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Pollination of exoplanets by nebulae

W.M. Napier*

Centre for Astrobiology, Cardiff University, Cardiff, UK
e-mail: smawmn@cf.ac.uk

Abstract: The Solar System passes within 5 pc of star-forming nebulae every ~50–100 million years, a distance which can be bridged by protected micro-organisms ejected from the Earth by impacts. Such encounters disturb the Oort cloud, and induce episodes of bombardment of the Earth and the ejection of microbiota from its surface. Star-forming regions within the nebulae encountered may thus be seeded by significant numbers of microorganisms. Propagation of life throughout the Galactic habitable zone 'goes critical' provided that, in a typical molecular cloud, there are at least 1.1 habitable planets with impact environments similar to that of the Earth. Dissemination of microbiota proceeds most rapidly through the molecular ring of the Galaxy.

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Introduction

Interstellar panspermia has widely been seen as improbable because of the huge distances involved, and the sterilizing environment of Galactic cosmic rays through which the journey has to take place. Melosh (2003) found that ~15 metre-sized, life-bearing boulders ejected from Earth escape from the Solar System each year, but their fate would simply be to wander indefinitely through interstellar realms. Thus for a star density in the Galactic disc of 0.1 pc^{-3} and a mean encounter speed 20 km s^{-1}, passage of such a boulder within 1 AU of a giant exoplanet occurs every $\sim 6 \times 10^{15}$ yr assuming one such planet per star. It is probable that no life-bearing boulder from the Earth has ever landed on an exoplanet by straightforward ejection and capture.

In this paper a simple mechanism whereby life may nevertheless be transmitted throughout the Galactic disc is described. Star-forming regions are found in cold, dense nebulae, which the Earth encounters quite frequently in geological terms. These nebulae are massive enough to disturb the Oort cloud during a close encounter, enhancing the bombardment rate of comets onto the Earth and resulting in the injection of microbiota into the passing nebula. In effect, the mountain comes to Mohammed: rather than send the microbiota to a distant exoplanet, the exoplanet or its precursor nebula comes to the microbiota. For modest assumptions about the frequency of habitable planets (1.1 or more in a typical star-forming region which may contain 10^3–10^4 incipient stars), life propagates rapidly throughout the molecular ring of the Galaxy and thence to the entire habitable zone of the disc.

The Oort cloud

The Oort cloud comprises perhaps 10^{11} comets at distances up to 50 000 AU from the sun, with orbital periods up to ~4 Myr. The mass of the system probably lies in the range 0.1–250 Earth masses. This reservoir is unstable in the Galactic environment, being prone to destruction by passing nebulae and stars. The half-life of the long-period system against disruption by stars is ~3 Gyr and by nebulae is ~1.9 Gyr (Bailey *et al.* 1990). The steady background flux of long-period comets into the planetary system is primarily due to the effect of the Galactic tide (Fernandez 1992).

Comets may not only arrive into Earth-crossing orbits directly from the Oort cloud but also through the intermediary of Halley-type comets which have Earth-crossing orbits with periods less than 200 years: about 1% of long-period comets arriving into the region of the giant planets are thrown into such orbits. Without replenishment, a typical Halley comet would be gone in about 100 000 years owing to interstellar ejection, falling into the sun or disintegration. The Halley system thus responds rapidly, in geological terms, to disturbances of the cloud. A typical Halley-type comet undergoes a thousand Earth-crossing passages (assuming it is preserved as a coherent entity after outgassing). It is probable, therefore, that the prime impact hazard during a significant Oort cloud disturbance comes from an enhanced Halley system, with a further contribution due to direct impacts by incoming long-period comets.

A number of other cometary reservoirs have been discovered in recent years, in particular the Kuiper Belt (or Edgeworth–Kuiper Belt), which lies just beyond the planetary system and feeds comets into the so-called Jupiter family of short-period comets (<20 yr) – the Oort cloud is also a significant supplier of the Jupiter family. However, to sufficient

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* Correspondence to Professor W.M. Napier, Kilbeg South, Bandon, County Cork, Ireland.

accuracy, the terrestrial impact flux due to comets may be taken to vary *pro rata* with the flux of Oort cloud comets into the planetary system.

Oort cloud perturbations

Having arrived at the planetary system, a long-period comet is perturbed and either falls into the sun, is ejected into interstellar space or otherwise destroyed. Thus, in each element of volume in the Oort cloud a gap in configuration space – a 'loss cone' – builds up. Without replenishment of this cone, the supply of long-period comets capable of entering the planetary system would decline to zero. Replenishment comes from orbital evolution of the Oort cloud comets as a whole, and can conveniently be divided into background and episodic components.

Background flux

The average change in perihelion distance q of a long-period comet over an orbit, owing to tidal perturbation by the vertical Galactic tide, is

$$\delta q \sim 12.4(25000/a)^{-6.3 \pm 0.2} \tag{1}$$

(Yabushita 1989) where a is the semi-major axis of the orbit in astronomical units. For the long-period comets, this is an order of magnitude greater than that caused by a typical stellar perturbation

$$\delta q \sim 0.66(25000/a)^{3.5} \tag{2}$$

(Yabushita 1989) and so the vertical Galactic tide is the main source of perturbation giving a smooth background flux of comets from the long-period system (the break-even point between tide and stars is at $a \sim 18500$ AU, where $\delta q \sim 1.88$ AU per orbit).

The long-period comet flux is thus proportional to the vertical tide T, and hence the ambient density $\rho(Z)$ of material in the Galactic disc at a height Z above or below the plane:

$$T = -4\pi G \rho(Z) r_z \tag{3}$$

where r_z is the z-component of the comet's instantaneous heliocentric distance. Thus the comet flux varies in periodic fashion with $\rho(Z)$, reflecting the carousel-like bobbing of the sun's motion around the Galaxy (Napier 1987). The amplitude of the flux variation is of the order of 2–5, depending on the specific model adopted (Matese *et al.* 1995); the expected period lies in the range 35–45 Myr, and this should be reflected in the terrestrial impact cratering record.

Episodes of bombardment

Surges in flux ('comet showers' or 'bombardment episodes') are expected owing to discrete perturbations of the Oort cloud. Giant molecular clouds have masses characteristically $M \sim 5 \times 10^5 M_\odot$ (Mundy 1994). The mass distribution $n(M)\,dM$ of molecular clouds is found to be a power law over at least eight decades of mass, and is given by

$$n(M) \propto M^{-\alpha} \tag{4}$$

with $\alpha = 1.6 \pm 0.2$ (Mundy 1994).

The interval between encounters with nebulae at distances at most d is

$$\Delta t \sim 800 M^{0.75}/d^2 \text{ Myr} \tag{5}$$

in units of $M = 5 \times 10^5 M_\odot$, radius $R = 20$ pc typical of a giant molecular cloud (GMC). Close encounters with GMCs are known to have a strongly disruptive effect on the Oort cloud (Napier & Staniucha 1982), but of interest here are the bombardment episodes expected during nebula fly-bys. Thus, for a significant bombardment episode to take place, the nebula must fill the loss cones which the Galactic tide cannot reach. The amplitude of the episodes depends on the unknown radial structure of the Oort cloud. For a distribution $n(a) \propto a^{-\gamma}$, the radial distribution varies roughly as $n(r) \propto r^{-\gamma-2}$. With $\gamma = 2$, an episode of amplitude $A \sim 4$ times background occurs when a $5000 M_\odot$ nebula has a grazing encounter (passage within 5 pc); for $M = 50000 M_\odot$, a grazing encounter yields $A \sim 15$. The amplitude increases only slowly with increasing mass thereafter, but is enhanced somewhat for Oort cloud models with greater central condensation; for example, when $\gamma = -3$, a close encounter with a GMC yields a bombardment episode with amplitude $A \sim 30$. The recurrence times of encounters with nebulae of various masses are listed in Table 1. It is clear that close encounters with, or penetrations of, cold dense nebulae have occurred quite frequently over geological timescales.

Table 1. *Encounter intervals with nebulae of mass greater than* M *Solar masses. The corresponding radii* > R *pc are listed.* t_5 *refers to passages within 5 pc,* t_{pen} *to actual penetrating encounters (units are Myr).*

M	R	t_5	t_{pen}
500 000	20.0	12 800	800
50 000	6.5	2270	1450
5000	2.0	400	2500
500	0.6	70	5000

Figure 1 shows the bombardment profile resulting from a grazing encounter with a GMC, an event which has probably happened five to ten times in Solar System history. The comets in this 90 000-particle simulation initially had a random, isotropic distribution of orbits such that $n(r) \propto r^{-4}$ in the range $10000 \leqslant r \leqslant 60000$ AU. Their evolution was followed by numerical integration. The survival probability of a comet entering the planetary system is ~ 0.5 during each return, due not only to physical destruction but also to the risk of ejection into interstellar space through encounters with the giant planets. For simplicity, this was introduced 'by hand' in the simulation. The figure illustrates the flux of comets entering the planetary system, represented by a sphere of heliocentric radius 40 AU. We see a distinct bombardment episode,

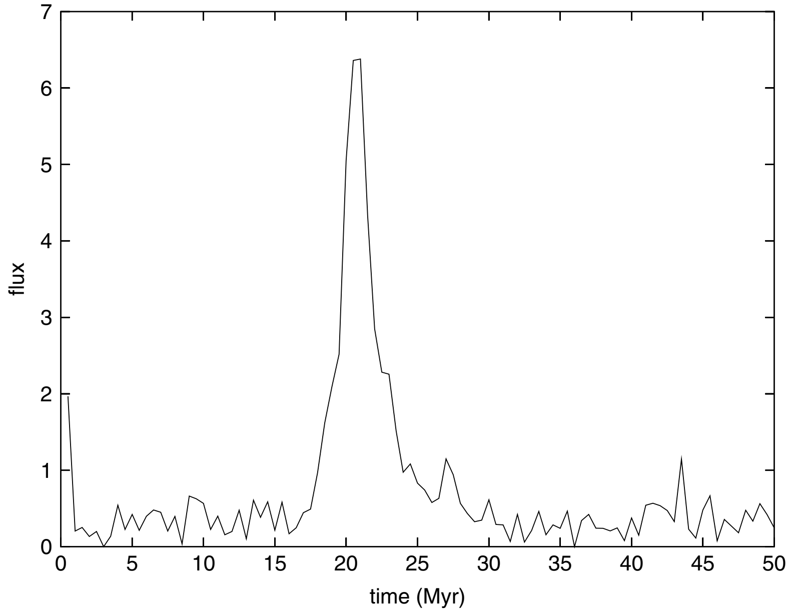

Fig. 1. Flux of long-period comets into a heliocentric sphere 40 AU in radius due to an encounter at 15 km s^{-1} with a nebula of mass $500\,000 M_\odot$ (impact parameter 20 pc). Initial number 90 000, distributed as $n(r) \propto r^{-4}$ in the range $10\,000 \leqslant r \leqslant 60\,000$ AU. The comet flux – units arbitrary – rises while the GMC is approaching and reaches a peak just after its point of closest approach 20 Myr into the run.

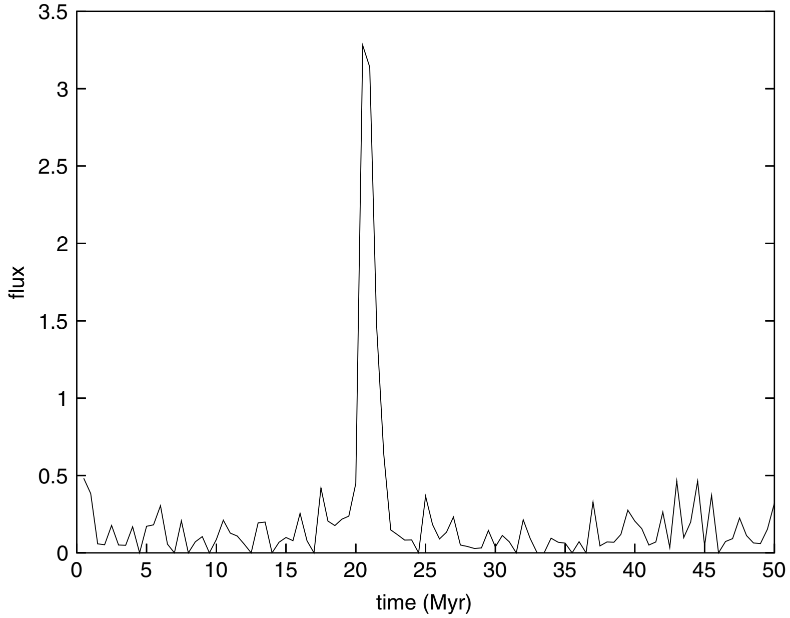

Fig. 2. As Fig. 1, but with 25 000 comets and the perturbing nebula now having a mass $20\,000 M_\odot$, passing within 5 pc at 15 km s^{-1}. Such encounters are expected at ~1 Gyr intervals.

declining with a half-width ~3 Myr. A key feature which emerges is that the bombardment rate is enhanced while the nebula is still in the neighbourhood of the Solar System, and indeed increases for several million years while the nebula is approaching.

Figure 2 shows the effect of a grazing encounter with a $20\,000 M_\odot$ nebula, expected at similar intervals to GMC encounters; again, a strong comet shower is seen.

Sporadic comet showers will also occur when stars penetrate the Oort cloud (Hills 1981; Fernandez 1992). The intensity and frequency of such showers is a matter for speculation; if there exists a dense, inner cloud of radius 10 000 AU, then stellar passage through such a cloud would occur at random intervals of about 100 million years and could yield a shower with amplitude ~100 times the background (Hills 1981).

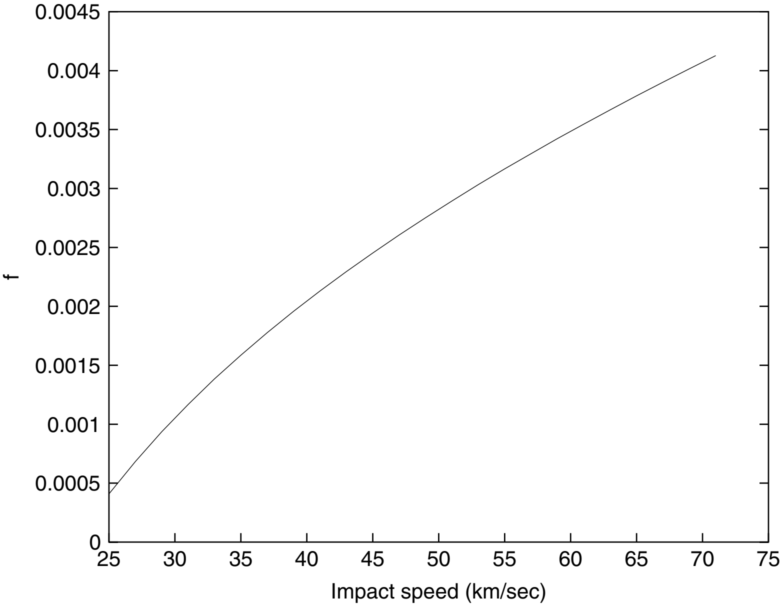

Fig. 3. Mass of ejecta thrown out from Earth, expressed as a fraction *f* of the impactor mass, as a function of impact speed. Mass for mass, a Halley-type comet (57 km s^{-1}) ejects about 10 times as much material into space as a typical NEA (22 km s^{-1}).

The impact crater record

A close encounter with a massive nebula thus generates a noisy interplanetary environment and a cometary impact rate which may be an order of magnitude above background. The ejection rate of life-bearing material from Earth by impacts is correspondingly enhanced. Bombardment episodes can be seen with some degree of statistical confidence in the terrestrial impact record of the past 250 million years (Napier 2006). Eight impact episodes have been tentatively identified, although it is not possible to discriminate between comet showers due to stars or nebulae, or even enhanced rates due to the periodic peaks in the Galactic tide. There is a strong tendency for larger craters to occur within them. For the 40 precisely dated craters known at present, the (in, out) division is (9, 1) for >40 km craters as against (16, 14) for smaller ones (Napier 2006). The hypothesis of random arrival of large impactors has significance level of $\sim 10^{-3}$.

There is a long history of claims and counterclaims about whether the terrestrial cratering record shows a periodicity. The dataset has grown to the point where this too can be tested, and a weak periodicity does seem to be present; it is seen more conspicuously in the case of larger impact craters. The periodicity may be ~ 36 Myr (Yabushita 2004; Napier 2006) but harmonics are present and other values cannot be excluded. It likely has a Galactic provenance, consistent with the Sun's vertical motion through the Galactic disc and the tendency for nebulae to be concentrated towards the plane (Wickramasinghe & Napier, in preparation). The phase of the periodicity is close to zero, consistent with the Sun's current passage through the Galactic plane and implying that we are in, or just past, an impact episode now.

The upshot is that the record of large terrestrial impacts seems to be in satisfactory agreement with the hypothesis of Oort cloud disturbance, given all the uncertainties. The main belt asteroids are incapable of yielding either a sufficiently high flux of large impactors, the observed bombardment episodes or the periodicity (Napier 2006).

Ejection of microbiota

The mean impact speed of a Halley-type comet on Earth is almost three times that of a typical near-Earth asteroid (NEA) (~ 57 km s^{-1} as against ~ 20 km s^{-1}, with a peak at ~ 70 km s^{-1}). Thus, on hitting the Earth, a Halley-type comet ejects an order of magnitude more material into interplanetary space than an NEA of the same mass (Fig. 3; Armstrong *et al.* (2002); Napier (2004)).

The ejection times of metre-sized boulders from the Solar System will characteristically be measured in millions of years. However, in the inner planetary system, a 1 m boulder is subject to destruction by erosion and fragmentation. Sufficiently small bodies are prone to non-gravitational forces, and ejection times are reduced by many orders of magnitude. In the case of micrometre-sized particles, Solar radiation pressure exceeds gravitational acceleration resulting in their rapid ejection.

Consider a body of density ρ_b and initial radius r_0, struck by zodiacal cloud particles with speed V and space density ρ_z. Then its radius is reduced to r by erosion in a time t given by

$$r = r_0 - t/\tau, \tag{6}$$

where

$$\tau = 4r\rho_b/(V\Gamma\rho_z). \tag{7}$$

Here the excavation factor $\Gamma \sim 5\times10^4$ for typical rock impacted by a particle at 10 km s^{-1} (Grün *et al.* 1985). With the

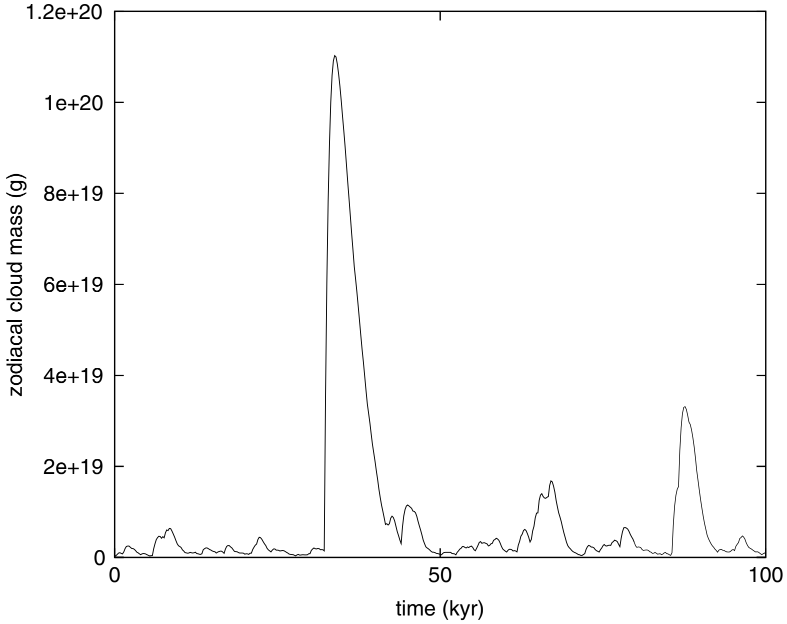

Fig. 4. Random variations in the mass of the zodiacal cloud caused by the erratic arrival and disintegration of rare, giant comets. After Napier (2001).

current zodiacal cloud, a 1 m boulder would be destroyed by erosion in $19\,000 \leqslant \tau \leqslant 230\,000$ yr; fragmentation timescales are an order of magnitude shorter.

However, the cometary dust input to the zodiacal cloud is highly variable in time and, in the immediate wake of a giant comet dust input, the mean eccentricities of dust particles impinging on the Earth are higher, as are their asymptotic encounter speeds. The volume excavated per unit of time scales as V^3 and, in the presence of a large disintegrating comet, these timescales are further reduced by two or three orders of magnitude; this comes from a combination of enhanced number density of particles in the zodiacal cloud and their higher mean velocity (Fig. 4). Metre-sized boulders ejected from Earth may then be collisionally reduced to submicrometre particles on timescales of a few centuries, whereupon Solar radiation pressure will expel them from the Solar System (Napier 2001).

If the Solar radiation force is 10% in excess of the gravitational one, the meteoroid attains a terminal velocity $v_t \sim 13\ \mathrm{km\ s^{-1}}$ and travels 1.9 pc from the Solar System in 140 000 years; with an excess radiation force of 40%, v_t is doubled, and a meteoroid will travel ~ 6 pc in this time. A 1 μm grain with a graphite coat 0.02 μm thick would achieve this. This timescale may be compared with the half-life of deep-frozen microbiota against destruction by Galactic cosmic rays, which according to Mileikowsky *et al.* (2000) is $\sim 75\,000$ yr for some micro-organisms. Thus a significant fraction of microbiota would survive exposure to Galactic cosmic rays while travelling out to a few parsecs from the Solar System (arguments have been given to suggest much longer survival times). The Galactic cosmic ray count within a GMC is low and will increase the half-life taken for the biosphere radius calculation.

The Solar System may thus be surrounded by a biosphere extending out to at least ~ 5 pc, capable of infecting a star-forming nebula during a close encounter. One readily finds that, conservatively, $\sim 3 \times 10^{15}$ g of unshocked surface material from the Earth is injected into the GMC during the ~ 3 Myr of the passage. Furthermore, as this material is largely in micrometre-sized particles, the efficiency of spread of biological information is hugely enhanced over that of the same mass of boulders. If there are 10^6 microorganisms per gram of terrestrial material ejected, this yields a concentration of one organism from the Earth per 10^{16} g of GMC dust, reduced by whatever sterilization processes are at work and enhanced by whatever replication takes place in warm, organic-rich cometary interiors (Wallis & Wickramasinghe 2004). Only a few microorganisms are required to create a population explosion in a receptive planet or comet. While there are several orders of magnitude uncertainty in aggregate, it is clear that – unless material ejected from the Earth is sterilized to an incredible degree – passage of the Solar System through a GMC will seed the GMC with microbial life.

Discussion

Massive nebulae are scavengers, disturbing the comet clouds of star systems penetrating them and gathering up the expelled dust, which will include any microbiota ejected in unshocked planetary material. A typical GMC may have $\sim 50\,000$ stars passing through it at any time. They are also sites of star and planet formation (an OB association may contain several thousand stars) and so there is a clear potential for propagating life throughout the Galaxy as a chain reaction.

Comet clouds cannot be detected directly, but submillimetre imaging of nearby extrasolar planetary systems shows that they commonly possess dust rings, even in systems several gigayears old (Greaves 2006); our own debris disc is very small both in mass and dimensions compared with resolved exosystems. If comets are formed in such rings or in the protostellar nebulae themselves, then 'Oort clouds' too are likely to be widespread. Thus the mechanism described here is unlikely to be peculiar to the Earth.

In the Galactic disc, nebulae are concentrated in the molecular ring 4–6 kpc from the centre, where the number density of molecular clouds is a factor of ~ 4.5 higher than at the Solar circle. Diffusion of life throughout the Galactic habitable zone would proceed most rapidly through the molecular ring of the Galaxy and spread from there. The mean interval between significant encounters in the ring is ~ 50 Myr. In the ring, only 1.12 habitable planets or their precursor material need be inoculated per encounter with a molecular cloud for panspermia to go to completion within the age of the Galaxy. Two inoculations per encounter would lead to complete dissemination in less than 400 Myr. A multiplying factor of 1.05, on the other hand, would lead to the inoculation of only 17 000 planets. Thus, typically of a chain reaction, either interstellar panspermia has proceeded to completion or it has not taken place at all. If life has indeed spread by a chain reaction through the disc, then it is most implausible that the Earth should have initiated it. A further corollary is that life should take hold almost immediately whenever conditions become suitable on a young planet.

Conclusions

The idea that life might arrive from celestial realms is very old, certainly pre-Christian. It had a brief revival in the mid-19th century, and in recent years has been strongly supported by Hoyle & Wickramasinghe (2000). The perception that living organisms would need to survive for billions of years as they travelled around the Galaxy has widely been seen as an insuperable barrier to interstellar panspermia. However, the mechanism described here shows that survival over cosmological timescales and distances is not required: a typical star system in the Galaxy is repeatedly pollinated by molecular clouds, which may collect microbiota in sufficient abundance to seed the star-forming regions within them. Propagation of life through the Galaxy goes to completion provided there are 1.1 or more suitable planetary systems within a typical GMC. Wallis & Wickramasinghe (2004) have also proposed a transfer model, in which comets in the Edgeworth–Kuiper Belt – containing implanted microorganisms – leak out to interstellar space, permitting survival for very long timescales.

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