**The extinction of sunlight by atmospheric loading**

*Buckingham Centre for Astrobiology,*
*The University of Buckingham, Buckingham MK18 1EG*
coulson@aldpartners.com

**Abstract**

Hoyle was probably the first to recognize that interplanetary dust particles can affect the earth's climate. In this paper we review the contribution made by Hoyle and his collaborators over a period of sixty years. We present calculations of the extinction efficiencies of porous particles and discuss the likely change in the average global temperature resulting from a veil of porous, sub micron-sized particles in the Earth's atmosphere. It is found that a relatively small mass of dust ~ 100 tonnes of highly porous particles could reduce the global average temperature by 1 - 2 K.

## 1. Introduction

Hoyle was one of the first to calculate the contribution of scattering by small particles to the albedo of the Earth and hence changes in global temperatures. In a series of papers published with different collaborators between 1939 and 1999, Hoyle argued that the presence of micron-sized particles in the mesosphere would significantly affect the Earth's equilibrium temperature. Here we review three of Hoyle's papers and extend some of the results to include the contribution of scattering by small, porous particles to the Earth's albedo.

## 2. Hoyle's Papers on small particles & the Earth's albedo

Hoyle & Lyttleton (1939) examined the rate of accretion of small particles that would result from the Solar System traversing a large, interstellar dust cloud. By considering the potential increase in the Sun's luminosity from the influx of interstellar material, Hoyle & Lyttleton concluded that the changes in solar radiation that occurred when the Sun passed through a diffuse region of space were sufficient to produce an ice age and passing through a dense dust cloud produced periods of global warming (carboniferous epochs).

In concentrating on the change in solar radiation resulting from an influx of small particles Hoyle & Lyttleton ignored the effects radiation scattering by the particles themselves, this was addressed by Hoyle & Wickramsinghe (1978) who calculated that small, dielectric grains with a surface mass density of would give an optical depth of ~ 1 in the visual, and that a mass of $\sim 5\times10^{13}\ g$ of these grains would be sufficient to prevent sunlight from penetrating to ground level.

As the optical opacity for porous silicate particles with radii ~ *10 μm* is two orders of magnitude greater than the infrared, a layer of such grains in the upper atmosphere would not only shield the Earth from incoming solar radiation, it would also allow infrared radiation to escape into space. The overall effect would be significant cooling of the Earth's surface. Hoyle & Wickramasinghe calculated that the latent energy reserve in the Earth's oceans was equivalent to ~ 10 years supply of sunlight, so that if the loading of dust within the Earth's atmosphere was maintained for decade, the result would be an ice age.

In the same paper Hoyle & Wickramsinghe argued that the $\sim 5 \times 10^{13}\ g$ mass of particles required to produce this effect is comparable to the mass emission of a typical comet with perihelion passage < 1 AU. By assuming that ~ 5 comets a year cam within a heliocentric distance of 1 AU, they calculated that the probability of a 'dust-acquiring' encounter as $\sim 10^{-8}$ per year.

In a later paper (Hoyle & Wickramasinghe 1991) Hoyle considered not only the ability of small particles to absorb solar radiation, but also the effects of backscattering of radiation by ice grains with radii ~ *0.25 μm* located in the mesosphere. Using Mie theory to calculate the scattering amplitude function $S(\theta)$, the average fraction of radiation lost from a hemisphere of sunlit particles was determined.

It was found that Rayleigh particles backscattered half the radiation incident upon them at all angles relative to the earth, while Mie particles only achieved this efficiency near the Earth's limb (e.g. $\sim \frac{\pi}{2}$) at sunrise or sunset.

The main results from Hoyle's work on the effect of small particles on the Earth's albedo are that: the presence of small particles in the Earth's upper atmosphere and in free space can produce significant changes in global temperatures; small particles affect the Earth's albedo by both absorption and backscattering of radiation; and, the response of small particles to radiation is highly dependent on their size, shape and composition.

In the next section we extent some of these results by examining the absorption and scattering of porous, magnetic grains.

## 3. The absorption and extinction of porous grains

Heterogeneous particles can often exhibit very different absorption and extinction properties compared with equivalent homogeneous particles of the same size. Porous grains composed of a continuous material interspersed with vacuum inclusions can also show significant variation in radiation efficiencies from solid grains.

Coulson & Wickramasinghe (2007) used the Maxwell-Garnett theory to calculate the equilibrium temperatures of porous, organic grains at solar distances of 1 AU. These authors found that for small grains with radii $< 0.1 \mu m$, the absorption efficiency of grains increased with porosity; while grains with radii $> 0.1 \mu m$, the absorption efficiency decreased as the porosity increased.

From Mie theory, the forward scattering amplitude is given by

$$S(\theta=0)=\frac{1}{2}\sum_{n=1}^{\infty}(2n+1)(a_n+b_n) \tag{3.1}$$

where $a_n$ and $b_n$ are the Mie Scattering functions of the electric and magnetic multipole coefficients

$$a_n=\frac{\mu_1 m^2 j_n(mx)[xj_n(x)]'-\mu j_n(x)[mxj_n(mx)]'}{\mu_1 m^2 j_n(mx)[xh_n^{(1)}(x)]'-\mu h_n^{(1)}(x)[mxj_n(mx)]'} \tag{3.2}$$

and

$$b_n=\frac{\mu_1 j_n(mx)[xj_n(x)]'-\mu j_n(x)[mxj_n(mx)]'}{\mu_1 j_n(mx)[xh_n^{(1)}(x)]'-\mu h_n^{(1)}(x)[mxj_n(mx)]'} \tag{3.3}$$

where $\mu$ and $\mu_1$ are the permeabilities of the medium and the particle respectively. $j_n$ and $h_n^{(1)}$ are the spherical Bessel functions and the Hankel (Spherical Bessel functions of the third kind) respectively.

Consider the simplest form of heterogeneous grain, a matrix material with dielectric constant $\varepsilon$ and relative permeability $\mu$, filled with void inclusions that can be approximated as spherical vacuuo of volume fraction *f*. The radiation properties of such grains can be calculated by assuming that they are solid, homogeneous particles with effective dielectric constant $\tilde{\varepsilon}$ and effective relative permittivity $\tilde{\mu}$. Where $\tilde{\varepsilon}=g_1(f,\varepsilon,\mu)$ and $\tilde{\mu}=g_2(f,\varepsilon,\mu)$ for complex functions $g_1$ and $g_2$.

Assuming that the size parameter, $x=\frac{2\pi a}{\lambda}\ll 1$, the effective relative permittivity can be written as (Coulson 2008)

$$\tilde{\mu}=\mu\left(\frac{1+\frac{2f(1-\mu)}{(1+2\mu)}}{1-\frac{f(1-\mu)}{(1+2\mu)}}\right) \tag{3.4}$$

and the effective dielectric constant

$$\tilde{\varepsilon} = \varepsilon \left\{ \frac{1 + \dfrac{2f(\mu - \varepsilon)}{(\mu + 2\varepsilon)}}{1 - \dfrac{f(\mu - \varepsilon)}{(\mu + 2\varepsilon)}} \right\} \left\{ \frac{1 + \dfrac{2f(1 - \mu)}{(1 + 2\mu)}}{1 - \dfrac{f(1 - \mu)}{(1 + 2\mu)}} \right\} \tag{3.5}$$

Defining the bulk refractive index $\tilde{m}(\lambda)$ as

$$m^2(\lambda) = \tilde{\mu}(\lambda)\tilde{\varepsilon}(\lambda) \tag{3.6}$$

In the limit, $x \ll 1$, the absorption efficiency is given by

$$Q_{abs} = 4x\ lm\left(\frac{\tilde{m}^2 - 1}{\tilde{m}^2 + 2}\right) \tag{3.7}$$

and the extinction efficiency is

$$Q_{ext} = 4x\ lm\left(\frac{\tilde{m}^2 - 1}{\tilde{m}^2 + 2}\right) + \frac{8}{3}x^4\ \mathrm{Re}\left\{\left(\frac{\tilde{m}^2 - 1}{\tilde{m}^2 + 2}\right)^2\right\} \tag{3.8}$$

For composite grains, the values for $\varepsilon$ and $\mu$, vary with particle radii, for simplicity, we restrict the calculations presented here to 7 μm diameter iron composite grains. Figure 3.1 shows the variation of the extinction efficiency ($Q_{ext}$) with frequency for micron-sized iron grains with vacuum inclusions For solid iron grains ($f = 0$), the extinction is close to zero, but increases by several orders of magnitude as the degree of porosity increases. The rate of increase is greatest between $f = 0.4$ and $f = 0.6$, so that extinction over microwave frequencies starts to become significant as the volume of iron within the grains becomes less than the volume of the inclusions. Physically, this can be interpreted as the interactions between the inclusions increasing the absorption of incident radiation.

The absorption and extinction efficiencies for porous iron vary greatest over the microwave frequencies. By considering the absorption and extinction properties of slender, iron whiskers in free space, Hoyle & Wickramasinghe (1988) noted that a distribution of such particles within the Milky Way would be sufficient to account for the observed *microwave background temperature*. If the iron whiskers were assumed to be highly porous, the increased extinction from including the magnetic permittivity in radiation scatterings would reduce the mass of iron whiskers required by approximately an order of magnitude.

**4. Extinction of sunlight from atmospheric loading**

The Stardust probe recovered organic particles of ~ 10 μm size within the inner halo surrounding the coma of the comet Wild 2 (Coulson 2010). These grains were found to be highly heterogeneous and porous in composition. A typical cometary coma is ~

$10^{-7}$ *m* in diameter, based on the assumption that ~ 5 comets reach a perihelion distance < 1 AU every year, Hoyle & Wickramsinghe (1978) calculated the probability of the Earth's atmosphere being loaded with cometary grains $\sim 10^{-8}$ per year. The percentage of extraterrestrial particles incident within the 60 tonnes of matter daily entering the Earth's upper atmosphere which are organic, bacteria has been estimated from balloon experiments ~1% (Wainwright & Wickramasinghe 2004). This implies that the probability Earth's atmosphere receives a significant loading of organic material is $\sim 10^{-10}$ per year.

Assuming that the Earth passed through the inner halo of a cometary coma composed of organic material, the loading of the upper atmosphere with small particles would form a dust veil, cloaking sunlight from the surface of the Earth. By considering the optical depth $\tau$ of the aggregation of these particles within the atmosphere defined by

$$I = I_0 e^{-\tau} \tag{4.1}$$

where $I$ is the intensity of solar radiation penetrating the dust veil to arrive at the surface of the Earth, $I_0$ is the original intensity of solar radiation.

The optical depth can be obtained from the scattering efficiency $Q_{ext}$ obtained in equation 3.8 using the relationship

$$e^{-\tau} = e^{-\gamma l} \tag{4.2}$$

where $l$ is the depth of the dust veil and

$$\gamma = n\pi a^2 Q_{ext}\left(a, m\right) \tag{4.3}$$

for a dust veil composed of identical particles of radii *a* and number density *n*, uniformly distributed over the Earth's upper atmosphere.

Deceleration by sputtering or evaporation in the upper atmosphere can reduce a 10 micron sized particles to a distribution of sub-micron grains. Using equations 3.4 and 3.5 in equation 3.8, the extinction efficiency $Q_{ext}$ plotted across the UV frequency (Hz) for $0.024\ \mu m$ diameter, organic grains with vacuum inclusions. The different curves correspond to different degrees of porosity *f*, ranging from solid iron grains $f = 0$, to $f = 0.9$. Using bulk refractive index data given by Wallis et al. (1987) is given in Figure 4.1. It can be seen that, as with iron grains, the extinction efficiency increases with porosity.

Analysis of tree ring data suggests that atmospheric loading with dust from the comet recorded in 536 AD caused the average global temperature to decrease by ~ *3 K* (Rigby, Symonds & Ward-Thompson 2004).

By energy-balance, from 4.1 the ratio of average temperature under a dust veil to the average temperature in the absence of a dust veil is

$$\frac{T'}{T_0} = e^{-\frac{\tau}{4}} \tag{4.4}$$

Hence, a dust veil with optical depth $\tau \sim 0.04$ is required to create a decrease in average temperature of *3 K* from an ambient temperature of *288 K*. The intensity of solar radiation is maximum at $\lambda = 0.6\ \mu m$; combining the values of $Q_{ext}\left(\lambda = 0.6\ \mu m\right)$ from Figure 4.1 with equations 4.2 and 4.3, the number density and hence the total mass of particles forming the dust veil can be obtained, assuming that the grains are uniformly distributed over the Earth's atmosphere.

The total mass of 0.058 μm diameter organic grains required to form a dust veil with optical depth $\tau \sim 0.04$ is $\sim 10^9\ Kg$, for solid grains. As grain porosity increases, the total mass required to produce the same optical depth as equivalent solid grains decreases significantly as porosity increases. Figure 4.2, shows the decrease in mass required to produce an optical depth of $\tau \sim 0.04$ as the porosity *f* increases from *0* to *0.9,* the total mass of particles decreases by several orders of magnitude from $\sim 10^9\ Kg$ to $\sim 10^5\ Kg$. A relatively small mass of dust ~ 100 tonnes of highly porous particles has the potential reduce the global average temperature by ~ 3 K. Hoyle and Wickramasinghe (1978) have estimate that such a decrease in average temperature would be sufficient to cause noticeable climate change for the duration the lifetime of the dust veil.

This work illustrates the sensitivity of Mie calculations to the properties of the scattering particles: changes in the composition of the scattering particles such as inclusion of porous voids or magnetic materials may alter the extinction efficiencies by several orders of magnitude. The estimate $\sim 10^9\ Kg$ to $\sim 10^5\ Kg$ of dust to create a veil with optical depth of $\tau \sim 0.04$ as in good agreement with the work of Hoyle, Wickramasinghe and Rabilizirov (1989), who calculated that $\sim 10^9\ Kg$ of porous grains of 0.15 μm diameter were sufficient to create an optical depth of $\tau \sim 0.02$.

Of the 60 tonnes of matter incident daily onto the upper atmosphere, the majority is in the form of submicron particles which are decelerated to settling speeds of ~ $cms^{-1}$ at altitudes of ~ 100 Km. In a static atmosphere, this implies an equilibrium mass of $\sim 7\times10^6\ Kg$ of interplanetary dust in the atmosphere, with a transit time of ~ 100 days to reach the surface of the Earth. Turbulence and mixing within the atmosphere could raise the total mass of interplanetary dust by one or two orders of magnitude. This suggests that any model of future global climates should include the radiative properties of submicron particles along with molecular scattering from 'greenhouse gases'.

The sensitivity of detailed particle properties for the optical depth formed by the dust veil formed by small interplanetary dust particles in the Earth's upper atmosphere has implications for the level of precision required for any schemes to attempt to engineer the climate using aerosols of small particles.

## References


Coulson, S. G. Monthly Notices of the Royal Astronomical Society, Volume 389, Issue 4, pp. 1885-1890 (2008).

Coulson, S. G. & Wickramasinghe, N. C. International Journal of Astrobiology, 6 (4) 263-266 (2007)

F. Hoyle & R. A. Lyttleton Proceedings of the Cambridge Philosophical Society, vol. 35, issue 03, p. 405 1939

F. Hoyle & N. C. Wickramasinghe Astrophysics and Space Science, 147, 245-256 1988

F. Hoyle & N. C. Wickramasinghe Astrophysics and Space Science, 53, 523-526 1978

F. Hoyle & N. C. Wickramasinghe Earth, Moon, and Planets, vol. 52, Feb. 1991, p. 161-170.

Rigby, E., Symonds, M. and Ward-Thompson, D. (2004), A comet impact in AD 536?. Astronomy & Geophysics, 45: 1.23–1.26.

Wainwright M, Wickramasinghe N C et al. 2004 Int Journal Astrobiology 3(1) 13-15

Wallis M. K., Rabilizirov R., Wickramasinghe N. C., 1987, A&A, 187, 801

N. C. Wickramasinghe, F. Hoyle, and R. Rabilizirov, Earth Moon & Panets 46, 297 – 300, 1989

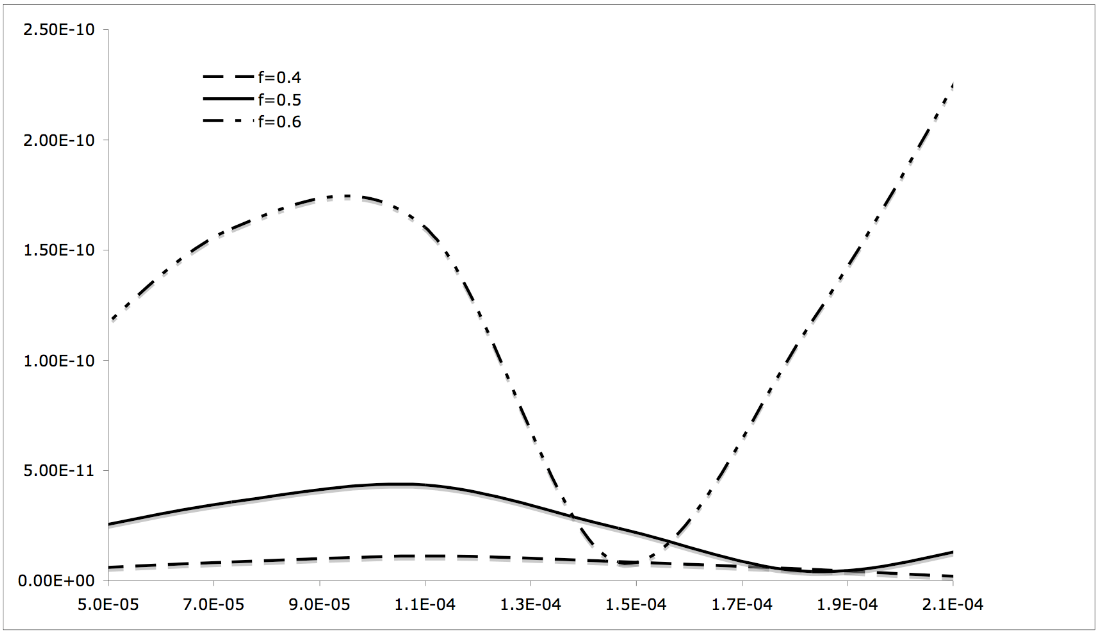


**Figure 3.1:** The extinction efficiency $Q_{ext}$ plotted against frequency (GHz) for 7 μm diameter, composite iron grains with vacuum inclusions. The different curves correspond to different degrees of porosity *f*, ranging from solid iron grains $f = 0$, to $f = 0.6$.

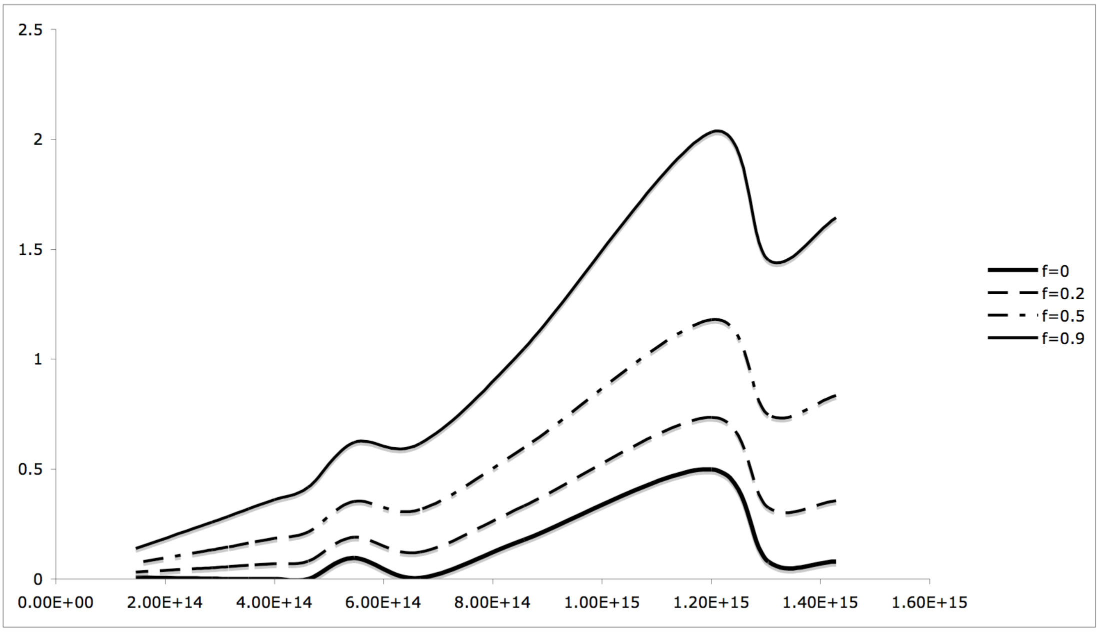


**Figure 4.1:** The extinction efficiency $Q_{ext}$ plotted across the UV frequency (Hz) for 0.058 μm diameter, organic grains with vacuum inclusions. The different curves correspond to different degrees of porosity *f*, ranging from solid iron grains $f = 0$, to $f = 0.9$. Using bulk refractive index data given by Wallis et al. (1987)

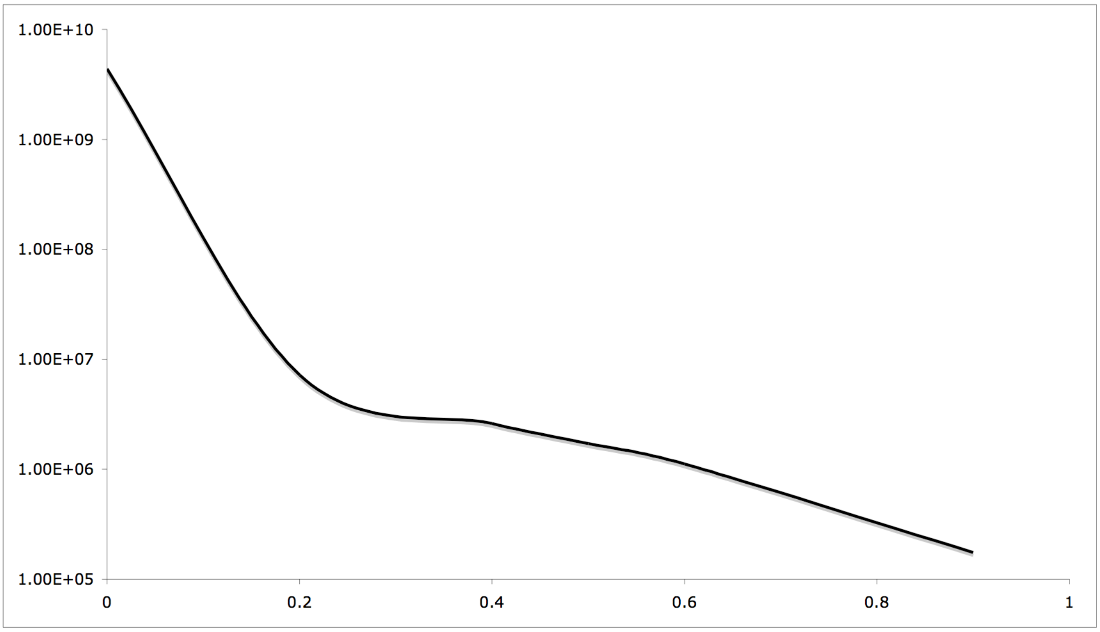


**Figure 4.2:** The mass of 0.058 µm diameter, organic grains with efficiency $Q_{ext}$ from Figure 4.1 required to give an optical depth of $\tau \sim 0.04$ at $\lambda = 0.6\ \mu m$ plotted against porosity from $f = 0$, to $f = 0.9$.