmetric dust shells. We use a radial grid of 125 points and a frequency grid of 79 wavelengths. A fixed model parameter for the dust envelope is the wavelength dependence of the dust opacity. The dust condensation temperature \( T_d \) is assumed to be 1000 K and the dust condensation radius \( R_d \) is obtained after a few trials. The outer radius of the dust shell is always taken to be 1000 \( R_e \). The adjustable input parameters are the dust optical depth at 10 \( \mu \)m \( \tau_{10} \) and the radial dust density distribution. First-order anisotropic scattering is considered for all the models.

For the central star, the luminosity is taken to be \( 10^4 \, L_\odot \) and a stellar blackbody temperature of 2000 K is used. A change in the luminosity does not affect the shape of the output spectra, it only affects the overall energy output. However, a significant change in the blackbody temperature of the central star does affect the output spectra, especially for the models with optically thin dust shells. This is because the underlying energy distribution of the star strongly influences the emergent near-infrared continuum in optically thin dust shells.

### 2.1 Dust opacity

Amorphous carbon (AMC), silicon carbide (SiC) and magnesium sulphide (MgS) appear to be the best candidates for the dust grains in the envelopes around infrared carbon stars. Rowan-Robinson & Harris (1983) reproduced large-sample SEDs of carbon stars with AMC adopting the absorption efficiency law, \( Q_{abs} \propto \lambda^{-4} \). Recently, many authors have modelled carbon stars with AMC and SiC. Chan & Kwok (1990) used the empirical opacity function of SiC. This opacity pattern resembles the one with mixture of AMC and a small amount of SiC. Lorenz-Martins & Lefèvre (1993) and Groenewegen (1995) modelled infrared carbon stars with the opacity functions for both SiC and AMC by using the same dust condensation temperature, but a different radiative transfer model and opacity functions from ours. Lorenz-Martins & Lefèvre (1994) improved the model by adopting different inner radii of the dust shells for AMC and SiC. They found that the ratio of SiC to AMC grain content, which is small, appears to decrease as the total optical depth increases and the flux due to SiC dust grains is small relative to the flux due to AMC dust grains. Many dust-thick infrared carbon stars show 30-\( \mu \)m emission features. It was suggested that for AGB stars the 30-\( \mu \)m band could be produced by a small amount of MgS particles (Omont et al. 1995).

As we will discuss later (Section 3), we expect that the absorption efficiency function for dust grains in infrared carbon stars at infrared wavelengths (\( \lambda = 0.7-100 \, \mu \)m) should not be very different from the \( \lambda^{-4} \) law. This opacity pattern is close to that measured by many authors for several AMC materials (e.g. Koihe, Hasegawa & Hanabe 1980; Borghesi, Bussoletti & Colangeli 1985; Bussoletti et al. 1987). Therefore, SiC and MgS dust grains have only a minor effect on the overall opacity of the dust grains in infrared carbon stars except for the small 11-\( \mu \)m SiC and 30-\( \mu \)m MgS features. The main purpose of this work is to find the effect of thermal pulses on the dust shells around infrared carbon stars from their overall infrared SEDs. Therefore, modelling without SiC and MgS is a reasonable approximation for our purpose. In this work, we use the opacity function for AMC dust grains. We use the optical constants of AMC measured by Duley (1984) in the visible band (\( \lambda = 0.2-0.7 \, \mu \)m). In the infrared band (\( \lambda = 0.7-100 \, \mu \)m), we extend the efficiency factors according to simple power laws \( Q_{abs} \propto \lambda^{-4} \). In Fig. 1, we present the absorption and scattering efficiency factors versus wavelength for various AMC and SiC dust grains as well as the efficiency factors that have been used for this work. We calculate them by using the Mie theory (e.g. Bohren & Huffman 1983) from the optical constants listed in the corresponding reference for a spherical dust grain with a radius of 0.1 \( \mu \)m. The opacity for graphite is calculated from the optical constants listed in Draine (1985). We also try to use other opacity functions for AMC. However, we cannot fit observations of infrared carbon stars with the opacity pattern from the optical constants listed in Rouleau & Martin (1991) for AMC. It shows a steeper \( Q_{abs} \) function (close to a power-law \( \lambda^{-1.3} \) at \( \lambda = 1-100 \, \mu \)m) but flatter than the one for graphite at infrared. Additionally, we test the opacity pattern of SiC from the optical constants obtained by Pégoùrie (1988). Presently, the radiative transfer model used for this work cannot handle multiple inner dust shell radii. If we assume the same dust condensation temperature for both AMC and SiC, we find that the model results with both dust grains do not fit observations well even with various combinations of parameters (e.g. the density distribution, the ratio of SiC to AMC). Instead, the opacity pattern with only AMC fits observations much better except for the small 11-\( \mu \)m SiC feature. This may be because the dust condensation temperatures are significantly different for each dust grain (e.g. Lorenz-Martins & Lefèvre 1994). Alternatively, actual dust grains may have SiC cores, which form at higher temperature in the inner dust shell, and AMC mantles, which grow at lower temperature in the outer shell (e.g. Kozasa et al. 1996). In this case, the opacity function should be different for different radial positions of the dust grain in the shell.

### 2.2 Dust density distribution

Radiative transfer models for carbon stars have been developed by a number of authors with various assumptions on input parameters and different levels of sophistication (e.g. Jones & Merrill 1976; Rowan-Robinson & Harris 1983; Chan & Kwok 1990; Lorenz-Martins & Lefèvre 1994; Groenewegen 1995). All these models assumed a smoothly distributed spherically symmetric dust shell with a power-law description of the radial density distribution. The dust density distribution was most often taken to be inversely proportional to the square of the distance, as would be expected for the constant velocity winds found in AGB stars. Simple radiation pressure models (Kwok 1975; Kozasa, Hasegawa & Seki 1984) or models that add pulsation and shocks (Bowen 1988; Suh, Jones & Bown 1990) predict \( r^{-2} \) density laws. These models show that dust grains are accelerated relatively fast and approach and maintain terminal velocity within \( (3-5)R_e \). Dust formation and growth timescales are very short compared with other timescales typical in AGB star winds (e.g. Suh, Jones & Bown 1990). This burst-like grain formation implies a constant outflow velocity for most of the dust shell. The modest departures from constant velocity near \( R_e \) have minor effects on the emergent spectrum. Therefore, a flatter or steeper dust density distribution (i.e. \( \rho \propto r^{-1} \) or \( \rho \propto r^{-3} \)), as suggested by Werner et al. (1980) and van der Veen et al. (1995) to fit observations of many dust-thick AGB stars, is not physically plausible.

The dust condensation radius \( R_d \) is about \( 2 \times 10^4 \, \text{cm} \) for typical infrared carbon stars. At a typical expansion velocity of \( 10-20 \, \text{km s}^{-1} \), the lifetime of the thermal pulse (~500 yr) corresponds to about \( 2 \times 10^6 \, \text{cm} \), or about 100\( R_e \). Therefore, the region of enhanced mass loss should be about 100\( R_e \) thick, and it travels
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outward from the star with time. The dust distribution in infrared carbon stars beyond 1000\(R_e\) does not contribute significantly to the infrared (\(\lambda=1-100\ \mu\text{m}\)) SED and thus has little observable effect. However, the distribution of the circumstellar matter around carbon stars beyond 1000\(R_e\) can be detected by radio observations (e.g. Bujarrabal & Cernicharo 1994). In planetary nebulae, optical images often reveal shells of material far beyond 1000\(R_e\). Frank, van der Veen & Balik (1994) found that multiple shells are typically separated by \((2-30) \times 10^{17}\ \text{cm}\), which corresponds to the dynamic time-scale of \((1-15) \times 10^4\ \text{yr}\), comparable to the theoretical thermal pulse interval \((10^4-10^5\ \text{yr})\). The travel time for dust to reach the outer edge of the shell at 1000\(R_e\) is about 5000 yr, which is comparable to the interval between thermal pulses on the AGB.

Therefore, on average, there should be at most only one discontinuity or density enhancement detectable from the infrared SED for any carbon star shell, but we may expect that a significant fraction of infrared carbon stars have discontinuities in their dust shells.

If we take the effects of a superwind into consideration, the dust density distribution should be different from a smooth distribution. Fig. 2 illustrates a description of the hypothesized density discontinuity we use in the models. The radial density distribution is still an \(r^{-2}\) power law, except for an abrupt elevation of the density in the region of the superwind. The controlling parameters for this enhancement are its inner and outer radii \(R_1\) and \(R_2\) and the factor by which the density is enhanced over the distribution for the rest of the shell (i.e., 10\(x\), 20\(x\), etc.). Initially, a 10 times enhancement of

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**Figure 1.** Absorption and scattering efficiency factors for the model dust grains.
the mass-loss rate will produce a narrow region of enhanced density at the inner boundary of the dust shell. The leading edge of this enhancement ($R_2$) will travel outward with time. The radial thickness of the region of enhanced dust shell density will continue to grow until it is 100$R_e$ thick, at which time the superwind stops and the inner edge ($R_1$) begins to move outward in radius as well. The total mass ejected by a thermal pulse is to be conserved, hence the density falls as $r^{-2}$ when it moves outward. The controlling parameter for any specific shell model, the optical depth at 9.7 $\mu$m, is the total line-of-sight optical depth through all portions of the shell. Groenewegen (1995) modelled infrared carbon stars using an accelerated mass-loss rate profile. The profile could roughly correspond to the density distribution shown in Fig. 2 with fixed $R_1$ (which is 1$R_e$) but with various values of $R_2$ and degrees of the enhancement.

The actual density law within the enhancement itself may be more complicated than the $r^{-2}$ law in our model (Fig. 2). The boundary may not be sharp, and the density within the enhancement may reflect some of the variations seen in hydrodynamic models (e.g., Vassiladis & Wood 1993). The density distribution in the superwind enhancement could be predicted with far more detail by using sophisticated hydrodynamic models, including shocks, formation and destruction of molecules and dust, etc. However, this sophistication is beyond the scope of this work. We find that our model results are primarily sensitive to the optical depth through the density enhancement and the radial location of the boundaries of the
enhancement. Our model SEDs are largely insensitive to the details of the boundary of the density enhancement or fluctuations in the density law between these boundaries. Additionally, minor fluctuations in stellar temperature and some significant changes in luminosity due to a thermal pulse do not make significant differences to the model SEDs either. Therefore, our model with sharp boundaries using appropriate parameters is good enough for our purpose.

2.3 General model characteristics

In Fig. 3, we show the results for a series of models with the same optical depth, $\tau_{10} = 0.5$. The conventional model corresponds to a continuous $r^{-2}$ density distribution. For each superwind model, the density enhancement spans a thickness of $100R_e$ or less and has the same density contrast of a factor of 10 at the boundaries of the enhancement. The three superwind models differ only in the radial location of the enhancement in the shell. Note that since all these models have the same optical depth, the presence of a density enhancement reduces the amount of dust outside the enhancement relative to the continuous model.

If the dust density enhancement begins at $1R_e$ and ends at $(10-100)R_e$ (very early in a superwind phase), the model SED shows less flux at far-infrared than the flux expected from continuous models. Clearly the most dramatic departure from continuous models takes place when the inner edge of the density enhancement is placed close to the condensation radius within about $(10-30)R_e$. If the density enhancement begins at $100R_e$ and ends at $200R_e$, the difference between superwind model and continuous model SEDs...
3 SPECTRAL ENERGY DISTRIBUTION COMPARISON

In this section, we compare the observed SEDs for a selection of infrared carbon stars with model results. Most of the data for these stars are taken from the Third Catalog of Infrared Observations (Gezari et al. 1993) and references therein. Because carbon stars are long-period variables (Miras), the observational data for different dates will show these variations. In a few cases, we simply scale observed SEDs taken on different dates to produce similar results at one or more common wavelengths. This allows us to create a more complete SED than what would otherwise be possible with a single data set from a single date.

For modelling, we choose seven carbon stars covering a wide range in optical thickness for the dust shell as representatives of our results. Results of the model calculations (lines) superimposed on observational data (symbols) for IRC+60255 ($\tau_{10} = 0.15$), IRC+50338 ($\tau_{10} = 0.2$), IRC+30374 ($\tau_{10} = 0.25$), IRC+50096 ($\tau_{10} = 0.3$), IRC+40540 ($\tau_{10} = 0.5$), AFGL 2686 ($\tau_{10} = 0.5$) and IRC+10216 ($\tau_{10} = 0.8$) are shown in Figs 4 to 7. All the superwind

becomes smaller except at far-infrared. Even at far-infrared, the difference becomes smaller as we place the dust enhancement farther away from the star. This is because the fraction of the total optical depth to the star contributed by the enhanced density region becomes progressively smaller as the enhancement approaches the outer edge of the model shell at 1000$R_e$. We made the same calculations with different factors of density enhancement. We found a similar tendency, but with larger (smaller) extent for a larger (smaller) density enhancement.
models share the same density enhancement factor of 10. IRC+60255, +30374 and +40540 are well fitted by a continuous \( r^{-2} \) power-law dust shell density distribution. On the other hand, for IRC+50338, IRC+50096 and AFGL 2686, the superwind models with the enhancements placed at \( R_1 = 1R_e \) and \( R_2 = 50R_e \) fit much better. For IRC+10216, the superwind model with the enhancement placed at \( R_1 = 1R_e \) and \( R_2 = 10-20R_e \) fit much better. All of these seven stars show the 11-\( \mu \)m SiC feature. Although we do not use SiC dust grains to reproduce this feature, the overall SEDs are fairly well fitted.

The discrepancy between the conventional model (standard opacity of AMC with absorption-law \( Q_{\text{abs}} \propto \lambda^{-1} \), and the continuous dust density distribution \( \rho \propto r^{-2} \)) results and the observations of IRC+10216 at far-infrared has been controversial. A similar discrepancy appears for IRC+50338, IRC+50096 and AFGL 2686. A steeper power law of the dust absorption efficiency \( (Q_{\text{abs}} \propto \lambda^{-1.3}) \) for IRC+10216 was proposed by Jura (1983) to fit a 30-100\( \mu \)m infrared SED. As mentioned, we could fit the observed SEDs of infrared carbon stars showing similar SiC features well with the absorption law \( \lambda^{-1} \) using either the continuous dust density distribution (IRC+60255, +30374, +40540) or the density distribution with the enhancement (IRC+50338, IRC+50096, AFGL 2686, IRC+10216). Therefore, the idea suggested by Le Bertre (1988) that SiC dust is the dominant agent in a carbon-rich dust shell with absorption law \( \lambda^{-1.3} \) is not plausible. We expect that the absorption opacity function for infrared carbon stars at infrared (\( \lambda = 0.7\text{--}100\mu\text{m} \)) should not be very different from a \( \lambda^{-1} \) law. The opacities for AMC materials measured by many authors also show that the
overall absorption law is given by $Q_{abs} \propto \lambda^{-1}$ in the wavelength range $\lambda = 0.7-100\ \mu m$ (e.g. Koike et al. 1980; Borghesi et al. 1985; Bussoletti et al. 1987). Therefore, SiC dust grains have only a minor effect on the overall opacity of dust grains in infrared carbon stars except for the small 11-\mu m SiC feature. We suggest that the discrepancies for some infrared carbon stars are due to the change of the dust density distribution generated probably by a superwind.

4 IRAS TWO-COLOUR DIAGRAM

Only a relatively small number of carbon stars have complete or nearly complete SEDs. A large number of stars have far-infrared fluxes from the IRAS Point Source Catalog (1986). Although less useful than a full SED, the large number of observations with less extensive wavelength coverage can be used to form two-colour diagrams that can be compared with our model predictions.

The IRAS four-colour photometric data (IRAS Point Source Catalog 1986) are available for many carbon stars. We have collected 40 objects from Rowan-Robinson et al. (1986), 249 objects from Egan & Leung (1991), 28 objects from Volk, Kwok & Langill (1992), 67 objects from Chan (1993), 28 objects from Volk, Kwok & Woodsworth (1993), 14 objects from Groenewegen (1995) and 17 objects from Groenewegen, van den Hoek & de Jong (1995). Most of these objects are identified as carbon stars by the 11-\mu m SiC feature. Fig. 8 plots these carbon stars in an IRAS $\lambda F_{\lambda}$ two-colour diagram using $[60]-[25]$ versus $[25]-[12]$. Stars with only upper limits at any wavelength were not used. The small triangles in Fig. 8 are the observed data and the lines with large symbols are the model calculations for a range of dust shell optical depths ($\tau_{10}$) of 0.01, 0.05, 0.1, 0.5, 0.8 and 1. Carbon stars are distributed along a curve in the shape of a 'C'. A group of stars at the upper left part are visual carbon stars that show excessive flux at 60 \mu m which is due to the remnant of an earlier phase when the star was an oxygen-rich AGB star (e.g. Chan & Kwok 1990). A group of stars at the lower part, which extend to the right-hand side, are infrared carbon stars. In this diagram, differences between the continuous and superwind models are more pronounced. By placing a density enhancement at various locations in the dust shell, portions of the diagram that are inaccessible to the continuous models can be covered.

Continuous models extend from the centre of the 'C' curve to the right-hand side along the higher part of the group of infrared carbon stars. All the superwind models share the same density enhancement factor of 10. The superwind models with close density enhancements $[R_2 = (10-100)R_e]$ produce hotter $[60]-[25]$ colours where more infrared carbon stars are located. The superwind models with $R_1$ larger than $100R_e$ produce colder colours at both $[60]-[25]$ and $[25]-[12]$ for a given optical depth. Superwind models with $R_1$ larger than $100R_e$ produce colder colours at both $[60]-[25]$ and $[25]-[12]$ for a given optical depth. In general, our superwind models cover a larger portion of the IRAS two-colour diagram than do continuous models alone.

Our model has some limitations in calculating the exact IRAS four-colours. The opacity for our model does not include the small 11-\mu m SiC and 30-\mu m MgS features, which may affect the 12- and 25-\mu m fluxes. Therefore, there may be some systematic errors for


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5 TIME EVOLUTION OF THE SED

The evolution of the optical depth of a dust shell with a superwind model is shown in Fig. 9 as a function of the position of \( R_2 \) when the quiescent phase optical depth at 10 \( \mu \text{m} \) (\( \tau_0 \)) is 0.1. The superwind phase has a mass-loss rate 10 times that of the quiescent phase and lasts long enough (about 500 yr) to produce an enhancement that is 100\( R_c \) thick. The transient superwind model cannot produce high shell optical depths when the outer edge of the density enhancement has moved much beyond 100\( R_c \).

Fig. 10 shows the evolution of the superwind models in the IRAS two-colour diagram. The two models are distinguished by a quiescent phase optical depth at 10 \( \mu \text{m} \) of \( \tau_0 = 0.01 \) and 0.1. Table 1 lists the changes in several physical parameters with time for these models. In each case, the superwind is set to produce a tenfold increase in the mass-loss rate for a time long enough to produce an enhancement 100\( R_c \) in thickness. The mass-loss rate then returns to the preceding level as the enhancement moves steadily further from the star at the terminal wind velocity. The behaviour of these evolutionary superwind models in the IRAS two-colour diagram is interesting. The track for the model beginning with a thin dust shell (\( \tau_0 = 0.01 \) and 0.1) sweeps out a large area in the diagram. Although this model seems to cover a large portion of the IRAS two-colour diagram as it evolves, most of the observed infrared carbon stars are in the early history (less than about 1000 yr) of this model.
Figure 10. Evolution of the colours for two superwind models in the IRAS two-colour diagram. The arrows point to the IRAS colours at the start of the superwind phase. The models extend to ~ 5000 yr after the onset of the superwind.

Table 1. Time evolution of optical depths and the IRAS colours.

<table>
<thead>
<tr>
<th>Time (yr)</th>
<th>Region</th>
<th>$\tau_0 = 0.01$</th>
<th>$\tau_0 = 0.1$</th>
<th>$\tau_0 = 0.01$</th>
<th>$\tau_0 = 0.1$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0.01</td>
<td>0.1</td>
<td>-0.79</td>
<td>-0.68</td>
</tr>
<tr>
<td>100</td>
<td>1-20</td>
<td>0.096</td>
<td>0.91</td>
<td>-0.81</td>
<td>-0.65</td>
</tr>
<tr>
<td>500</td>
<td>1-100</td>
<td>0.092</td>
<td>0.99</td>
<td>-0.70</td>
<td>-0.51</td>
</tr>
<tr>
<td>600</td>
<td>20-120</td>
<td>0.014</td>
<td>0.14</td>
<td>-0.52</td>
<td>-0.34</td>
</tr>
<tr>
<td>1000</td>
<td>100-200</td>
<td>0.01</td>
<td>0.1</td>
<td>-0.68</td>
<td>-0.52</td>
</tr>
<tr>
<td>3000</td>
<td>500-600</td>
<td>0.01</td>
<td>0.1</td>
<td>-0.78</td>
<td>-0.67</td>
</tr>
</tbody>
</table>

$^a$The time (yr) after the superwind enters into the inner edge of the dust shell.

$^b$The region of the 10 times dust density enhancement; $R_1-R_2$ ($R_c$).

6 DISCUSSION

If our hypothesis of a superwind driven by a thermal pulse is correct, the vast majority of carbon stars with density enhancements in their dust shells will have an enhancement that begins at radial distances of $100R_c$ or more. Contrary to this prediction, only a small fraction of carbon stars are located in that region of the IRAS two-colour diagram (Fig. 8). As mentioned earlier, SED comparison also showed that most stars that benefit from superwind models have the density enhancements located close to the stars.

Most of the infrared carbon stars in our sample have been identified by the 11-µm SiC features. However, there may be many more infrared carbon stars without (or with very weak) SiC features that thus could not be identified as infrared carbon stars. Lorenz-Martins & Lefèvre (1994) and Groenewegen (1995) suggested that the ratio of SiC to AMC grains decreases as the total optical depth increases or as infrared carbon stars evolve. The SiC emission feature is either very weak or does not exist in the spectra of extreme-infrared carbon stars with optically thick dust envelopes (e.g. Kozasa et al. 1996).

Lorenz-Martins & Lefèvre (1994) suggested the dust condensation temperature of SiC is hotter than that of AMC. Therefore, the major re-emission processes will be dominated by AMC for the dust shell with a higher optical depth or the dust shell with dust density enhancement farther out from the star. Kozasa et al. (1996) suggested that SiC cores are formed at higher temperatures and...
AMC mantles are formed later in the outer region of dust envelope. If either of these possibilities is true, we may be able to explain why most of the observed infrared carbon stars are in the early history of our superwind model. The SiC feature will be more prominent for less evolved stars with thin dust envelopes or for stars with the dust density enhancements located closer to the stars. An alternative interpretation may be that there is a gradual increase in the mass-loss rate on the AGB as suggested by Groenewegen (1995).

7 CONCLUSION

We investigate the effects of a superwind on the emergent SED of infrared carbon stars with appropriate modifications of the dust density distribution. We find that the new results fit the observations of some carbon stars better. In particular, the deficiency in 30–100 \( \mu \)m observed fluxes of many infrared carbon stars, compared with conventional model results, can be explained by the superwind model with standard dust grains. Our superwind models cover a larger portion of the IRAS two-colour diagram than conventional models alone. The time evolution of the SED after a superwind can explain some observations of infrared carbon stars. We find that most of the observed infrared carbon stars are in the early history of our superwind model. This may be due to a gradual increase in the mass-loss rate on the AGB or the selection effect of infrared carbon stars identified by the 11–\( \mu \)m SiC feature.

Although we are not very sure about the dust opacity for infrared carbon stars, we expect that the overall absorption opacity function at infrared (\( \lambda \approx 0.7–100 \mu m \)) should not be very different from a \( \lambda^{-1} \) law. This suggests that AMC is the dominant material and SiC dust grains have only a minor effect on the ongoing infrared SED, except for the small 11–\( \mu \)m SiC feature. We suggest that the change of dust density distribution, probably due to a superwind, is necessary to explain observed SEDs of some infrared carbon stars and should be considered as a general property of the dust envelopes. Suh & Jones (1997) arrived at similar conclusions by investigating the observational effect of a superwind for OH/IR stars.

In principle, the radiative transfer model, which can handle multiple components of dust envelopes with different inner radii, or the radius-dependent opacity function in the dust shell, could improve our understanding of the dust opacity for infrared carbon stars. In addition, we can draw more solid conclusions if we are able to compile a larger sample of infrared carbon stars identified by various methods. A more realistic model must take into account the nonturbulent dust envelope shape and discontinuous density distribution into consideration.

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