Icarus 233 (2014) 348–351

Contents lists available at ScienceDirect

Icarus

journal homepage: www.elsevier.com/locate/icarus

Note

Spatial ecology goes to space: Metabiospheres

Milton de Souza Mendonça Jr. *

Departamento de Ecologia, Instituto de Biociências, Universidade Federal do Rio Grande do Sul (UFRGS), Av. Bento Gonçalves, 9500, Porto Alegre, RS CEP 91501-970, Brazil

ARTICLE INFO

Article history:
Received 14 October 2013
Revised 29 November 2013
Accepted 24 January 2014
Available online 3 February 2014

Keywords:
Planetary dynamics
Meteorites
Exobiology
Extra-solar planets
Terrestrial planets

ABSTRACT

Lithopanspermia is increasingly accepted as a possible mechanism for the exchange of organisms between planets. Meteoritic impacts on inhabited planets can generate ejecta reaching escape velocity, which could carry endolithic ecosystems from the deep biosphere into space. If the ejecta travel long and fast enough they could be captured by another planet. Organisms inside the rock might survive re-entry, reaching the planet lithosphere. These processes re-enact spatial ecology at an astronomical level, for example mirroring metapopulation ecology: empty (of life) and occupied patches (planets and large moons) are separated by an inadequate matrix (space), being colonised (turned into biospheres) and perhaps suffering extinctions. As in metapopulations, we can predict this colonisation/extinction dynamics will lead to higher probabilities of life persisting longer times in a Solar System given adequate conditions. This system may be called a metabiosphere, and this ecological dynamics at an astronomical level astroecology, a new scientific branch mingling ecology and astrobiology.

1. Introduction

Lithopanspermia is a recent term, describing the possibility of exchanging organisms, living within rocks, among terrestrial Solar System bodies (planets, moons, asteroids, etc., heretofore planet for brevity) (Nicholson, 2009). Panspermia is a very old idea (Demets, 2012), being proposed in different times and contexts (Arrhenius, 1903; Tepfer, 2008), and discussed sometimes at the fringe of science (Burchell, 2004). However, recent experimental and observational developments on our understanding of how organisms live inside rocks and their resistance to extreme conditions (Horneck et al., 2010; Meyer and et al., 2011) linked to our knowledge on Solar System impact dynamics (Reyes-Ruiz and et al., 2012), have given credence to the hypothesis that life might travel at least within a Solar System, if not even among them (Valtonen and et al., 2009; Belbruno et al., 2012).

Large enough meteorites can generate high speed rock ejecta when hitting a planet through a process known as spallation, such that some of these ejecta can reach escape velocity (Melosh, 2011). Thus, rocks have been exchanged among terrestrial planets of the Solar System throughout its history, with many meteorites found on Earth being recognised as originating at different times from Mars or our Moon (Véronique and et al., 2012). Recent simulated empirical tests also indicate launch by spallation is possible (Fajardo-Cavazos et al., 2009; Horneck and et al., 2008). These impacts can affect not only the surface rocks where life thrives on Earth but also the so-called deep subsurface biosphere, which has long been neglected (Gold, 1992). It is increasingly evident that life thrives in rock crevices down to a few kilometres beneath the surface of the Earth (Hinrichs and Inagaki, 2012), with a still undescribed, rich extremophilic biota. Thus, impact ejecta can carry not only life, but whole endolithic ecosystems within them, a diversity of organisms and their environment.

Some ejecta can end up being captured by nearby planets, in a time-scale of perhaps only a few months to a few years (Melosh, 1988) but more likely thousands to a few million years (Belbruno et al., 2012). Organismal survival during such process may depend on a series of capabilities and conditions, since even protected inside the rock life needs to stand the stages of ejection, travel and re-entry. For example, bacteria might need to enter some form of dormancy, or sporulate, although survival to space conditions has been reported as higher than expected in at least one species (Horneck et al., 1994). Among the conditions already deemed important as dynamical stress, high temperatures, radiation, and vacuum exposure for a long time (Mileikowsky and et al., 2000), it seems either terrestrial organisms might be able to withstand them or they are not as important in lithopanspermia, since radiation inside the rock will be diminished and vacuum exposure might be low or incomplete. Lastly, the projectiles must reach a habitable zone when falling on the recipient planet, as the lithosphere itself or at least the hydro(cryo)sphere (Burchell, 2004), completing the seeding of life. Although probabilities of each step of the lithopanspermia process seem to be low, different reviews

---

* Fax: +55 51 3308 7626.
E-mail address: milton.mendonca@ufrgs.br

http://dx.doi.org/10.1016/j.icarus.2014.01.027
0019-1035/© 2014 Elsevier Inc. All rights reserved.

on the subject return optimistic views that it might be not only possible but probable (Nicholson, 2009; Burchell, 2004; Valtonen and et al., 2009; Mileikowsky and et al., 2000), for example between Mars and Earth. Another point to make is that different periods of the history of the Solar System may have had distinct rates of ejecta exchange, for example much more common exchanges during the Late Heavy Bombardment (Gomes et al., 2005), just before life appeared on Earth (as far as the best fossil record to date attests).

From the viewpoint of an ecologist, these dynamics do not look new. These processes re-enact spatial ecology in a more complex fashion, at an astronomical scale. The similarity of this system with island biogeography, for example, has been pointed out, but not pursued further (Cockell and et al., 2007). Here I will argue that extending the ecological understanding of space on Earth, spatial ecology, to the dynamical system generated by lithopanspermia is necessary and useful, leading to new insights and an increase in the understanding of this new level of complexity for life.

2. Spatial ecology in space

2.1. Metapopulation ecology

Among a number of theoretical viewpoints within spatial ecology, metapopulation ecology provides perhaps a simpler example for comparison than island biogeography by focussing on spatial relations for a single species, as lithopanspermia focusses on life (for a rather complete take on metapopulation ecology, see the book by Hanski (1999)). The argument begins by observing that most environments on Earth are heterogeneous in terms of conditions and resources needed by organisms, such that in some cases there is a mosaic of patches were conditions and resources are sufficient (habitable), interspersed with unsuitable environment, usually called a matrix (uninhabitable). Depending on the dispersal capacity of the organisms, they can traverse the distance between patches more or less easily/frequently. If dispersal is too common, one single "patchy" population is formed. If dispersal is nearly impossible, the separated populations would probably go on distinct evolutionary trajectories and will eventually become different species. In between these extreme cases, a population of populations (the metapopulation) is occupying a portion of the habitable patches in the landscape, with inter-patch dispersal uncommon but not unlikely. On each occupied patch there is a local population (or subpopulation) which has its own size and dynamics, sometimes affected by the arrival of propagules (dispersing individuals) from other subpopulations, sometimes affecting other subpopulations by generating propagules that might successfully disperse. Habitable but unoccupied patches may have never been reached before or been occupied previously by a now extinct population. These patches may in turn be (re)colonised by propagules from other subpopulations. Thus colonisation and extinction are two important factors determining the proportion of occupied patches in the landscape.

Planets hosting life (biospheres) stand for habitable, occupied patches where populations of a given species (life) occur. Planets without life but with environments potentially able to sustain life forms (habitable but uninhabited (Cockell et al., 2012), or potential biospheres) are like the unoccupied patches of metapopulation ecology, where no individuals of a species are found. These patches are separated by the inadequate matrix, in the astronomical case space itself. But individuals/life can disperse through this matrix as propagules from one patch to another – in the astronomical case, through lithopanspermia. Empty patches/planets can be colonised by these individuals/life when they successfully complete this dispersal and establish themselves. A gamut of external and internal factors could also lead a formerly inhabited patch/planet to local/global (biosphere) extinction. A problem in common between metapopulation ecology and the dynamic system guided by lithopanspermia is to recognise inhabitable from uninhabitable patches, in the latter case planets. A difference related to this problem resides in that we know planets can be potential patches, because they can host life, whilst in ecology unoccupied inhabitable patches might sometimes just be confounded with the matrix.

The Levins' model of metapopulation (Levins, 1969) could thus be applied to this ecologically astrobiological system (or astroecosystem): $\mathrm{d}P/\mathrm{d}t = cP(1 - P) - \varepsilon P$, where P is the proportion of occupied planets (biospheres) in a given Solar System, c is the colonisation rate (the rate at which lithopanspermia spreads life between planets) and ε is the extinction rate (the rate at which life faces extinction on a biosphere). The equilibrium value of P is such that: $\widehat{P} = 1 - \varepsilon c$, that is, if colonisation by lithopanspermia is greater than extinction, then there can be at least one biosphere in a given Solar System.

Because lithopanspermia considers endoliths as the most probable dispersers, focal organisms are expected to be chemosynthetic (lithoautotrophs), some thermophilic, some barophilic, some others cryophilic (Walker and Pace, 2007), unusual for our anthropocentric view. Optimal resources and conditions are quite different from what we usually consider, and habitability changes its original anthropocentric meaning (e.g. the Goldilocks zone concept (Smith et al., 2013)). This is not to say that surface endoliths (some of which are even photoautotrophs (Friedmann and Ocampo, 1976)) could not be dispersed, but given the distribution and abundance of the deep biosphere (Gold, 1992; Hinrichs and Inagaki, 2012), these would perhaps represent the majority of propagules. Habitable planets for lithopanspermia may thus be quite distinct from our expectations, with a focus on the lithosphere instead of the hydrosphere or atmosphere, following a recent trend for a change in the concept of exoplanet habitability (Seager, 2013).

2.2. Other models from metapopulation ecology

Source-sink dynamics are important in more realistic versions of metapopulation theory (Dias, 1996). Sources are patches where populations can grow due to optimal resources and conditions, generating a surplus of propagules. In sinks, populations tend to decline to extinction unless dispersal replenishes the local population (the rescue effect (Gotelli, 1991)). As landscape patches differ highly in "quality" for populations, so would planets differ in habitability and the likelihood of producing lithopanspermic propagules. The same two axes would be important for a planet: (1) quantity, quality and diversity of resources such as energy, water, relative abundance of different elements and (2) conditions, such as temperature, radiation, acidity and fluctuations in these values. From this point of view, perhaps large terrestrial planets (super-Earths (Charbonneau et al., 2009)) may be good sources, as they would have larger amounts of resources, lighter elements in abundance, lasting geothermal energy (also increasing global biogeochemical cycles), stronger magnetic fields, all leading perhaps to a larger occupation by the biosphere (including the deep one). Counter to this is that escape velocity may be higher and ejecta fewer. On the other hand, small terrestrial planets (Mars-sized and smaller) might end up as sinks for the same, though reversed, reasons (although producing more ejecta due to lower escape velocities).

This is not to say that life is not present or could not have even originated on small planets, only that it may not be expected to persist there unless a continuing stream of propagules rescues said biospheres. This is a possibility for the history of Mars which has not been considered until now. Currently, evidences of a wet history for Mars have increased our expectation for life on Mars to