

RADIATION PRESSURE ON BACTERIAL CLUMPS IN THE SOLAR VICINITY AND THEIR SURVIVAL BETWEEN INTERSTELLAR TRANSITS

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Abstract: Radiation pressure cross-sections for clumps of hollow bacterial grains with thin coatings of graphite are calculated using rigorous Guttler formulae. The carbonized skins are expected to form through exposure to solar ultraviolet radiation, but a limiting thickness of about $0.03 \mu\text{m}$ is determined by opacity effects. The ratios of radiation pressure to gravity P/G are calculated for varying sizes of the clumps and for varying thickness of the graphite coatings. Bacterial clumps and individual desiccated bacteria *without* coatings of radii in the range $0.3 - 8 \mu\text{m}$ have P/G ratios less than unity, whereas particles with coatings of $0.02 \mu\text{m}$ thickness have ratios in excess of unity. Such coatings also provide protection from damaging ultraviolet radiation. Putative cometary bacteria, such as have been recently collected in the stratosphere, are thus not gravitationally bound in the solar system provided they possess carbonised exterior coatings. They are rapidly expelled from the solar system reaching nearby protosolar nebulae in timescales of a few million years. Even with the most pessimistic assumptions galactic cosmic rays are unable to diminish viability to an extent that vitiates the continuity of panspermia.

1. Introduction

The Hoyle-Wickramasinghe model of panspermia requires a fraction of bacterial particles released from solar system comets to become available in viable form to seed embryonic cometary/planetary systems forming elsewhere in the galaxy (Hoyle and Wickramasinghe, 1981). Ultraviolet light in the immediate vicinity of a star (Sun) poses the first threat to survival, followed by low energy cosmic rays in the interstellar medium over transit times of ~ 30 million years. We shall show here that this latter hazard, although real, is not sufficient to reduce viability to the extent of vitiating the operation of panspermia.

The best prospect for retaining viability is for small clumps (colonies) of bacteria travelling together as integral units. In such cases interior organisms would be well shielded from damaging ultraviolet radiation. Bacterial clumps of this kind with diameters in the range $1 - 10 \mu\text{m}$ have indeed been recently recovered from the stratosphere up to heights of 41 km and have been provisionally interpreted as being of cometary origin (Wickramasinghe et al, 2003). An interesting question arises as to the confinement or otherwise of these clumps within the solar system. Under certain circumstances can desiccated bacteria, individually or in small clumps, be

accelerated to the outermost regions of the solar system and beyond? And under what conditions do they survive long interstellar journeys before becoming incorporated in a new generation of comets? We attempt to address these issues in the present communication.

2. Carbonisation of the surface

A small clump of desiccated bacteria after prolonged exposure to solar ultraviolet radiation at ~ 1 AU, would inevitably become charred/graphitised at the surface. The interior bacterial material would have an estimated volume filling factor of $\sim 30\%$ and its average refractive index will be $\langle n \rangle \cong 1.0 + 0.3(1.5 - 1) = 1.15$, assuming $n = 1.5$ for the hydrated bacterial material. (Hoyle and Wickramasinghe, 1979). Solar ultraviolet photons impinging on the surface would eventually lead to a thin layer of reduced carbon, but the growth of this layer would be self-limiting. A graphite sphere of radius $0.02 \mu\text{m}$ has a peak extinction efficiency $Q_{ext} \approx 3.348$ at the ultraviolet wavelength of 2175\AA giving a mass extinction coefficient of $5.7 \times 10^5 \text{ cm}^2 \text{ g}^{-1}$, assuming a bulk graphite density of $s = 2.2 \text{ g cm}^{-3}$ (Wickramasinghe, 1973). A closely similar mass extinction coefficient will also be relevant for a thin layer of graphite (Wickramasinghe, 1967). A layer of thickness t comprised of such material will thus produce an optical depth

$$t = 5.7 \times 10^5 \times 2.2t \quad (1)$$

A value $t = 3$ will be achieved for a graphite thickness of $t = 0.024 \mu\text{m}$. It is unlikely, therefore, that the overlying graphite layer will grow to much more than $\sim 0.03 \mu\text{m}$ before the ingress of ultraviolet photons is checked. In which case genetic material residing in the interior would be well protected from damaging solar ultraviolet light.

3. Radiation pressure effects

We next model the effects of radiation pressure on a spherical clump of hollow bacterial grains (or an individual bacterial grain) of radius a surrounded by varying thicknesses t of graphite mantle. For the bacterial clump we take the radius to be defined by a , and assume a refractive index $m = 1.15$ consistent with the discussion in section 2. (Here we ignore the effect of a small absorption coefficient that may apply within the cells.) For the overlying graphite mantle we adopt the wavelength dependent values of n, k from the laboratory data of Taft and Phillip (1963) (see tabulations in Hoyle and Wickramasinghe, 1991).

Each particle is now regarded as an idealised concentric core-mantle grain. The dielectric core radius is defined as $r_c = a$, and the outer mantle radius is $r_m = a + t$. The rigorous Guttler formulae for coated spheres were programmed from equations set out in Wickramasinghe (1973). For given values of (a, t) we can calculate at any wavelength λ the optical efficiencies $Q_{ext}(\lambda)$, $Q_{sca}(\lambda)$, and the phase parameter $\langle \cos \mathbf{q} \rangle$. The efficiency factor for radiation pressure $Q_{pr}(\lambda)$ is then given by

$$Q_{pr}(\lambda) = Q_{ext}(\lambda) - \langle \cos \mathbf{q} \rangle Q_{sca}(\lambda) \quad (2)$$

For the purpose of evaluating the effect of solar radiation on grains we next compute an approximation to the ratio

$$\bar{Q}_{pr} = \frac{\int_0^{\infty} F_{\lambda} Q_{pr}(\lambda) d\lambda}{\int_0^{\infty} F_{\lambda} d\lambda} \quad (3)$$

for each of the cases under discussion. Here $F_{\lambda} d\lambda$ is the relative energy flux of sunlight in the wavelength interval $(\lambda, \lambda + d\lambda)$, and a simple quadrature procedure with truncations at $\lambda = 0.25$ and $1.0 \mu\text{m}$ is used in evaluating the integrals. In all cases we found that the strongly dominant contribution to the average arises from a wavelength close to 4500\AA , and indeed

$$\bar{Q}_{pr} \approx Q_{pr}(4500\text{\AA}).$$

5. Ratio of radiation pressure to gravity

A bacterial grain or grain clump of external radius r_m located at a distance R from the centre of the Sun of radius R_{\odot} ($R \gg R_{\odot}$), will experience a force directed radially outward due to radiation pressure of magnitude

$$P = \frac{L_{\odot}}{c} \rho r_m^2 \bar{Q}_{pr} \frac{1}{4\rho R^2} \quad (4)$$

where L_{\odot} is the bolometric luminosity of the Sun. The oppositely directed gravitational attractive force to the sun is

$$G = k \frac{mM_{\odot}}{R^2} \quad (5)$$

where M_{\odot} is the solar mass, m is the grain mass and k is the Universal gravitational constant. The mass m of the grain clump is given by

$$m = \frac{4}{3}\rho [(a+t)^3 - a^3]s + \frac{4}{3}\rho a^3 r \quad (6)$$

where s is the bulk density of graphite and r is the mean density of the hollow clump material. With $s = 2.2 \text{ g cm}^{-3}$, $r = 0.3 \text{ g cm}^{-3}$ and $L_{\odot}/M_{\odot} = 3.83/1.99$ equations (4), (5) and (6) yield

$$\frac{P}{G} = 0.57 \frac{(a+t)^2}{2.2(a+t)^3 - 1.9a^3} \bar{Q}_{pr} \quad (7)$$

where a and t are in micrometres. Our computations of \bar{Q}_{pr} described in section 3 combined with (7) then gives P/G ratios for each of the grain models considered. The results are plotted in Figure 1.

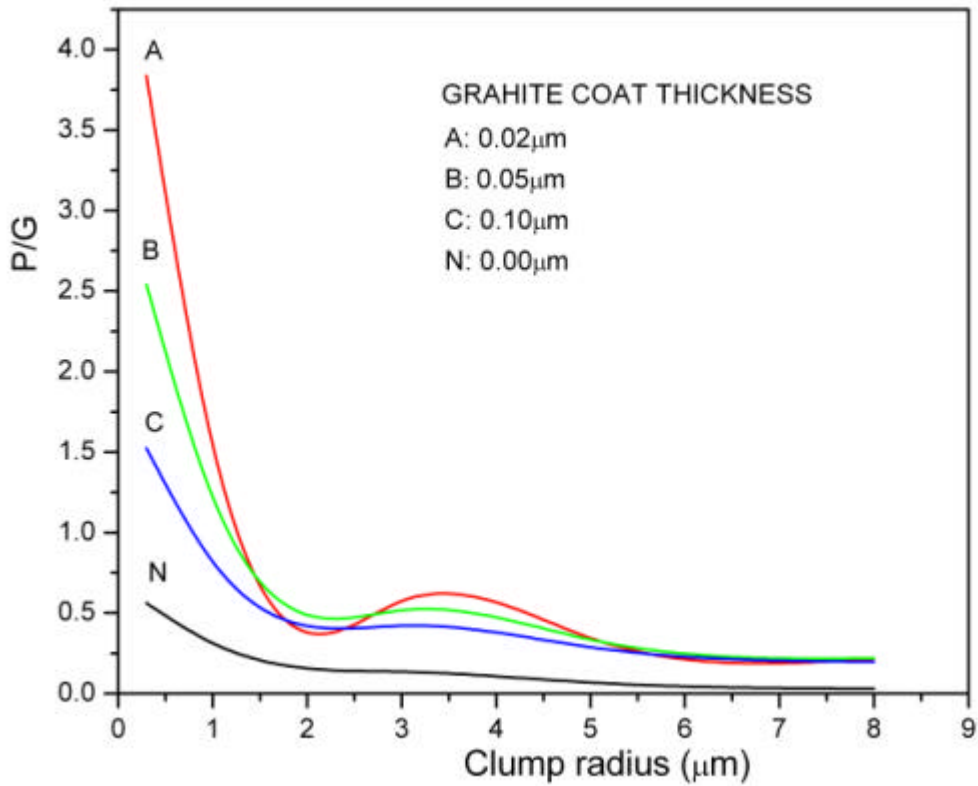


Fig. 1: The ratio of radiation pressure to gravity for bacterial grains/grain clumps of radius a with concentric mantles of graphite of thickness t .

6. Results and dynamical considerations

For particles without graphite coatings the curve marked (N) shows that the ratio P/G stays well below unity for all the cases we have considered. This means that such grains will remain gravitationally bound to the solar system and will not readily contribute to interstellar panspermia. The curves A, B, C show, however, that this situation changes dramatically as the particles begin to acquire carbon coatings. For a graphite coating of thickness $0.02\mu\text{m}$ P/G exceeds unity for bacterial spheres of diameters in the range $0.6\text{-}2.5\mu\text{m}$. The lower limit being appropriate to a single bacterium, or a few small bacteria and the upper limit to small clumps of bacteria such as were discovered in the stratosphere (Wainwright et al, 2003; Wickramasinghe et al, 2003). The smaller particles and clumps once carbonised at the surface are seen to be well suited as candidates for interstellar panspermia. Much larger clumps, on the other hand, as well

as those with greater thicknesses of exterior graphite will on the whole tend to be gravitationally bound to the solar system.

For a grain satisfying $P/G > 1$ radial acceleration at a heliocentric distance R would be governed by the equation

$$\ddot{R} = \mathbf{a} \frac{kM_{\odot}}{R^2} \quad (8)$$

where $\mathbf{a} = P/G - 1$. (Gas drag at interplanetary densities of $n_H \approx 10^{-23} \text{ cm}^{-3}$ is negligible within the solar system.) Integration of (8) then leads to

$$\dot{R}^2 = -2\mathbf{a}kM_{\odot} \left(\frac{1}{R} - \frac{1}{R_0} \right) \quad (9)$$

where R_0 is the heliocentric distance at which radial acceleration of the grain is assumed to begin. As $R \rightarrow \infty$ the asymptotic velocity given by (9) is

$$V_{\infty} = \sqrt{\frac{2\mathbf{a}kM_{\odot}}{R_0}} \quad (10)$$

Taking $\mathbf{a} = 0.5$ ($P/G = 1.5$) as a typical case and $R_0 = 1 \text{ AU}$, equation (10) gives

$v_{\infty} \cong 3 \times 10^6 \text{ cm/s}$. With this speed a bacterial clump would reach the outer edge of the Kuiper belt, $\sim 100 \text{ AU}$ in ~ 15 years and a nearby star-forming system (protosolar nebula) at $\sim 10 \text{ pc}$ in $3 \times 10^5 \text{ yr}$. If acceleration begins from zero velocity at the edge of the Kuiper Belt (from Kuiper-Belt comets for instance) with $R_0 = 100 \text{ AU}$, then $v_{\infty} = 3 \times 10^5 \text{ cm/s}$, and a 10 pc interstellar journey will now take 3 million years.

7. Surviving the hazards of galactic cosmic rays

Whilst a thin layer of graphitised carbon around a bacterium or clump of bacteria provides complete protection from ultraviolet light, exposure to galactic cosmic rays poses a more serious potential threat (Mileikowski, et al, 2000). Radiation doses that limit viability are critically dependent on bacterial species, some species such as *B. subtilis* and *M. radiodurans* being evidently more resistant than others. In vegetative cultures, doses equivalent to 2 megarads (2Mr) have been found to limit residual viability of *Streptococcus faecium* by a factor of 10^{-6}

(Christensen, 1964), whereas similar doses have little or no effect on cultures of *M. radiodurans* or *M. radiophilus* (Lewis, 1971).

Within the solar system the radiation doses received by an outward moving bacterium depends critically on the phase of solar activity, being highest at times near the peak of the solar cycle. The average radiation dose received over a timescale comparable to the 11 yr period of the solar cycle is however less than 1Mr, and so viability will not be expected to be significantly reduced for bacteria during their travel within the solar system to the Kuiper Belt of comets.

We next estimate the doses of ionising radiation intercepted by bacterial clumps in an unshielded interstellar cloud. To do this we compute the rate of deposition of ionisation energy E due to cosmic ray nuclei passing through a spherical grain of radius a and density $s \approx 1 \text{ g cm}^{-3}$:

$$\frac{dE}{dt} \cong Ja \quad \text{MeV cm}^{-2} \text{ s}^{-1} \quad (11)$$

where J is given by

$$J = \left(\sum_i f_i Z_i^2 \right) \int_{1\text{MeV}}^{\infty} F(E) \frac{1\text{MeV}}{E} dE \quad (12)$$

Here f_i denotes the fraction of cosmic ray nuclei with atomic number Z_i , and $F(E)dE$ is the flux of cosmic ray protons with energy in the range $(E, E+dE)$ (Salpeter and Wickramasinghe, 1969). The value of J would vary from place to place in the interstellar medium, and is in general dominated by a low energy tail of the cosmic ray spectrum which is cut off here at $E = 1\text{MeV}$.

For a spherical grain of radius a equation (11) gives an energy dissipation rate into solid material

$$q = \frac{4\pi a^2}{4\pi a^3 s / 3} Ja \quad \text{MeV g}^{-1} \text{ s}^{-1} \quad \text{which with } s = 1 \text{ g cm}^{-3} \text{ converts to}$$

$$q \gg 1.5 J \text{ r yr}^{-1} \quad (13)$$

remembering that a radiation dose of 1 rad (1 r) corresponds to a deposition of ionisation energy of 100 erg g^{-1} .

A value of J in the range $1\text{-}10 \text{ cm}^{-2} \text{ s}^{-1}$ seems plausible in the light of available astronomical data (see, for example, arguments in Spitzer, 1978). A value $J = 1 \text{ cm}^{-2} \text{ s}^{-1}$ thus delivers 1.5 Mr in 1 Myr whereas $J = 10 \text{ cm}^{-2} \text{ s}^{-1}$ gives 1.5 Mr in 0.1 Myr. Adopting the higher J value let us consider the residual viability of a hypothetical microbial species that halves its culturable fraction with a radiation dose of, say, 1.5 Mr. Over the 3 Myr timescale calculated in section 6 for reaching the cosy protection of a protosolar nebula, and consequent inclusion in a new generation of comets, the integrated radiation dose received is 45 Mr, leading to our hypothetical species being attenuated by a factor $(1/2)^{30} \approx 10^{-9}$. For a more radiation-susceptible microbial species that halves its viable population with a radiation dose of 750 kr, the corresponding culturable fraction reaching the new protosolar nebula will be 10^{-18} . To incorporate a million viable bacteria of this type in every comet condensing in the new system requires the accommodation of a total of 10^{24} iterant bacteria, dead and alive. This would contribute only $\sim 10^{11} \text{ g}$, which is less than one tenth of a millionth of the mass of a 10 km sized comet. According to the present argument interstellar panspermia will be assured even with the most pessimistic of assumptions.

In conclusion we note that there still remains an uncertainty as to how the delivery of a low flux of ionising radiation over astronomical timescales to dormant freeze-dried bacteria relates to equivalent doses delivered to vegetative cultures in the laboratory. There are indications that a very much higher tolerance is appropriate in the former situation, however. Viable cultures of bacteria have been recovered from ice drills going back 500,000 years, from isolates in amber over 25-40 million years (Cano and Borucki, 1995; Lambert *et al*, 1998), and from 120 million year old material (Greenblatt *et al*, 1999). Viable bacteria have also been recovered in salt crystals from a New Mexico salt mine dated at 250 Myr (Vreeland *et al*, 2000). The present day dose rate of ionising radiation on the Earth arising from natural radioactivity is in the range $0.1\text{-}1 \text{ r yr}^{-1}$. Well-attested recoveries of dormant bacteria/spores after 10^8 yr imply tolerance to ionisation radiation with total doses in the range $\sim 10\text{-}100 \text{ Mr}$. For the case $J = 10 \text{ cm}^{-2} \text{ s}^{-1}$

considered here the equivalent exposure times in the interstellar medium would be $\sim 10^7 - 10^8$ years, which offers a substantial margin of safety for transfers between planetary systems.

8. References

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