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THE ROSSELAND MEAN OPACITY OF INTERSTELLAR GRAIN *

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ABSTRACT

We have calculated the opacity of interstellar grains in the temperature range $10°K$ – $1500°K$. Two composite grain models have been considered. One of them consists of silicate coated with ice mantle and the second has a graphite core coated also with ice mantle. These models are compared with isolated grain models. An exact analytical and computational development of Güttler's formulae for composite grain models has been used to calculate the extinction coefficient.

It has been found that the thickness of the mantle affects the opacity of the interstellar grains. The opacity of composite models differs from that of the isolated models. The effect of the different species (ice, silicate and graphite) is also clear.

1. INTRODUCTION

Radiative transfer is a critically important process for calculations of the energy equation during star formation. The Rosseland mean opacity is required as an input. It is dominated by atomic, ionic and molecular opacities at temperatures higher than $1500^\circ K$. At lower temperatures scattering and absorption from interstellar grains become the effective sources of opacity. Pioneering work on the grain opacity was performed by Knacke (1968), Kellman and Gaustad (1969). Gilra (1972) and Jones and Merrill (1976) have included the effects of silicate grain on the opacity. Cameron and Pine (1973) have improved the treatment of grains by utilizing more complete optical constants for both silicate and iron grains. Alexander (1975) has computed the grain opacity and Alexander *et al.* (1983) have improved the calculations of Alexander by including the effect of magnesium silicate using the optical constants given by Day (1979). But the calculations of Alexander were carried out at temperatures higher than $700^\circ K$. The more recent calculations given by Pollack *et al.* (1985) were done on grains containing some components which have been estimated for the primordial solar system. They included the anisotropic scattering in their calculations.

Under certain conditions, particularly in dense clouds, ice may condense on either graphite or silicate particles forming composite grains (Bussolite *et al.*, 1974; Greenberg, 1985). In addition there are some other species which should exist in the composite interstellar grains, like: amorphous carbon, organic refractory materials and polycyclic aromatic hydrocarbons. It has been found that these grains satisfy the observations in the interstellar clouds in the visible and ultraviolet regions more than the isolated grain models. Tielens and Allamandola (1987), Shalabia *et al.* (1987) and Shalabia *et al.* (1990) presented new and exact analytical and computational developments of Güttler's formulae for isolated and composite grains. Using their calculations of the efficiency factors of extinction for interstellar grains would help us to get a specific picture of interstellar grain opacity. Therefore it is interesting to calculate the opacity due to isolated and composite grains regarding their chemical composition, size distribution and radii as exist in dense interstellar clouds.

2. PROCEDURE

The Rosseland mean opacity is given by (Pollack *et al.*, 1985),

$$\bar{K}_e = \frac{\int_0^\infty \frac{\partial B(\nu,T)}{\partial T}\, d\nu}{\int_0^\infty \frac{1}{K_e(\nu)}\,(1-\tilde{\omega}\beta)\,\frac{\partial B(\nu,T)}{\partial T}\, d\nu}\,, \qquad (1)$$

$$K_e(\nu) = \sum_{j=1}^{J} \alpha_j\, Q_{ext,j}\,. \qquad (2)$$

$$\tilde{\omega} = Q_{sca}/Q_{ext} \qquad (3)$$

The summation in Eq.(2) runs over the different species existing in the interstellar grains. And,

$$\alpha_j = \frac{3 f_j}{4 d_j}\,\frac{\int_0^\infty n(r)\, r^2 dr}{\int_0^\infty n(r)\, r^3 dr}\,, \qquad (4)$$

where ν is the frequency, T is the temperature, B is the Planck function, Q_{ext} and Q_{sca} are the efficiency factors for extinction and scattering. f_j and d_j are the fractional abundance by mass and density of a species j, respectively. $n(r)$ is the grain size distribution function, and r is the grain radius. The factor $(1-\tilde{\omega}\beta)$ in Eq.(1) takes account of anisotropic scattering. β is zero for isotropic Rayleigh scattering and one for totally forward scattering. What we need is to specify the extinction coefficient, the grain species (models), their abundances, densities, optical constants and size distribution. In order to calculate the extinction efficiency factor, we have used the computer code given by Shalabia *et al.* (1987) for isolated grains and the extended one by Shalabia *et al.* (1990) for composite grain models. Two models of interstellar grain have been assumed. One of them consists of silicate core coated with ice mantle and the second model has a graphite core and is also coated with ice mantle.

The icy grain mantle, called dirty ice, contains in addition to H_2O other molecules like $H_2CO, N_2, O_2, CO_2, CO, H_2O_2, NH_3$ and CH_3OH (Tielens and Allamandola, 1987 and Tielens, 1989). The density and fractional abundances by mass for ice, silicate and graphite are taken from Barlow (1978) and Pollack *et al.* (1985). To our knowledge, the optical constants of the organic refractory material and polycyclic aromatic hydrocarbons are only defined in a narrow band of wavelength, Greenberg and Chlewicki (1987). As a matter of simplicity, we have considered the two models of interstellar grains mentioned previously and studied by Shalabia *et al.* (1990). The optical constants for ice, graphite and silicate from the UV to microwave domain are given in Table 1. Due to lack of information, the optical constants of several available close analogues were combined to represent the required optical constants of the species of interest.

To calculate the grain size distribution we have used the power law form of Mathis *et al.* (1977). Accordingly $n(r)$ is given by,

$$n(r) = (P_0/r)^{3.5} \qquad P_0 \le r \le 1\ \mu m \qquad (5)$$

where $P_0 = 0.005\ \mu m$.

3. THE RESULTS

We have calculated the opacity for a grain model of isolated ice with radius $r = 0.2\ \mu m$ and another grain model of isolated graphite with $r = 0.05\ \mu m$. These two models have been calculated in order to make a comparison with the calculations of Kellman and Gaustad (1969). The results of these two models are shown in Fig.1. The increase of opacity with temperature has a similar trend as that given by Kellman and Gaustad. There are some differences between our and their results. This is because of our use of a large band of wavelengths for the refractive indices - more than the wavelength range 3–200μm used by Kellman and Gaustad. While they have considered only the efficiency factor of absorption we have used the extinction efficiency factor which has been calculated by an exact and detailed method (Shalabia *et al.*, 1990). In Fig 2a the opacity is calculated for three models of dust grains. The first model consists of isolated silicates with $r = 0.1\ \mu m$ and the second model is composite silicate with total radius $r = 0.2\ \mu m$ and the radius of the silicate core is $r = 0.1\ \mu m$. The third model is isolated ice with $r = 0.2\ \mu m$. Since the mantle of the composite grain model has a radius half of the total radius of the grain, the two models of ice and composite silicate are nearly equal. In Fig.2b, the radius of the mantle is taken to be small. Therefore the opacity of the silicate composite grain differs much (particularly at $T > 100°K$) from that of the isolated ice model. This result confirms that the thickness of the mantle may greatly affect the values of the opacity. The models of isolated and composite silicate grains will have a similar trend at temperatures higher than $200°K$. We stopped the calculations of the composite model at $T \geq 273°K$ where the ice mantle is certainly evaporated (see Pollack *et al.*, 1985). The calculations carried out for the silicate model have also been repeated for the graphite model and the results are shown in Figs.3a and 3b. In general the two composite models of silicate and graphite indicate that the opacity of the composite model is clearly different from that of the isolated one. There is also a clear difference in the values of opacity resulting from the different species: ice, silicate and graphite. Comparing our results for the Rosseland mean opacity for the composite grains with that of Pollack *et al.* (1985) one finds that there is a similar increase with temperature, however, the different approaches have been used. We have calculated the model of isolated silicate under the assumption of isotropic scattering in order to compare it with the results of anisotropic scattering. The results are shown in Fig.4. The opacity decreases in the case of anisotropic scattering as compared to the isotropic scattering at temperatures higher than 300°K.

It has to be mentioned that the assumption that different components exist in the interstellar grain model may help to find a more real picture of the opacity. In order to do that the optical constants of the different components are required.

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REFERENCES

Alexander, D.R., 1975, Astrophys. J. Suppl. **29**, 363.

Alexander, D.R., Johnson, H.R. and Rypma, R.L., 1983, Astrophys. J. **272**, 773.

Barlow, M.J., 1978, Monthly Notices Roy. Astron, Soc. **183**, 417.

Bertie, J.E., Lappe, H.J. and Whalley, E, 1969, J. Chem. Phys. **50**, 4501–4520.

Bussolite, E., Borghesi, A., Leggiere, G. and Blanco, A., 1974, Solid State Astrophysics, Proceedings of a symposium held at the University College, Cardiff, Wales, p.143.

Cameron, A.G.W. and Pine, M.R., 1973, Icarus **18**, 377–406.

Day, K.L. 1979, Astrophys.J. **234**, 158.

Gilra, D.P., 1972, Scientific results from OAO(NASA SP–31, Washington, D.C., GPO).

Greenberg, J.M., 1985, Physica Scripta, **T11**, 14–26.

Greenberg, J.M. and Chlewicki, G., 1987, Q. Jl. R. Astr. Soc. **28**, 312–322.

Isobe, S., 1975, Ann. Tokyo Astron, Obs, Second series, Vol.XIV, No.3, 141.

Jones, T.W. and Merrill, K.M., 1976, Astrophys. J. **209**, 509.

Kellman, S.A. and Gaustad, J.E., 1969, Astrophys. J. **157**, 1465.

Knacke, R.F., 1968, Nature **217**, 44–45.

Leung, C.M., 1975, Astrophys. J. **199**, 340.

Mathis, J.S., Rumple, W. and Nordsieck, K.H., 1977, Astrophys. J. **217**, 425.

Pollack, J.B., McKay, C.P. and Christofferson, B.M., 1985, Icarus **64**, 471–492.

Shalabia, O.M., Sharaf, M.A., El Shalaby, M.A. and Aiad, A., 1987, 12th International Congress for Statistic, Computer Science, Ain Shams University, Cairo, Egypt, pp.315–330.

Shalabia, O.M., El Shalaby, M. and El–Nawawy, M.S., 1990, Astrophysics and Space Science, in press.

Tielens, A.G.G.M., 1989, IAU Symposium No.135, Interstellar Dust, eds. L.J. Allamandola and A.G.G.M. Tielens.

Tielens, A.G.G.M. and Allamandola, L.J., 1987, in Interstellar Processes, eds. D.J. Hollenback and H.A. Thronson, Jr., 397–469.

Toon, O., Pollack, J.B. and Sagan, C., 1977, Icarus **30**, 663–696.

Table 1

Sources of the optical constants

Species	Wavelength Domain (μm)	References
Ice	0.01 – 100	Isobe, 1975
	100.00 – 333	Berties *et al.*, 1969
	333.00 – 1600	Leung, 1975
Graphite	0.01 – 100	Isobe, 1975
	100.00 – 1600	Leung, 1975
Silicate	0.1 – 5	Isobe, 1975
	5.00 – 40	Toon *et al.*, 1977
	50.00 – 1600	Leung, 1975

FIGURE CAPTIONS

Fig.1 The Rosseland mean opacity (in cm/gm) is plotted as a function of temperature (in K). a) For isolated ice with $r = 0.2\ m$. b) The curve of Kellman and Gaustad (1969) for isolated ice. c) Isolated graphite with $r = 0.05\,\mu m$. d) The curve of Kellman and Gaustad for isolated graphite with r as given in c).

Fig.2a The Rosseland mean opacity (in cm/gm) as a function of temperature (in °K). a) Isolated silicate with $r = 0.1\,\mu m$. b) Composite silicate with $r = 0.2\,\mu m$ and $r = 0.1\,\mu m$. c) Isolated ice with $r = 0.2\,\mu m$.

Fig.2b The same as in Fig.2a with a) isolated silicate, $r = 0.1\,\mu m$. b) Composite silicate, $r = 0.11\,\mu m$ and $r = 0.1\,\mu m$. c) Isolated ice, $r = 0.11\,\mu m$.

Fig.3a The same as in Fig.2a for graphite.

Fig.3b The same as in Fig.2b for graphite.

Fig.4 The Rosseland mean opacity (in cm/gm) as a function of temperature in °K) for isolated silicate. a) Isotropic scattering. b) anisotropic scattering.

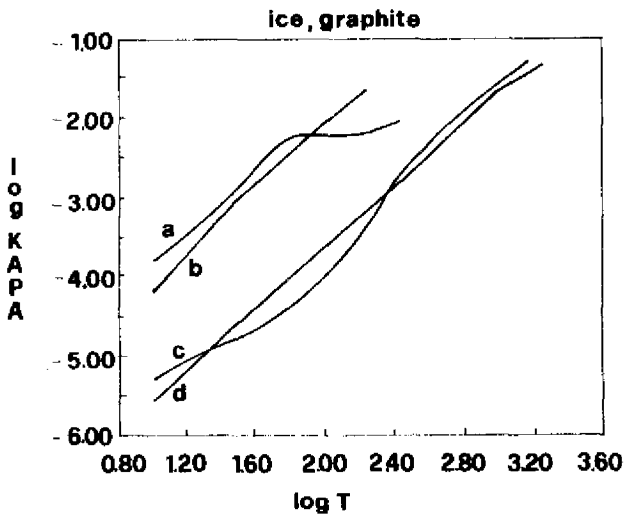
ice, graphite
1.00
2.00
3.00
4.00
5.00
6.00
log KAPA
a
b
c
d
0.80 1.20 1.60 2.00 2.40 2.80 3.20 3.60
log T

Fig.1

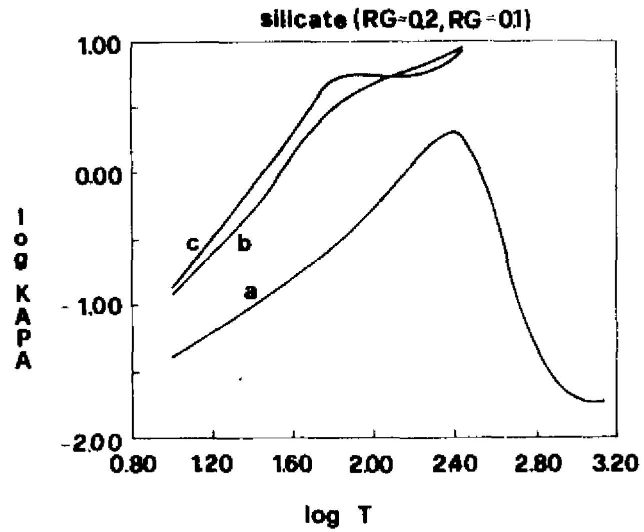
silicate (RG=0.2, RG=0.1)
1.00
0.00
-1.00
-2.00
log KAPA
c
b
a
0.80 1.20 1.60 2.00 2.40 2.80 3.20
log T

Fig.2a

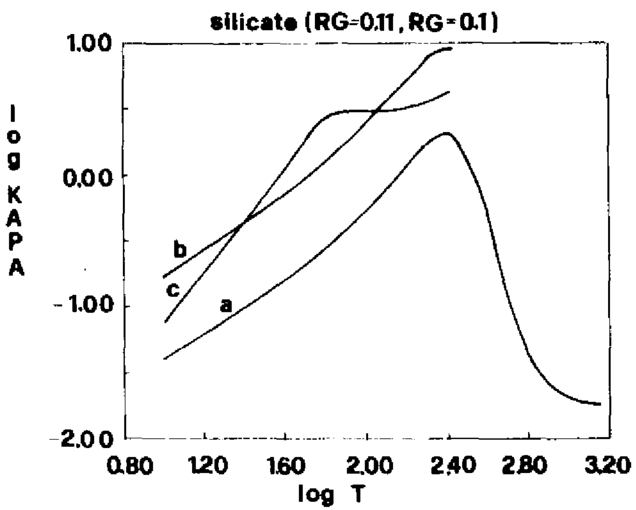
silicate (RG=0.11, RG=0.1)
1.00
0.00
-1.00
-2.00
log KAPA
0.80
1.20
1.60
2.00
2.40
2.80
3.20
log T
a
b
c

Fig.2b

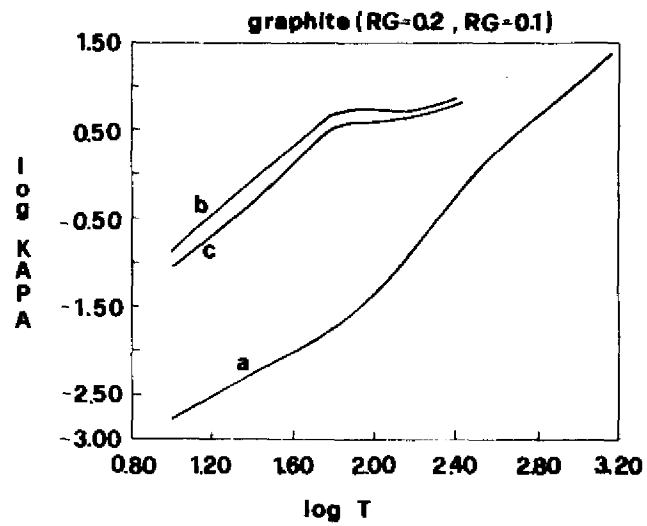
graphite (RG=0.2, RG=0.1)
1.50
0.50
-0.50
-1.50
-2.50
-3.00
log KAPA
0.80
1.20
1.60
2.00
2.40
2.80
3.20
log T
a
b
c

Fig.3a

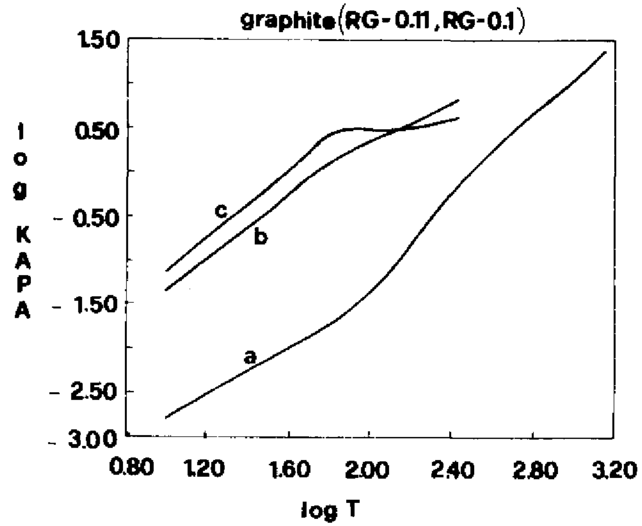
graphite(RG-0.11,RG-0.1)
1.50
0.50
- 0.50
- 1.50
- 2.50
- 3.00
0.80
1.20
1.60
2.00
2.40
2.80
3.20
log KAPA
log T
a
b
c

Fig.3b

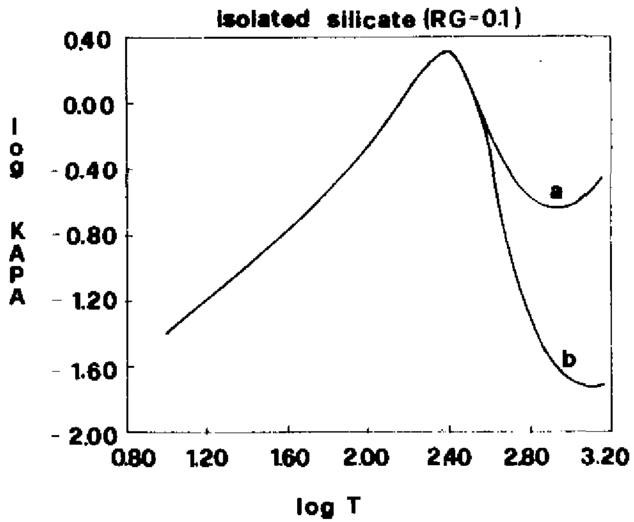
isolated silicate (RG-0.1)
0.40
0.00
- 0.40
- 0.80
- 1.20
- 1.60
- 2.00
0.80
1.20
1.60
2.00
2.40
2.80
3.20
log KAPA
log T
a
b

Fig.4

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