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Equilibrium temperatures of porous spheres and their relevance to astrobiology

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Abstract: Equilibrium temperatures are calculated for porous, organic spheres at a Solar distance of around 1 AU. It is found that the equilibrium temperature of porous grains is highly sensitive to their composition and radius. For porous organic grains of radius 0.1 μm the temperature ranges from 355 to 386 K as the porosity (vacuum volume fraction) increases from 0 to 0.9; for organic grains of radius 0.1 μm with 10% charring the corresponding range is from 448 to 431 K. Such superheated submicron grains, porous or otherwise, may have only a limited role as transporters of fragile biomolecules. Clumps of biological particles with radii in excess of 5 μm are, however, at low enough temperatures to permit such transport at 1 AU.

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Introduction

Many solid particles commonly encountered in astrophysics have densities significantly lower than those commonly assigned to solid materials. From analysis of the trajectories of cometary micrometeorites, Millman (1972) has shown that the majority of meteorite fragments have bulk densities less than 0.5 g cm^{-3}, with an average mean density of around 0.3 g cm^{-3}, independent of the nature of material. Similar low densities have been reported for dust raised in the Deep Impact mission.

More recently, organic material recovered at altitudes of around 40 km above the Earth (Wainwright *et al.* 2004) has been found to consist of highly porous material. High-resolution scanning electron microscopy (SEM) pictures have revealed this material to consist of low-density, porous grains with typical sizes of the order of micrometres (for a review, see Coulson (2004)).

As well as cometary fragments, porous organic grains are believed to be a key constituent of interstellar dust (Hoyle & Wickramasinghe 1979). Despite the potential for the widespread occurrence of porous grains in nature, there have been few attempts to calculate the thermal properties of such grains. Blanco & Bussoletti (1980) calculated the interstellar temperature for graphite and Lunar silicate grains. Prior to this, Abadi & Wickramasinghe (1976) and Hoyle & Wickramasinghe (1979) calculated the extinction efficiency Q_{ext} of a porous grain material; however, no attempt has been made to calculate the absorption efficiency Q_{abs} of porous organic grains, nor how this affects their equilibrium temperatures at Solar distances of around 1 AU. Such calculations are of fundamental astrobiological interest when considering the survival of porous organics, including viable biomaterial, in both free-space and descending through the Earth's atmosphere.

Optical properties of porous grains

To model porous grains, we consider a highly idealized situation consisting of a solid medium with dielectric function ε. Uniformly distributed through this solid material are small, spherical inclusions, with dielectric function ε_i. The average dielectric function of the composite medium is given by the Maxwell–Garnett equation

$$\varepsilon_{av} = \varepsilon\left(1 + \frac{3f(\varepsilon_i - \varepsilon)(\varepsilon_i + 2\varepsilon)^{-1}}{1 - f(\varepsilon_i - \varepsilon)(\varepsilon_i + 2\varepsilon)^{-1}}\right) \quad (1)$$

where the heterogeneous nature of the material is defined by the parameter $f\,(1 > f \geqslant 0)$, so that f is the fraction by volume occupied by the inclusions (Bohren & Wickramasinghe 1977; Bohren & Huffman 1983). The case when f is equal to zero corresponds to a solid homogenous material.

In the simplest case, considering the inclusions to be small spherical vacuum bubbles, the expression for ε_{av} reduces to

$$\varepsilon_{av} = \varepsilon\left(1 + \frac{3f(1 - \varepsilon)(1 + 2\varepsilon)^{-1}}{1 - f(1 - \varepsilon)(1 + 2\varepsilon)^{-1}}\right) \quad (2)$$

and f defines the porosity of the material. For prescribed values of the bulk refractive index $m(\lambda)$ the corresponding

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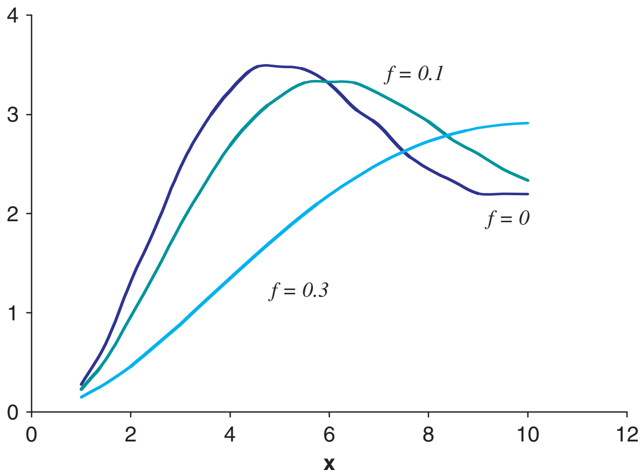

Fig. 1. Extinction efficiency Q_{ext} as a function of the size parameter x for spherical grains with $m=1.4-0.05i$. The fractional volume of spherical vacuum bubbles uniformly distributed throughout the grains is given by f. Identical results were derived by Abadi & Wickramasinghe (1976).

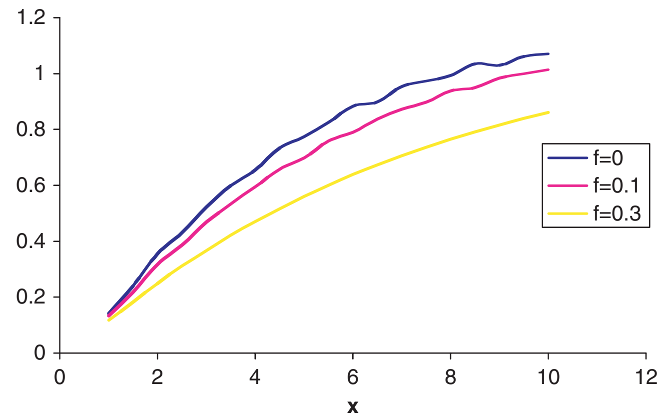

Fig. 2. Absorption efficiency Q_{abs} as a function of the size parameter x for spherical grains with $m=1.4-0.05i$. The fractional volume of spherical vacuum bubbles uniformly distributed throughout the grains is given by f.

dielectric function $\varepsilon(\lambda)$ to be used in (2) is given by

$$\varepsilon(\lambda) \approx m(\lambda)^2. \quad (3)$$

The average refractive index values $m=n-ik$ for porous grains in the present approximation are then immediately available from solving the equation

$$(n-ik)^2=\varepsilon_{av}. \quad (4)$$

We can now calculate extinction, scattering and absorption efficiencies (Q_{ext}, Q_{sca}, Q_{abs}) for spherical grains of various radii using the Mie formulae (van de Hulst 1957; Wickramasinghe 1973). Figures 1 and 2 show Q_{ext} and Q_{abs} as functions of the size parameter $x=2\pi a\lambda$, for spherical grains with $m=1.4-0.05i$. Here we see the effect that increasing the porosity of spherical grains has on their extinction efficiency Q_{ext} and absorption efficiency Q_{abs} (identical results to Fig. 1 have been obtained by Abadi & Wickramasinghe (1976)). There are significant differences between the Q_{ext} curves, even with the modest increase in porosity shown in Fig. 1, for all values of x, becoming most pronounced at higher values of x. The same is true for the absorption efficiency plotted in Fig. 2. This implies that for a given value of radius, the deviation in optical properties of porous grains compared with their equivalent solid particles is greatest at shorter wavelengths.

Equilibrium temperatures of porous grains

A grain in free-space thermally coupled to a radiation field radiates energy by thermal re-emission at a temperature T_g of the solid lattice. The energy re-emitted per unit time for a spherical grain of radius a is

$$4\pi a^2 \int_\lambda d\lambda Q_{abs}(\lambda, a) B(\lambda, T_g) \quad (5)$$

where B is the Planck function at temperature T_g. The use of the absorption coefficient for the emissivity is guaranteed by considerations of time-reversal symmetry (Bohren & Huffman 1983).

Consider a spherical grain composed of the porous medium described in the previous section, in free-space at a Solar distance of 1 AU; the main source of heating for such a particle comes from the Sun. The radiation absorbed per unit time, by such a particle is

$$W\pi a^2 \int_\lambda d\lambda Q_{abs}(\lambda, a) B(\lambda, T_0) \quad (6)$$

assuming that the radiation field from the Sun can be approximated as a blackbody with a Planck spectrum at an effective Solar temperature of $T_0 \sim 6000$ K. Here W is the dilution factor of the radiation field and is proportional to the inverse square of the distance from the Sun (at 1 AU, $W \approx 2.15 \times 10^{-5}$).

For grains in thermal equilibrium, equating (5) and (6) gives

$$4\pi a^2 \int_\lambda d\lambda Q_{abs}(\lambda, a) B(\lambda, T_g) = W\pi a^2 \int_\lambda d\lambda Q_{abs}(\lambda, a) B(\lambda, T_0). \quad (7)$$

The majority of particles forming interplanetary dust absorb radiation over the near-ultraviolet and visible wavelengths (0.2–0.8 μm) and emit over the infrared (2–12 μm) (Coulson & Wickramasinghe 2003).

From (7), the equilibrium temperatures of porous grains at 1 AU can be calculated, using suitable values for the complex refractive index at each wavelength and for various grain sizes.

When considering the thermal effects on grains released in the coma of P/Halley, Wallis *et al.* (1987) modelled the complex refractive indices for organic grains. Their grain model used a refractive index of $m=1.4-ik$, with values of $k(\lambda)$ in the visible and infrared obtained from measurements of

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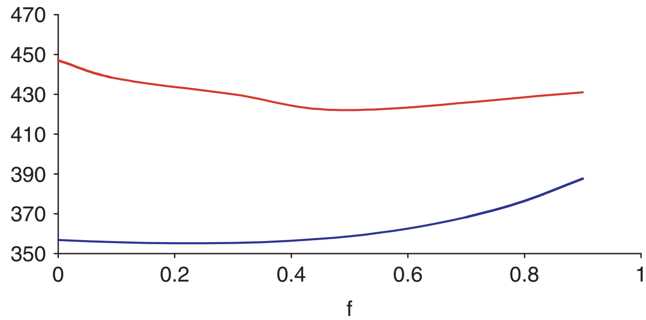

Fig. 3. Equilibrium temperatures for organic, spherical grains of 0.1 μm in free-space at a Solar distance or around 1 AU, plotted against the porosity parameter *f*. The bottom curve is for a material with a refractive index of $m=1.4-0.08i$ in the visible and $m=1.4-0.94i$ in the infrared. The top curve is for particles composed of an organic material with 10% carbon inclusions.

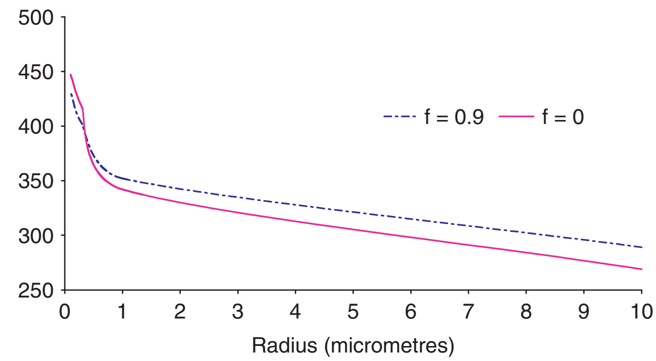

Fig. 4. Equilibrium temperatures for organic, spherical grains in free-space at a Solar distance of around 1 AU, plotted against grain radius in micrometres. The solid curve represents particles with a porosity parameter $f=0$ and the dashed curve represents particles with $f=0.9$. Both the solid and porous particles are composed of an organic material with 10% carbon inclusions.

biological, organic material. Averaging these results over the main absorption peaks, Coulson & Wickramasinghe (2003) found values for the refractive index of $m=1.4-0.08i$ in the visible and $m=1.4-0.94i$ in the infrared.

Using these values for the refractive index in (2), the equilibrium temperatures for spherical 0.1 μm grains are plotted against a range of values for *f* in Fig. 3. When $m=1.4-0.08i$ in the visible and $m=1.4-0.94i$ in the infrared, it is found that equilibrium temperatures for grains with $f=0.1-0.4$ are lower by 1–2 K than the bulk material. For grains with $f>0.5$ the equilibrium temperatures of the grains are greater than for the bulk material. This difference becomes greater as the value of *f* increases until $f=0.99$, when the equilibrium temperature is approximately 9% higher than that of a non-porous grain.

At 1 AU, equilibrium temperatures for organic grains of radii or around 0.1 μm are between 350 and 390 K. These temperatures are probably high enough to produce some charring of the grain surface, thus altering their average optical properties. To allow for the effects of charring we assume the optical properties for a 0.1 μm grain to be represented by a weighted average of the refractive indices of 90% of the organic material described by Wallis *et al.* (1987) and 10% carbon, using the refractive indices calculated by Taft & Philipp (1965). Integrating over all wavelengths from 0.21 to 10.1 μm on both sides of (7), it was found that the presence of carbon gave rise to significant emission peaks in the infrared spectrum at 3.4 and 10.1 μm, compared with pristine organic material. For such composite grains, the equilibrium temperature of a grain with $f=0.9$ was 431 K, which is lower than the equivalent solid grain with an equilibrium temperature of 447 K.

For larger particles, such as those found in the Brownlee particles and the stratospheric collections by Wainwright *et al.* (2004), the temperatures are much lower. Figure 4 shows the equilibrium temperatures for porous and solid grains as a function of radius between 0.1 and 10 μm, composed of 90% organic material and 10% carbon inclusions. The equilibrium temperatures fall towards the effective blackbody temperature at 1 AU as radii increase beyond 5 μm, and solid grains have lower temperatures than porous grains.

Conclusion

For porous organic grains of radius 0.1 μm, the temperature ranges from 355 to 386 K as the porosity increases from $f=0$ to 0.9; for organic grains of radius 0.1 μm with 10% carbon (attributed to charring) the corresponding temperature range is from 448 to 431 K. Thus, for organic grains at Solar distances of 1 AU the temperature difference between porous and non-porous grains is not highly significant when considering the survival of these particles. If they were to be captured by the Earth and descend through the atmosphere, atmospheric heating on submicrometre-sized grains is proportional to T^5. Similarly, for superheated grains in free-space, sublimation rates are typically less than 10 s for 0.1–0.3 μm particles (Coulson & Wickramasinghe 2003). Based on such considerations, we conclude that the slightly lower equilibrium temperatures of porous organic grains may not offer a significantly increased rate of survival at 1 AU Solar distances. However, the situation is dramatically different for larger porous or non-porous organic grains.

The temperatures in Fig. 3 remained well in excess of the effective backbody temperature ($T_{\rm eff}$) at 1 AU due to the effect of superheating in small particles of radii $a=0.1$ μm. As the particle size increases much above 3 μm, the temperature begins to approach $T_{\rm eff}$ as is seen in Fig. 4. Figure 4 also shows that porous grains are heated to temperatures slightly above those corresponding to non-porous grains for a prescribed value of radius, opposite to the trend seen in Fig. 3, with the cross-over occurring at $a=0.5$ μm.

The astrobiological relevance of these calculations is that composite porous organic clusters, such as those that have been found in the stratosphere, are not significantly heated whilst they remain intact as large particles. Superheating, leading to the release/thermal degradation of organics and biological structures, occurs if they crumble into units much

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less than a micrometre in size. The best mode of planetary delivery of particulates relevant to astrobiology is thus in the form of intact clusters of sizes in excess of 5 μm.

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