Astrophysical and Biological Constraints on Radiopanspermia

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ABSTRACT

We have carried out a series of calculations involving bacteria and viruses embedded in dust grains, which are ejected from our solar system by radiation pressure, and travel through space to other star systems. Under many conditions, this kind of panspermia is impractical, primarily because the ultraviolet (UV) radiation of the present Sun inactivates the micro-organisms. However, if the organisms are shielded by an absorbing material like carbon, and if ejection takes place in the late-Sun (red-giant) phase of a one-solar-mass star like our Sun, there is a significant probability that these micro-organisms can reach another star system alive (i.e., with only sub-lethal damage from UV and ionizing radiation). In addition to panspermia with viable micro-organisms, we note that it is possible to seed the Galaxy with inactivated ones, whose DNA and RNA fragments may provide the initial information necessary to start biological evolution in favorable environments.

1. Introduction

The panspermia hypothesis proposes that life originated on a planet other than Earth, and that this life (in the form of primitive biological micro-organisms) was introduced onto the Earth after it traveled through interplanetary or interstellar space. Thus if panspermia is a viable mechanism for disseminating life throughout the galaxy, the origin of life on Earth is intricly connected to the origin and abundance of life on other planets in the Galaxy. Recently, the panspermia hypothesis and related areas of research have received considerable attention by Hoyle, Wickramasinghe and their collaborators (e.g., Hoyle & Wickramasinghe 1979, 1981, 1982, 1983; Jabir, Hoyle & Wickramasinghe 1983; Hoover et al. 1986; Hoyle, Wickramasinghe & Al-Mufti 1986). For a detailed review of panspermia, we refer interested readers to the literature (e.g., Shklovskii & Sagan 1966, p. 206; Crick & Orgel 1973; Tobias & Todd 1974, p.238; Horneck & Brack 1992; Horneck 1995).
The panspermia hypothesis can be separated into distinct classes, based primarily upon the method used to transport the micro-organisms through the space environment: among these are lithopanspermia, radiopanspermia and directed panspermia. Lithopanspermia refers to micro-organisms which are carried to the Earth's surface within meteorites. From probabilistic arguments, lithopanspermia is limited to interplanetary travel within an individual solar system (e.g., Tobias & Todd 1974, and references therein). Directed panspermia refers to the hypothesis that life was seeded on the Earth, deliberately, by an intelligent civilization on another planet (Crick & Orgel 1973). In this case, the transport mechanism would be a spacecraft constructed specifically for this task. On the other hand, radiopanspermia refers to single exposed micro-organisms, which are small enough to be accelerated to high velocities by solar radiation pressure, then exit the solar system and traverse interstellar space (Arrhenius 1908). Provided that some enormous number of micro-organisms were ejected from a solar system, it is conceivable that a small fraction may intersect a hospitable planet in a new star system, after $\sim 10^6$ years in interstellar space. In order for this radiopanspermia to effectively seed life on the new planet, some small fraction of the micro-organism must survive the radiation damage and the harsh environment of free space. However, it is known that exposed micro-organisms are immediately (i.e., within a few days) inactivated by solar ultraviolet (UV) radiation, even before they leave the original solar system.

We (Secker, Lepock & Wesson 1994; hereafter SLW94) have carried out a series of calculations on a plausible variant of the radiopanspermia hypothesis, which combines the radiation shielding inherent to lithopanspermia with the transport mechanism of radiation pressure. Herein micro-organisms embedded in cosmic dust grains are ejected from their original solar system by radiation pressure, traverse space, and arrive in another solar system, where after deceleration and deposition to a new planet is possible. However, we restrict the grain properties to the region of the radius-density parameter space for which the repulsive force of the Sun’s radiation pressure dominates over the attractive force of the Sun’s gravity, as required for distribution by radiation pressure.

Our motivation for this analysis was to see how far known astrophysical conditions can help spread biological micro-organisms through the Galaxy. Our calculations concentrated on the ejection of the bacteria and viruses from a solar system like ours by radiation pressure and the survival of these against harmful UV and ionizing radiation. The effects of vacuum and low temperatures are not as bad as might be expected, and it is the UV radiation of the host stars that presents the greatest biological hazard (e.g., Glenister & Lyon 1986; Horneck 1982; SLW94; Brack & Horneck 1995). For other aspects of the panspermia hypothesis, such as the departure of microbes from a planet into space (e.g., Melosh 1988; Moreno 1988; Hoyle, Wickramasinghe & Al-Mufti 1986), and a discussion of
other potentially-damaging processes (e.g., SLW94; Horneck & Brack 1992), we refer the reader to the literature.

Our main conclusion will be that panspermia with living micro-organisms may be viable, but only under a certain set of circumstances wherein they are shielded from radiation by the absorbing mantle of a carbonaceous dust grain and ejected into space in the red-giant (late) stage of a one-solar-mass star’s life. However, we were also interested to see if we could alleviate the problem that the origin of life by purely random chemistry, without the intervention of biological information from elsewhere, may be very unlikely (Wesson 1990). We will note as an addendum that panspermia with inactivated micro-organisms, even though it may sound unpalatable, may be viable from the informational point of view.

2. Conditions for Panspermia

We start by considering the ejection from our solar system of a particle which we later identify with a dust grain containing either a bacterium or a virus. Then we will consider the radiation dosage to which the organism is subjected in order to decide on its survival.

To first order, the net force on a particle is the difference between that due to radiation pressure and that due to gravity. Let \( L_\odot \) and \( M_\odot \) equal the Sun’s luminosity and mass, \( r \) equal the distance between the grain and the Sun, \( G \) equal the gravitational constant, \( c \) equal the velocity of light, and \( R \) and \( m \) equal the radius and mass of the particle. Then the force due to gravity and the classical expression for radiation pressure are

\[
F_g = \frac{G M_\odot m}{r^2} \quad (1)
\]

\[
F_p = \frac{L_\odot \pi R^2}{(4\pi r^2)c} \quad (2)
\]

Here we have assumed a radiation efficiency factor which is of order unity, that \( F_p \) and \( F_g \) are the dominant forces, and we assume that this classical expression adequately describes the ejection of carbonaceous dust particles (Burns, Lamy & Soter 1979; SLW94). The acceleration of the particle is then given by

\[
\frac{d^2 r}{dt^2} = \frac{C}{r^2}, \quad \text{where} \quad C \equiv \left( \frac{L_\odot R^2}{4mc} \right) - GM_\odot. \quad (3)
\]

The velocity at distance \( r \), assuming \( v(r = r_i) = 0 \) at \( t = t_0 \), is
\[ v(r) = \left( \frac{2C}{r_i} - \frac{2C}{r} \right)^{1/2}. \quad (4) \]

The time \( t \) corresponding to distance \( r \) is obtained by integrating (4) (with \( r = r_i \) at \( t = t_0 \)) to give

\[ t(r) = \left( \frac{r_i}{2C} \right)^{1/2} \left\{ r(1 - r_i/r)^{1/2} + r_i \ln \left[ \left( \frac{r}{r_i} \right)^{1/2} + \left( \frac{r}{r_i} - 1 \right)^{1/2} \right] \right\} + t_0. \quad (5) \]

For ejection, we require that \( C > 0 \) in (3), so that only small, low-density particles can be ejected. When a particle leaves the solar system, it will do so with a terminal velocity \( v_t = (2C/r_i)^{1/2} \) given by (4). And after a certain time to exit the solar system (given by 5), it will travel for a further period determined by \( v_t \) and the distance to a neighboring star system. The particle’s travel between neighboring stars will either be a random walk (a mean-free path with \( l \approx 10^9 \) cm, due to collisions with neutral hydrogen), or it will be bound-up in and travel with an interstellar cloud (Weber & Greenberg 1985; SLW94). The velocity of molecular clouds is about 10 km s\(^{-1}\) (Spitzer 1978; p.44), roughly equivalent to the terminal velocity of the particles as they exit a solar system. We therefore calculate the particle’s interstellar travel time using their exit velocity. Within about 20 light years there are more than 50 stars, and it is this distance we adopt for interstellar travel. Finally, it is the relative velocity of the particle with respect to that of the host planet that governs the energy of impact with the atmosphere, but the deceleration caused by the second star’s radiation pressure is also a factor. That is the panspermia transport mechanism as we envision it.

We (SLW94) have carried out a detailed set of calculations using different parameters for the preceding relations, which we only summarize here. For particles with sizes on the order of \( 10^{-6} \) cm and densities in the range \( 0.9 - 2.2 \) gm cm\(^{-3}\), and considering both the current Sun and a one-solar-mass red-giant star, times to exit the solar system are on the order of 35 years and times to reach a neighboring star system are of the order \( 10^6 \) years; Tables 1 and 2 of SLW94 describe the full results. Since these stars have a significant component of radiation that would harm a micro-organism, we need to inquire about survival. In SLW94, the radiation calculations were considered in three parts: the solar UV radiation, the solar ionizing radiation, and the interstellar radiation field.

The Sun’s UV radiation field can be conveniently modeled as part of a Planck function with an effective temperature of \( T_\odot \simeq 5785 \) K. Thus, if \( h \) is Planck’s constant and \( k \) is Boltzmann’s constant, the flux at a distance \( r \) from the Sun (radius \( R_\odot \)) at wavelength \( \lambda \) is given by
\[ F(r, \lambda) = \frac{R_\odot^2}{r^2} \left( \frac{2 \pi h c^2}{\lambda^5 \left(e^{\frac{hc}{\lambda kT_\odot}} - 1\right)} \right). \] (6)

Note that this black-body approximation overestimates the UV radiation emitted by the Sun. As described by Tobias & Todd (1974; p.241), about half of the UV radiation emitted by the Sun in the range 2500 – 2900 Å is absorbed by its corona. The ionizing component of the Sun’s radiation, \(0 < \lambda < 1600\) Å, was modeled using polynomial functions fit to experimentally-measured data (see SLW94). Then the total dose accumulated within the radius range \(r_i\) to \(r\) (i.e., the Solar System), with the wavelength integral taken over \(0 – 3000\) Å, is given by

\[ D(r) = \left( \frac{2(1 - r_i/r)}{r_i C} \right)^{1/2} \int F(\lambda) d\lambda. \] (7)

In interstellar space, the intensity of radiation is many orders of magnitude less than it is in the vicinity of the Sun. The interstellar radiation field is provided by an ensemble of stars at large distances, and this is best modeled as a Planck function with a temperature of \(10^4\) K, multiplied by a geometric dilution factor of \(10^{-14}\) (SLW94). In this case, the total radiation dose received in interstellar space \(D_{\text{is}}\) is calculated to be the interstellar travel time \(t_{\text{is}}\) multiplied by the integral over the wavelength range \(0 – 3000\) Å of the model Planck function. To determine the survival of an organism, we worked out total doses taking all components of radiation into account, and considered the radiation resistance of bacteria and viruses.

Three different micro-organisms were considered in these calculations. The *Micrococcus radiophilus* is the most radiation-resistant bacteria known at this time, and it is therefore a logical candidate for this radiopanspermia. The *Staphylococcus minimus* is a very common bacteria which is much smaller than the *Micrococcus radiophilus*. As well, the virus we considered combined properties of both the *T1 Bacteriophage* and the *phage C-36*. Refer to SLW94 for a discussion of the characteristics of these micro-organisms. The survivability of a given micro-organism was quantified using the relevant inactivation cross section \(\sigma\), in terms of which the number \(N\) surviving from an initial number \(N_0\) after dose \(D\) is

\[ N = N_0 \exp^{-\sigma D}. \] (8)

Here \(\sigma\) depends in general on \(\lambda\), and we used the appropriate polynomial functions fit to the experimentally-measured inactivation cross sections to interpolate between wavelength.
(Note however, that these behave somewhat differently in the low-pressure, low-temperature environment of space; e.g., Levine & Cox 1963; Ashwood-Smith, Copeland & Wilcockson 1968; Tobias & Todd 1974; Weber & Greenberg 1985). Using parameters for the current Sun, computing the total dose as described above (assuming the exposure in the new system is the same as in the old), and adopting these inactivation cross sections, leads to values of \( N/N_0 \) consistent with zero. We find that the Sun’s UV radiation is considerably more harmful than its ionizing radiation, and it is so intense at the present time that it effectively inactivates all exposed micro-organisms.

This situation might be avoided if the micro-organisms are embedded in dust grains. This might be a natural thing, depending on how they are put into space, through UV processing of a thin surface skin of organic matter, or through interactions and accretion of carbon-rich interplanetary dust particles (Chyba & Sagan 1988). And we know there are grains of the appropriate size in space (Mathis, Rumpl & Nordsieck 1977). We therefore considered the survival of bacteria and viruses shielded by thin films (spherical shells) of various materials known to exist in space. Of these thin films, water ice is common but does not help because it transmits too much UV radiation. On the contrary, carbonaceous material is an effective blocker. However, we now have another factor to contend with: a mantle that protects the organism also increases the mass of the particle to be ejected from the solar system, and it is difficult to get the organism-plus-grain out into interstellar space with the radiation pressure of the Sun as it is now. Thus, even shielded micro-organisms do not make panspermia work with the present Sun.

We should not conclude that panspermia is impossible, for in the late, red-giant stage of a star like the Sun its luminosity increases. Also, it is natural to consider the ejection of micro-organisms in the later stages of a stars life, because by then evolution will have had longer to run on any planets which may be around the star, increasing the chances of there being biological material to distribute. For these reasons, we examined the ejection of micro-organisms during the red-giant phase of a one-solar-mass star; the results are given in Tables 3 and 4 of SLW94. Our essential conclusion is that panspermia is viable in this case: given shielding by carbonaceous material with thicknesses on the order of 0.25-0.68 \( \mu \)m, the total doses are so low that the survival fraction \( N/N_0 \) is close to unity (i.e. 0.95 – 1.00) for all three micro-organisms considered here. That is, panspermia is viable, provided one considers micro-organisms shielded within carbonaceous dust grains and ejected from stars like the Sun in their late stage of life. An interesting aspect of these calculations concerns the total UV doses received by the two bacteria, after attenuation by the thin carbonaceous layer. These are \( D \approx 6 \times 10^2 \) erg/mm\(^2\) for the *Micrococcus radiophilus*, as compared to \( D \approx 6 \times 10^{-11} \) erg/mm\(^2\) for the *Staphylococcus minimus*. Thus the smaller micro-organisms can accrete a thicker coating of attenuating carbonaceous material, and still be within the...
mass-radius range for acceleration by radiation pressure.

A final comment with respect to the radiation exposure calculations is worthwhile. There is a fundamental difference between the radiation-induced damage to bacterial DNA and RNA and its subsequent repair. The total radiation dose imparted to a given micro-organism occurs continuously over a period of about $10^6$ years. However, micro-organisms cannot repair sub-lethal DNA and RNA damage in the extremely cold and desiccated conditions of interstellar space. Thus all structural damage accumulates until the micro-organisms arrive in a hospitable environment: provided that the total accumulated damage is below the lethal level, the micro-organisms can at this point repair the damage. This damage-accumulation effect has been accounted for in our calculations. A similar effect concerns viral DNA and RNA, which also requires a hospitable environment for repair, in this case a specific, living host which to infect.

3. Discussion

We have taken a new look at the old idea of panspermia, examining the astrophysical conditions under which an organism can leave one solar system under the influence of radiation pressure and gravity, as well as the biological conditions under which it can survive radiation damage and arrive at another solar system in a viable state. While work only scratches the surface of this subject, we conclude that the traditional idea of radiopanspermia is valid if micro-organisms (bacteria and viruses) are shielded inside grains whose material blocks significant UV radiation, and are ejected into space in the late stages of a (one-solar-mass) star’s life. Coupled with recent discoveries supporting other aspects of panspermia (Horneck & Brack 1992; Horneck 1995), our results suggest that the probability for life in any given solar system has increased. This finding is relevant to the current search for extraterrestrial intelligence (SETI; e.g., Horowitz & Sagan 1993; Tarter 1994), which is indeed a worthwhile endeavor.

As did others, (e.g., Horneck 1982; Greenberg & Weber 1985), we determine that the damage caused by solar UV radiation (i.e., during the time spent in either solar system) is the most deleterious to the micro-organisms, and which limits this panspermia. Our calculations reveal that the dominant factor in survival against UV radiation is not the radiation resistance of the micro-organism, but it is thickness of the carbon layer which attenuates the UV radiation. As illustrated in the above calculations, the maximum possible thickness of this layer depends upon the diameter of the micro-organism, and on the luminosity-to-mass ratio of the star.
Considering the origin and spread of life, it is worthwhile to extend the scope of this radiopanspermia from living (or potentially viable) micro-organisms to any form of biological material including dead (inactivated) micro-organisms. The rationale for this has simply to do with information. If the original atmosphere of the Earth was composed largely of carbon dioxide as opposed to the reducing atmosphere commonly hypothesized, then the organic compounds necessary for the origin of life would be more difficult to generate. A panspermia that distributes biological material in the form of fragmented DNA, RNA and protein bound up in inactivated bacteria and viruses supplies information. This biological material is available for replication, and if it is introduced to a hospitable environment, it may enhance the chance that life will evolve there, and could possibly explain the (apparently) rapid evolution of early life on Earth. With this approach, the seeding of life through the Galaxy via radiopanspermia need not rely solely on living organisms, as the dispersal of inactivated biological material such as fragmented DNA and RNA is relatively easy to accomplish.

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