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DUST GRAINS IN THE ENVELOPES OF INFRARED CARBON STARS

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ABSTRACT

We have investigated the properties of dust grains in the envelopes of infrared carbon stars by testing various radiative transfer model spectra with different stellar and envelope parameters. We have deduced a new opacity pattern for the dust grains reflecting both the experimental data and the model fitting with recent infrared observations. The best pattern we find is very similar to amorphous carbon with a slight modification that could be attributed to some unknown dust grain materials. Unlike oxygen-rich dust grains, the optical properties of carbon grains do not show any reasonable tendency of temperature dependence. We find that the Planck mean values of radiation pressure efficiency factors for the modified amorphous carbon are much larger than those for graphite.

1. INTRODUCTION

Carbon stars are believed to be the evolutionary successors of M-type Mira variables that have thin oxygen-rich dust envelopes. When the intermediate mass range asymptotic giant branch stars go through the carbon dredge-up, oxygen-rich grains cease from forming and the mass loss stops temporarily and becomes visual carbon stars. After that phase, carbon grains start forming and they become infrared carbon stars with thick carbon dust envelopes and very high mass loss rates (*e.g.*, Iben 1981, Kwok *et al.* 1989). The purpose of this work is to find the opacity pattern that fits the observations well for the infrared carbon stars. The chemical composition of dust grains in the envelopes of carbon stars is not very well known. The graphite particles that are believed to comprise of most carbon rich interstellar dust do not fit carbon stars any way. Instead, amorphous carbon grains (probably with a minor mixture of SiC and other materials) appear to be the best candidate.

Table 1. The Dust Opacity used for the Model Calculation (Modified Amorphous Carbon Grains)

λ (μm)	Optical Constants	Q_{abs}	Q_{sca}	g
0.2 - 0.7	Duley (1984)	Mie Theory		
0.7 - 7	Koike *et al.* (1980)	λ^{-1}	λ^{-4}	$\lambda^{-1.5}$
7 - 100	Modification	$\lambda^{-1.3}$	λ^{-4}	$\lambda^{-1.5}$

2. CARBON DUST GRAIN MATERIAL

Many kinds of grain materials have been suggested for the dust envelopes around carbon stars. Draine and Lee (1984) suggested graphite, Rowan-Robinson and Harris (1983) suggested amorphous carbon, and Gehrz (1989) suggested SiC. Some authors suggested a mixture of multiple grain materials. After testing various grain materials by the radiative transfer model calculations and the close comparison with observations that we will discuss in the next section, we have found that the amorphous carbon (AMC) with slight modification in the far-infrared band is the best choice.

We have used the optical constants for amorphous carbon measured by Duley (1984) in visible band (λ = 0.2 - 0.7 μm). Koike *et al.* (1980) found a Rayleigh scattering pattern in near-infrared band (λ = 0.7 - 7 μm). And in the far-infrared band (λ = 7 - 100 μm) we have tested a simple extension of Rayleigh scattering and a slight modification. As we will discuss in the next section, we find that the slight modification improves the fitting with observations. Table 1 summarizes our choice of opacity pattern. Figure 1 shows the opacity pattern of the modified amorphous carbon that we have used for modeling infrared carbon stars and the graphite for comparison. The absorption and the scattering efficiency factors (Q_{abs}, Q_{sca}) and the anisotropy factors ($g = < \cos\theta >$; where θ is the angle between the incident wave and the scattered wave) are very different. The optical constants of the graphite are from Draine (1985).

3. MODEL CALCULATIONS - INFRARED CARBON STARS

We have used Leung's radiative transfer code (Egan *et al.* 1988) for spherical symmetric dust shells. In the present calculations, a radial grid of 125 points and a wavelength grid of 90 points were used. The scattering is accurately considered. The radiation from a central hot source hits the inner part of the dust shells around it and the dust grains redistribute the energy spectra continuously toward longer wavelength bands.

For the dust envelope, we have adopted the absorption and scattering efficiency factors as described in the last section. The radii of spherical dust grains have been assumed to be 0.1 μm uniformly. According to the classical nucleation theory, the final grain size is calculated to be about 0.1 μm and dust formation and growth time-scales are much shorter than those

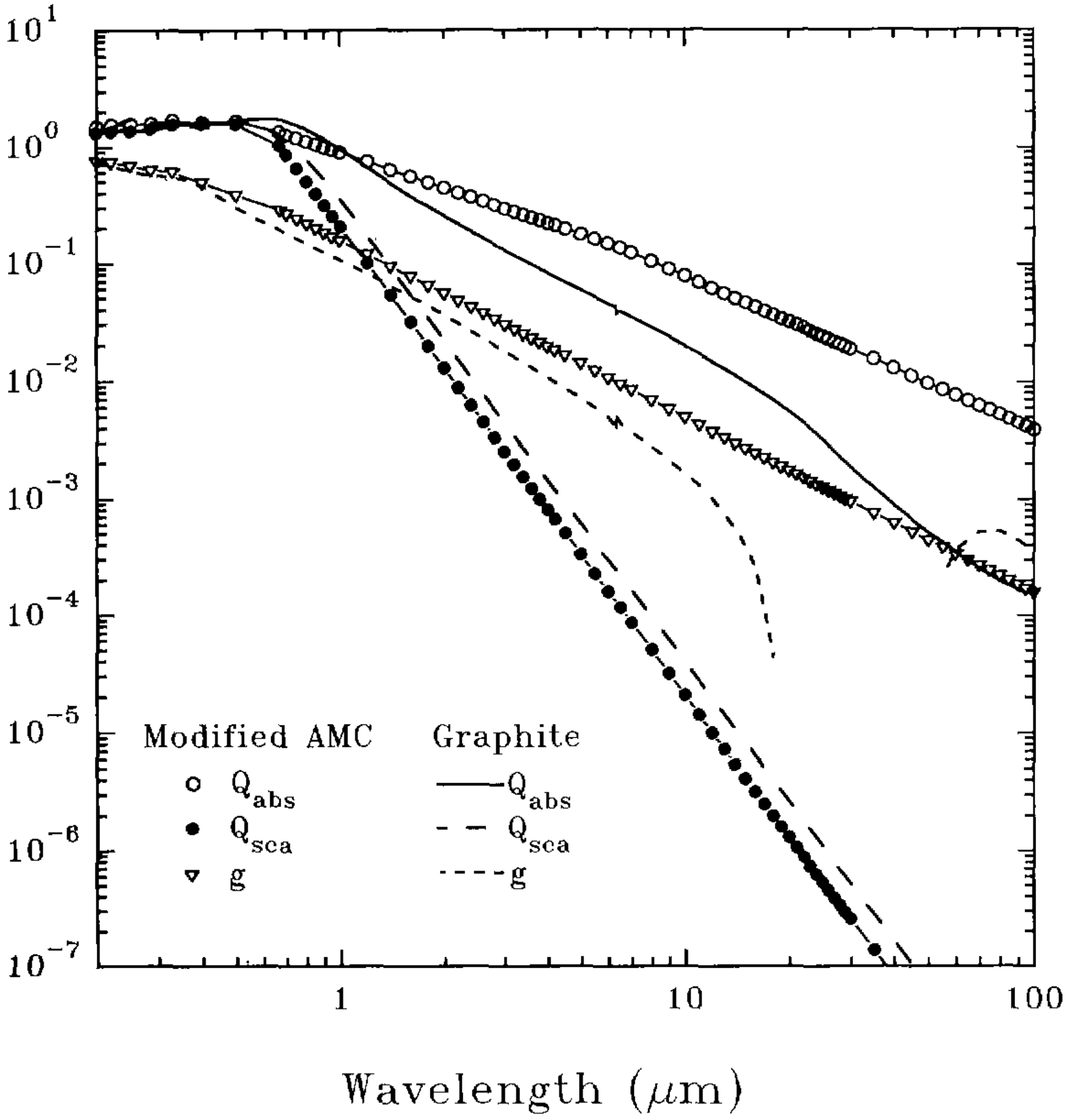

Figure 1. The opacity pattern used for present model calculations (symbols + lines) and for graphite (lines).

for OH/IR stars (*e.g.*, Suh 1991a) which is very short compared with other time scales for typical carbon stars' environments. This burst-like grain formation suggests overall constant outflow (*i.e.*, the density distribution is $\rho(r) \propto r^{-2}$). The dust condensation temperature (T_c) is assumed to be 1000 K and the dust condensation radius (R_c) is obtained after a few trials. The outer radius of the dust shell is always taken to be 1000 R_c. Finally, the dust optical depth at 10 μm ($\tau_{\lambda=10\mu m}$) is taken to fit the observations of each object. Their typical values are in the range of 0.05 - 1.0.

For the central hot source, the luminosity is taken to be $5.8 \times 10^4 L_\odot$ and the black body temperature of 2000 K is assumed. The change of the luminosity does not affect the shape of the output spectra very much, it only affects the overall energy output throughout wide wavelength ranges. The change of the central blackbody temperature does affect the output spectra. But the minor temperature changes between 2000 K and 3000 K do not make much difference.

Table 2. Model Stars and Their Parameters.

	IRC 50096	IRC 40540	IRC 10216
$\tau_{\lambda=10\mu m}$	0.2	0.4	0.7
References	Merrill and Stein 1976	Merrill and Stein 1976	Le Bertre (1987)
	IRAS (1986)	IRAS (1986)	IRAS(1986)

In selecting model stars, we have adopted the infrared observational data of carbon stars with various dust optical depths. Table 2 shows the model stars, the sources of observational data, and their optical depths that have been obtained by comparing with various model calculations and the observational data.

Figure 2, 3, and 4 show the result of model calculations (lines) superimposed on observation data (symbols) for IRC 50096, IRC 40540, and IRC 10216. The dotted line shows the energy spectrum of the central stellar radiation that has been assumed to be a black body radiation, the dashed line shows the model spectra with simple amorphous carbon (*i.e.*, Rayleigh scattering in the far-infrared band), and the solid line shows the model spectra with the modified amorphous carbon. We find that the models with the modified amorphous carbon improve the overall fitting. The modified amorphous carbon grains fit all model stars with almost the same accuracy regardless their total optical depth. We do not find any systematic deviations depending on the total optical depth.

The effect of temperature on the optical properties of dust has been noted by a number of authors (*e.g.*, Volk and Kwok 1988, Suh 1991b) for circumstellar silicate grains. They find that the deduced opacities at longer wavelengths ($\lambda > 12$ μm) for OH/IR stars are higher than the one for M-type Miras possibly because of the change of optical constants depending on the temperature of dust grains. And Colangeli *et al.* (1992) have found the similar temperature effect of opacity for hydrogenated amorphous carbon and polycyclic aromatic hydrocarbon molecules in their laboratory experiments. But contrary to our expectation, we do not find such variations for amorphous carbon showing uniform fitting for various dust optical depths with only one dust opacity pattern.

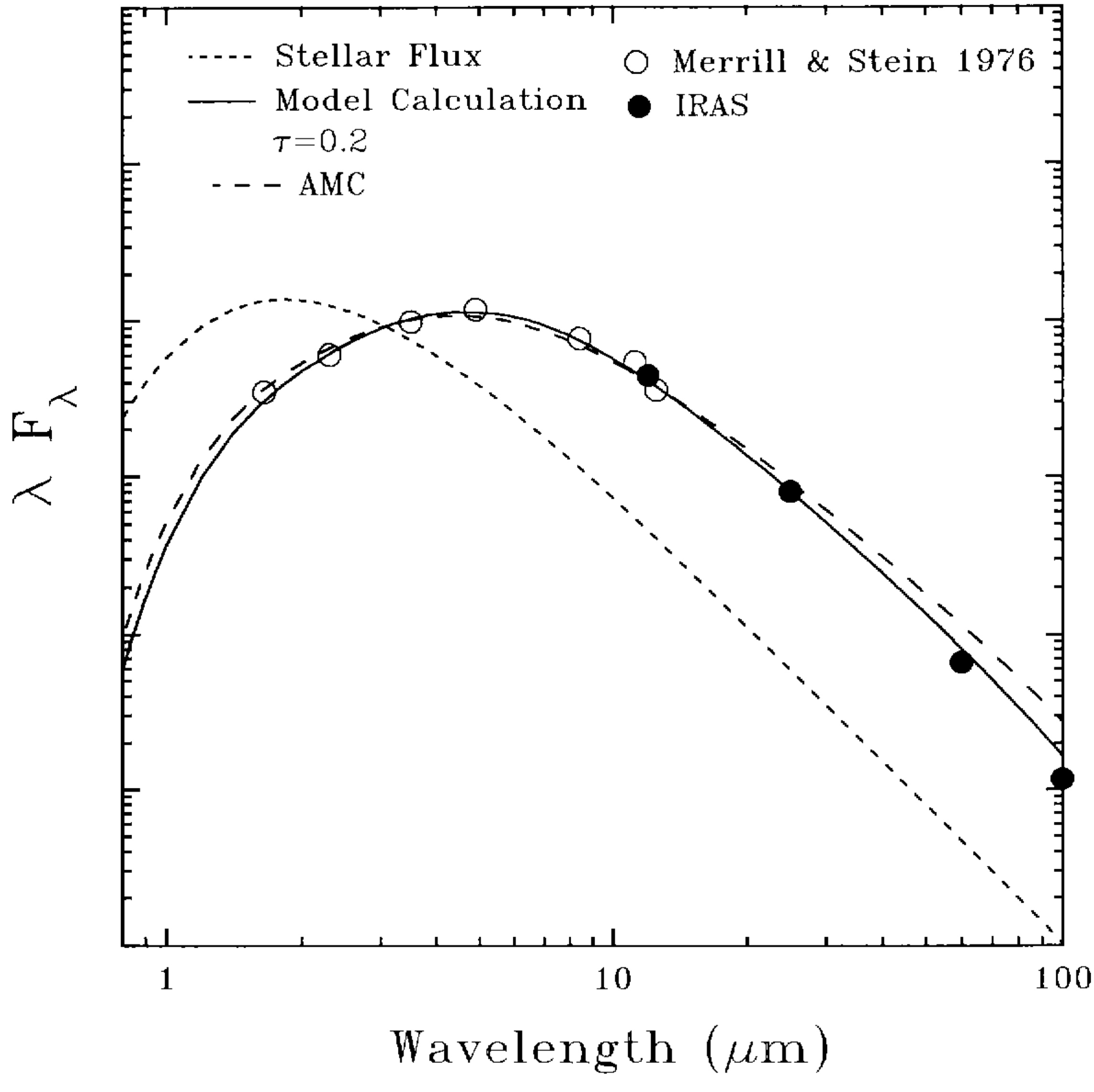

Figure 2. The model spectra and the observational data for IRC 50096.

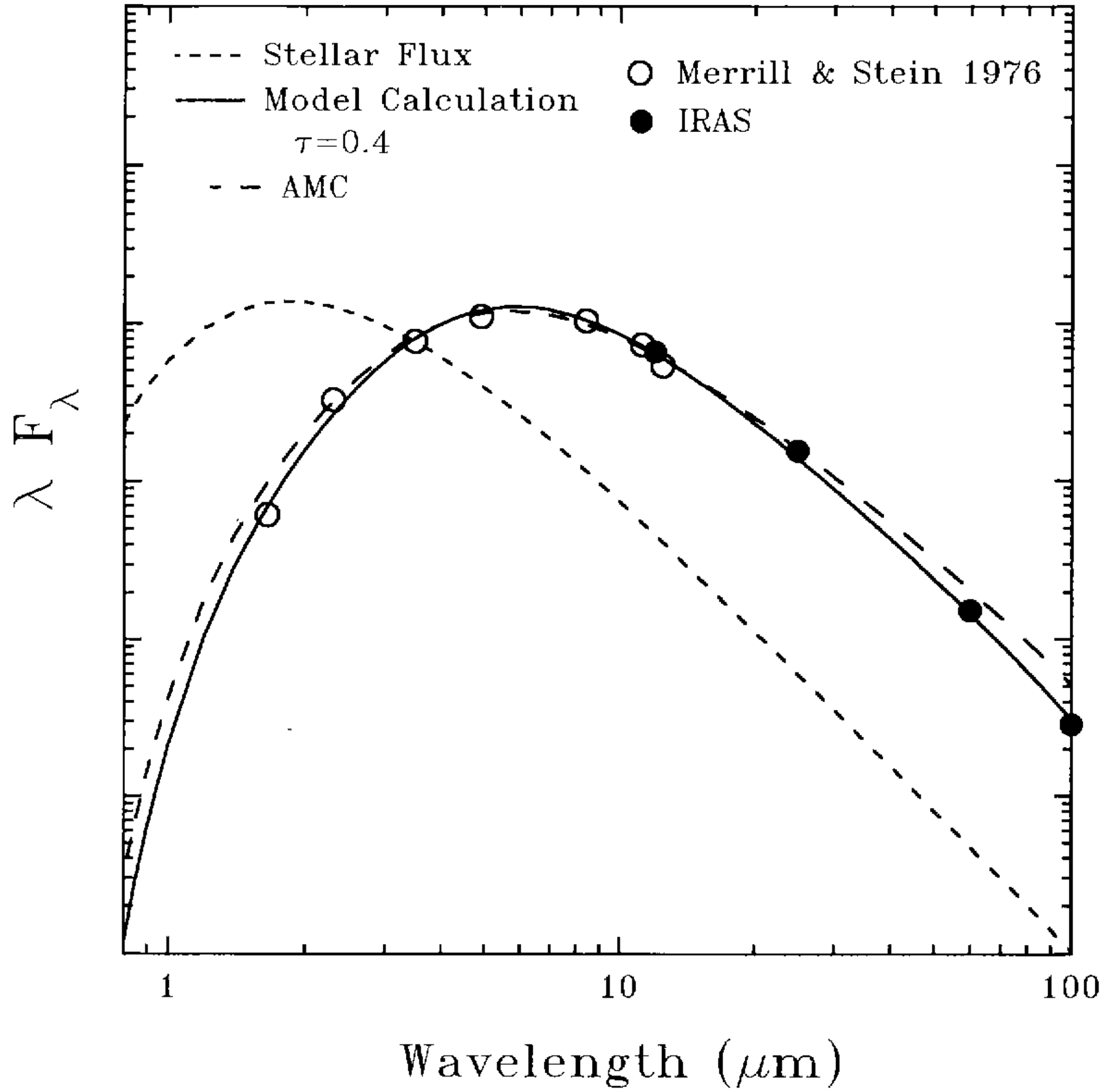

Figure 3. The model spectra and the observational data for IRC 40540.

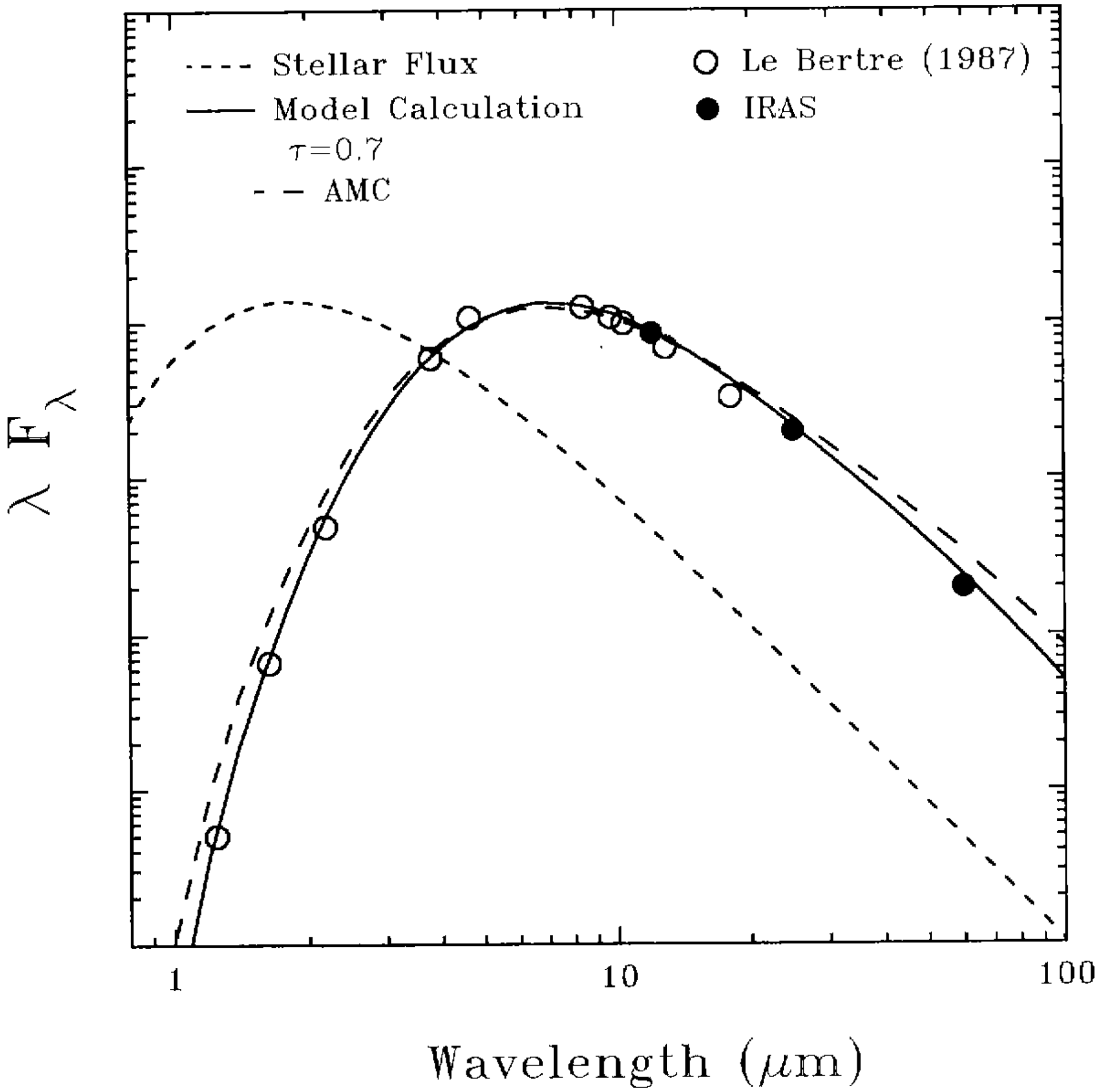

Figure 4. The model spectra and the observational data for IRC 10216.

4. STELLAR WINDS

Dust grains in circumstellar shells do not only affect the optical property redistributing the emergent spectra toward longer wavelengths but also affect their dynamic structure for their distinctively high opacities. It has been known that red giants cannot drive their mass out in their final stage of evolution if there were no dust grains in their outer shells. It is important to know the optical properties of dust grains to understand the efficiency of stellar winds to drive the dust grains (and gas) outward.

And the radiation pressure opacity is given by:

$$\kappa_{pr} = \frac{N < Q_{pr} > \pi a^2}{\rho} \tag{1}$$

where N, a, r are the number density of dust grains, mean radius of dust grains, and the mass density of the medium. And $< Q_{pr} >$ is the Planck mean value of radiation pressure efficiency factor (Q_{pr}). Figure 5 shows the Planck mean values of radiation pressure efficiency factors for the modified amorphous carbon (AMC), graphite and silicate as the functions of the dust temperature. The radiation pressure efficiency factors derived from infrared spectra of carbon stars are much larger than graphite, so the efficiency to drive the stellar winds for dust envelopes around carbon stars should be higher than conventional models (*e.g.*, York 1988, Sedlmayer 1989).

5. DISCUSSION

Amorphous carbon grains fit the observations of carbon stars fairly well. The models with a steeper decrease of the absorption efficiency factor at $\lambda > 7$ μm than standard amorphous carbon significantly improve the fitting. This could be due to a factor that dissuade absorbing at far-infrared. Other materials for carbon rich grains than amorphous carbon or graphite have been suggested. Polycyclic aromatic hydrocarbons (PAHs) could be one of the best candidates (*e.g.*, Leach 1989). But experimental data are not sufficient to be closely tested with infrared observations. We have to pay attention to that possibility.

Dust-thick carbon stars have more cool dust grains with the same optical properties as those for dust-thin ones. Unlike silicate grains and many other grain materials, the amorphous carbon grains do not show the temperature dependence of the opacity. Hydrogenated amorphous carbons and PAHs do show that temperature dependence (Colangeli *et al.* 1992, Blanco *et al.* 1988). So we may expect that if PAHs are present in the envelopes of carbon stars their content should be small enough not to show the temperature dependence and big enough to change the infrared opacity pattern.

The Planck mean values of radiation pressure efficiency factors for amorphous carbon are much larger than those for the graphite which have been widely used in stellar wind models of carbon stars. So the dynamic models for carbon stars should be reconsidered.

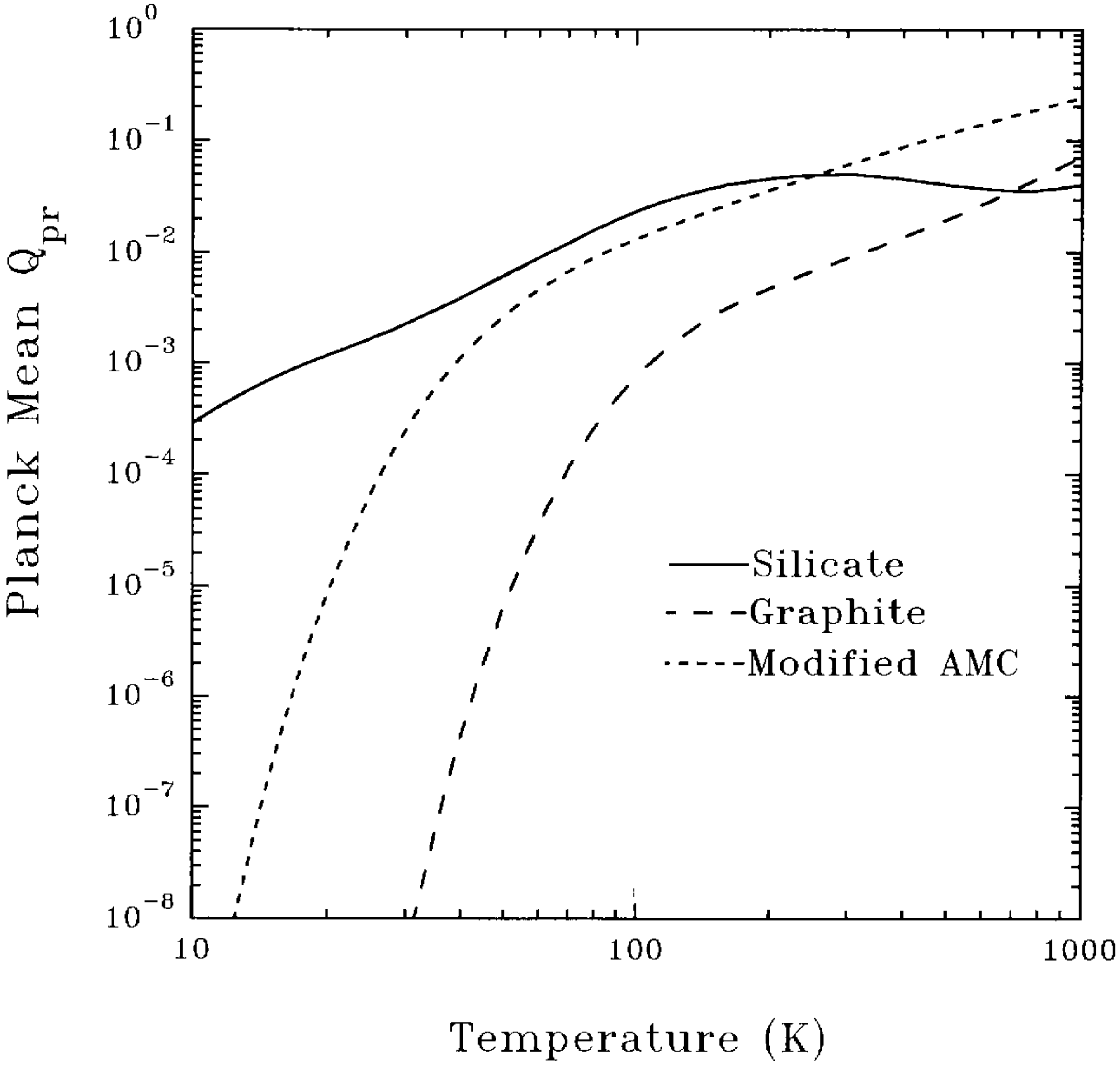

Figure 5. The Planck mean values of radiation presuure efficiency factors for silicate, graphite and modified amorphous carbon dust grain materials for given temperature.

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