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RESEARCH ARTICLE

Some Remarks about Asteroid Impact Triggered "Bioaerosol" Escape during a Putative Microbial Exchange between Early Earth and Mars

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ABSTRACT

In general, Panspermia theory discusses the possibility of the spread of life in the universe. The migration of living organisms between planets is crucial in such a "fertilization" process. This study focuses on one particular case and phase of such migration: the possible material transport between the early Earth and Mars with a focus on the phase of escape, i.e., the ejection of a microorganism-containing material into space. Specific characteristics of asteroid impacts and one of the possible processes, which may be able to transfer microorganisms to space, were investigated. The comparison of the terrestrial and Martian paleoenvironment showed that theoretically, early Mars, similar to Earth, might allow biological evolution and might be able to harbor life. Determining various pressure zones regarding the survivability of the mechanical compression in the case of an impact and the characterization of specific physical parameters of the ejected debris lead to the identification of the pressure—mass/size conflict and the conclusion, which indicates two possible ways of material escape. The possibly "common" and known way is the material ejection close to ground zero. It guarantees big enough debris to protect its passengers during their travel. Still, the survival rate at/close to ground zero is supposedly low, and the heat and overpressure-related compression may sterilize the material even before boarding. An alternative way, discussed in this study, provides a higher chance of survival further from the impact center. Still, the possibility of the ejectile reaching the escaping velocity and the minimum required size is low. Although solving such a problem is out of the scope of this manuscript, searching for an ideal combination of various parameters is a possible challenge for future studies.

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1. Introduction

The study presented here focuses on a particular segment of a Panspermia hypothesis-related theory, namely the research about the possibility of microbial exchange between early Earth and Mars.

Following the early pioneering studies [1,2], Rampelotto [3] suggested that the Panspermia hypothesis, the transfer of the "seeds of life" between planets, is one of the promising fields of astrobiological research. The proposed transfers between planets rely on a set of crucial steps, namely the escape, the transfer, and the landing phases [4]. Experiments and modeling have investigated all efforts. However, there are still numerous questions that need to be considered further, e.g., the paleoenvironment of the donor and the recipient planets, along with, e.g., appearance, as well the survival of a living organism in the case of, e.g., asteroid impact.

In particular, the potential material transfer between planetary bodies, especially Earth and Mars, has been the target of various studies from various aspects, including the role of asteroid impacts on bio-material production, the study of meteorites as a potential source of organic components, the search for the signs of microbial life, the search for the earliest marks of life, and the existence of LUCA—Last Universal Common Ancestor (see in detailed in Section 1.1). Among those studies, one focuses on the thorough research of the survival of a microorganism during the ejection, transfer, and landing phase of the transfer [5]. This study from Mileikowsky et al. [5] summarizes many aspects of the transfer, such as various factors of microbe survival, the size and number of unshocked meteorites, the possible transporters of microorganisms, and the approximate fraction of microbes. Their study concluded that viable transfer between Mars and Earth was highly probable. To provide additional information to their research, the early Martian and terrestrial paleoenvironment are compared below from the point of view of historical geology/planetary science. In addition, the possible survival of the shockwave-mechanical pressure and ejection of material further from ground zero, from the center of impact, are discussed.

1.1 Paleoenvironment on Early Earth and Mars and the Potential of Emerging Life

From the angle of the early Earth and Mars microbial exchange hypothesis, it seems essential to compare the early Martian and terrestrial paleoenvironment between approximately 4.6 to 2.5 Ga ago, to understand the potential for bioaerosols' escape and transportation between the two planets (Figure 1). Both planets suffered a catastrophic collision at their very early age, which might be responsible for the dichotomy, the sharp contrast between the northern and southern hemispheres of Mars (~4.5 to 4.47 Ga) [6], and the formation of the Earth's Moon, described by the Theia hypothesis (~4.51 Ga) [7]. The Martian Northern Hemisphere has a significantly lower elevation compared to the Southern regions, which may have functioned as a hydrological and sedimentary basin, be the location of the Martian ocean and one of the potential regions of the emergence of life in subsequent Martian periods (see below) (Figure 1). Despite the dichotomy-forming impact and the one indicated by the crater retention age of the Hellas basin (3.97 to 4.06 Ga) [8], the mean impact flux during the pre-Noachian was significantly lower compared to the Noachian Late Heavy Bombardment (LHB) period (c.a. 10% of the LHB flux) [9]. Along with the lack of impact events, no marks of pre-Noachian plate tectonism and volcanism can be recognized, along with the missing significant surface erosion—even if the Fe/Mg phyllosilicates exposed on the Noachian surface [10] may indicate pre-Noachian subsurface weathering processes and the presence of water, or groundwater hydrothermal circulation [9,11]. The lack of impact and volcanic activity might have significantly influenced the (lack of the) formation of the pre-Noachian atmosphere. The pre-Noachian paleoclimate might be strongly influenced by the faint young Sun, which provided less solar flux [12], and the lack of volcanism (tectonism), which might play a key role in increasing CO_2, CH_4, NH_3, hydrogen sulfides, and aerosol content of the atmosphere [9].

Contrasting with the Martian pre-Noachian paleoenvironment, there are significant differences in Earth's Hadean (~4.6 to 4 Ga) paleoenvironment. Following the Theia-collision, the formation of the global Hadean Ocean (~4.4 to 4.3 Ga), an aqueous planet with the possible appearance of proto-continental crusts and landmasses, set a different course in planetary evolution [13]. Compared to the pre-Noachian paleoenvironment, the rising crust-mantle cycle on Earth might help the formation of a CO_2 atmosphere, along with the global Hadean Ocean (and the lack of significant size landmass above sea level), which protected the CO_2 storage in continental rocks and its subduction into the mantle [14].

Despite the differences in the evolution of the two planets, there are common components that may have supported the emergence of life. Although there are some doubts about the existence of a Martian atmosphere in pre-Noachian (see above), a Noachian denser CO_2 atmosphere was formed by potentially volatile outgassing, which is expected to be efficient in pre-Noachian as well [12,15]. If it did exist, such outgassing made the Martian pre-Noachian

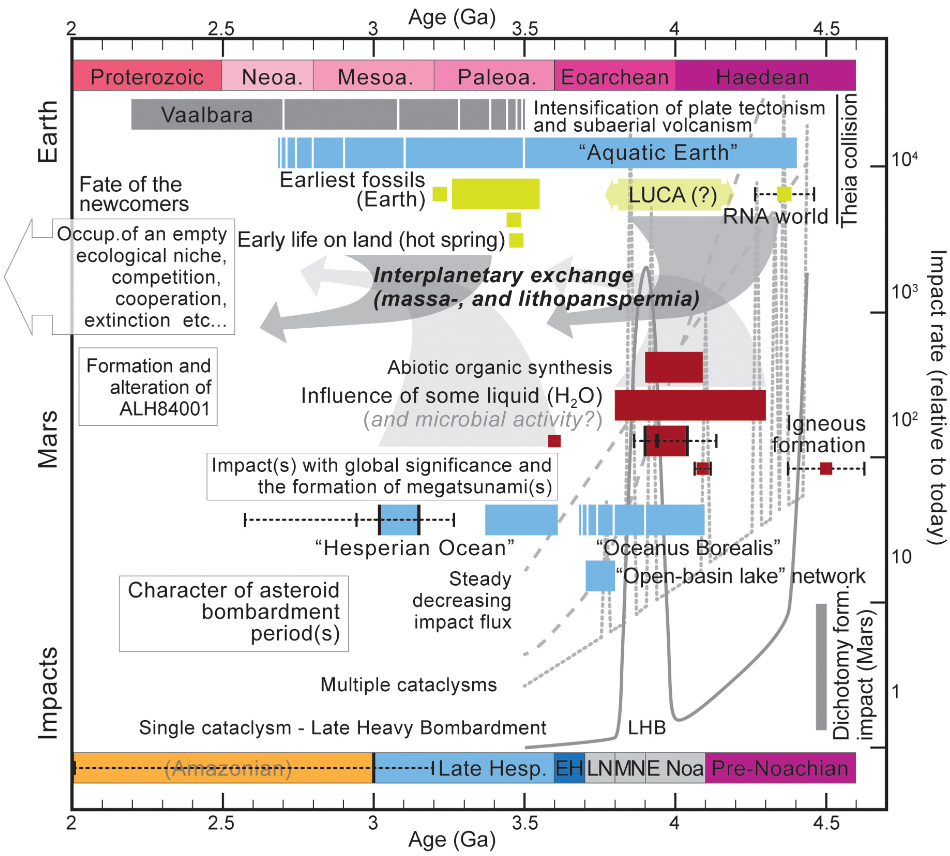

Figure 1. A chronological summary of various factors contributing to the possible microbial exchange between Mars and Earth.

atmosphere similar to the Hadean terrestrial atmosphere. In some sense, both the Martian and terrestrial paleoenvironment can be considered as "calm" as well, regarding the cold Martian world with the characteristic topographical dichotomy and without oceans, significant erosion and impact flux [9], and Earth covered by global Hadean Ocean providing shelter for the emerging life [13].

Among the possible paleoenvironmental similarities, there is one which may suggest similar abiogenesis in the early Mars and Earth: the mark of hydrothermal activity. Based on our current knowledge [13], hydrothermal processes and environment might be the key to abiogenesis, providing components for prebiotic synthesis and molecules, and via the so-called RNA world around 4.36 Ga [16], the building blocks of first cells and the so-called LUCA, i.e., the Last Universal Common Ancestor of life on Earth. The potential marks of hydrothermal processes were observed in the Martian environment as well [11] suggesting the possible evolution of exo-LUCA (the extraterrestrial correspondent of LUCA), the appearance of extraterrestrial life via abiogenesis [13]. Despite this hypothesis's speculative nature and missing information to prove it, the pre-Noachian environment is considered one of the best candidates for life's emergence on Mars [9].

Despite the ongoing argument about the natural, artificial, or organic origin of the identified features [17-20], some studies suggest that there are apparent similarities between terrestrial magneto fossils and the phenomenon observed in the Martian meteorite [19,20]. The one and currently only possible comparison of potential early Martian and terrestrial life is based on analyzing the mark of microbial life found in the Allan Hills (Antarctica) or ALH84001 meteorite [17]. Unfortunately, a recent study has also seen some distinct mechanisms of abiotic organic synthesis, which possibly operated on early Mars (4.1 to 3.9 Ga) and questioned the features' biogenic origin found in ALH84001 [21]. Regardless of the speculation about the possible fossils in ALH84001, it may provide some evidence about processes related to the appearance of some liquid (hydrothermal activity and/or weathering) around 4.3 to 3.8 Ga on Mars [22] (Figure 1).

1.2 Possible Bioaerosol Escape from the Gravity Well of the Studied Planets

Following the introduction to the planetary environment of emerging life, the possible way of escape, the first crucial step of life transportation [4], needs to be discussed. There are some potential ways of high-altitude transport of microbes by bioaerosols (fine particles suspended in the air, containing or consisting of various microbes), including i) giant meteorite impacts and ii) volcanic eruptions [4].

Following the "relatively calm" pre-Noachian/Hadean, the Noachian (Mars) and Archean (Earth) starts with the intense LHB impact event (~4.1 to 3.8 Ga). Like many components in the history of the young Solar system, there are arguments about the timing, nature, and even the existence of the LHB [23,24]. Regardless that LHB appeared as an intense asteroid bombardment period with spike-like, periodic, or steady decline impact flux in the history of the planets, it might eject a significant amount of aerosols and water to the atmosphere [25] carrying microbes to higher altitudes. The impacts seem to have some limitations in their sterilizing effect as well, leaving behind survivals in micro-habitats and the "deep biosphere" of the global ocean of the Hadean/Archean Earth [13], and theoretically, if life did exist on Mars, e.g., in Ocean Borealis [26]. The marks of such impacts can be identified on the surface of Mars, indicated by the crustal-scale Hellas, Isidis, and Argyre basins [8,27]. Earth's continuously changing surface makes identifying Archean age impact craters difficult. Still, indirect geochemical and petrographical evidence, such as the iridium abundance in the oldest sediments and the appearance of shocked quartz, suggest the escalation of extraterrestrial material influx by asteroid impacts [28].

Although the impact flux significantly decreased during the Hesperian, some potential candidates could still lift bioaerosols to higher altitudes. The Martian paleoenvironment during the Hesperian (3.71 to 3.37 Ga) is characterized by the intensification of volcanism, changing wet and dry periods, permafrost, catastrophic floods, and a possible ocean in the Northern lowlands [29,30]. Recently, a theory of large, planetary-scale impact(s) on Mars during the Late Hesperian triggered a scientific discussion [31-33]. If such an impact existed, it provided a potential explanation for escaping various bioaerosols from Mars by ejecting microbe-containing material into space [34].

Along with meteorite impacts, volcanic eruptions can also eject bioaerosols to high altitudes [35] if the type of volcanism allows it. Most likely, eruptions with a higher Volcanic Explosivity Index have some chance of ejecting material into space. On Mars, volcanoes and volcanic regions are comprised mostly of basaltic rocks of various types and morphology [27], which suggest volcanic activity ranging from the formation of effusive lava plains, shields, and lava flows to explosive eruptions (e.g., pyroclastic products around 4 Ga) [36,37]. Compared to Mars, the volcanic activity on Archean Earth (4 to 2.5 Ga) had various contributors. The appearance of one of the first super-craton, the continent-size Vaalbara (2.7 to 2.2 Ga) [38], meant the slow ending of the marine "monopoly" on the Earth's surface. The early continental evolution-controlled komatiite volcanism (3.5 to 1.5 Ga) was characterized by low-viscosity magma and created large volcanic flow fields [39] along the island-arc volcanism [40], which explosive eruptions might work as a supporter of ejection of early life developing on land (e.g., in hot spring deposits; [41]) into higher atmospheric altitudes (Figure 1).

Some short speculation can be made about the becoming of the bioaerosol following the escape phase. It has been proven by recent experiments on ISS (International Space Station; Tanpopo or Dandelion mission) that microorganisms can survive a minimum of three years, exposed to outer space during interplanetary travel by using the surface cells killed by radiation, as a protective layer (so-called massapanspermia) [42]. Such a shield might allow safe travel between Mars and Earth. Although the landing process on a recipient planet from the perspective of lithopanspermia (transfer of microbial passengers inside of asteroids) is well studied, there are only a few explanations about how bioaerosols might survive entry into the atmosphere [5,42]. Many theories can be built about the fate of the microbes arriving in an "alien world", e.g., the way of survival of a pre-Noachian/Noachian non-marine microorganism in the most likely ocean-dominated Hadean to (Eo)archean Earth [13,43], or vice versa. Several questions can be raised regarding the possible interaction between the endemic microbial life on Earth [44-46] and the cosmic newcomers. Such interaction might contain competition, cooperation [47], and the occupation of empty paleoecological niche as well, but (as the writer Michael Ende told in his famous novel, the Neverending Story), this and the summary of the evolutionary consequences of such interactions are "another story and shall be told another time."

This study aims to evaluate one critical problem during the first step of microbial transfer between planets, namely the character of an asteroid impact which can provide enough supporting energy to eject some material to leave the planet and does not destroy every living organism during the process.

2. Data and Data Analysis

2.1 Data Sources

The following datasets were used to analyze the potential bioaerosol transfer between Earth and Mars during their early period (older than 2.5–3 Ga). The impact crater data from early Earth is based on the simulation and dataset provided by Marchi et al. [48,49]. Two sources were used to collect impact crater data from Mars, including the study of Robbins and Hynek [50] and Robbins et al. [8].

Craters above 150 km diameter were used during the analysis, which crater size was possibly caused by a 10–20 km diameter size impactor. Mileikowsky et al. [5] used this minimum impactor size to evaluate the potential natural transfer of viable microbes between Earth and Mars and roughly equal the size of the Chicxulub impact (~10 km). This collision caused the mass extinction at the boundary of the Cretaceous and Paleogene (ca. 66 Ma).

2.2 The Calculation of Key Parameters

The following equations were used to characterize the mass and the size of the ejectiles. The size of the impactor was determined based on the size of the impact crater, following the equation of Hughes [51]:

$$\log D = (1.026 \pm 0.5) + (1.16 \pm 0.04) \log d \qquad (1)$$

where d (diameter in km) is the impactor's size, and D (diameter in km) is the size of the crater created by the impact.

The impact energy was derived from the so-called Shoemaker formula, presented in the study of Shoemaker et al. [52], including the impact angle factor:

$$D = 0.074\, c_f\, (g_E/g)^{1/6}\, (W\, \rho_i/\rho_t)^{1/3.4}\, (\sin i)^{2/3} \qquad (2)$$

where D (km) is the size of the impact crater, c_f is the so-called crater collapse factor: 1.3, g_E is the gravitational acceleration on Earth, g is the gravitational acceleration on other planets, where the crater was formed, ρ_i is the density of the impactor: 3.65 g/cm^3 [53], ρ_t is the density of the rock at the target location: 2.86 g/cm^3 [53], i (°) is the impact angle, defined as 45° in the case of this study, and W is the impact energy (kinetic energy of the impactor) in kilotons TNT equivalent.

The estimation of the peak overpressure, a key component during the characterization of various parameters of the ejectiles, is based on the review of Vijayaraghavan et al. [54], summarizing the methods applied during the study of nuclear experiments:

$$P_{s0} = 6784\, (W/R^3) + 93\, (W/R^3)^{1/2} \qquad (3)$$

where P_{s0} (bars) is the maximum (peak) blast overpressure, W is the yield of a nuclear explosion, which represents the kinetic energy of the impactor in this study in tons of TNT equivalent (see Equation (2)), and R (m) is the distance from "ground zero".

During the estimation of various characteristics of the ejectiles, some environmental conditions have to be considered regarding the survival and the successful transfer of the potential microorganism.

Melosh [55] and Armstrong et al. [53] suggested that the speed of the impactor (v_i) needs to be slightly more than double the second cosmic velocity to transfer the ejectile out of the gravity well of the planet. For such reason, in this study, viE, the minimum impact speed on Earth, and viM, the minimum impact speed on Mars, were set to 22.4 and 10.1 km/s, respectively. Along with studying the ejectile characteristics of an impact characterized by the minimum impact speed, an additional, possibly limiting condition was also investigated. Meteorites with a 300 km diameter size and 30 km/s speed or above are considered to be able to evaporate the water in case of an impact in an ocean [56]. Along with the use of the minimum impact speed, which can transfer bioaerosols in space (viE and viM), v_io, the ocean evaporating impact speed on Earth (30 km/s) was also applied during the data analysis to compare the results in the case of a potential ocean evaporating impact. In addition, along with 15 km/s, 30 km/s impact velocity was also used in the study of Mileikowsky et al. [5]. Such impact velocities represent the extreme ends of impactor speed which may appear in an impact with possible ejection of bioaerosols.

High temperature is a critical environmental component that endangers the microorganism's survival by sterilizing the bioaerosols during impact. Melosh [55] and Mileikowsky et al. [5] applied the following equation to determine the mass of the ejectile with temperature restriction (< 100 °C):

$$m_e(\sim E, M, Eo, Mo) = 1.2 \frac{P_s 0}{\rho_t\, C_T\, v_i} \left[1 - \left(\frac{2 v_e}{v_i} \right)^{1/3} \right] m_i \qquad (4)$$

where m_eE and m_eM (kg) are the mass of the ejected, (non-)sterilized materials, in the case of collision of Earth or Mars and an impactor with v_iE, v_iM, and v_io impact speeds, respectively (see the description above Equation (3)). m_eEo and m_eMo are the mass of the non-sterilized ejecta, in the case of a collision with an asteroid speeding up to 30 km/s, the potential minimal "ocean evaporating" speed. m_i is the weight of the projectile. During the determination of the mass, first, the volume of the impactor was calculated by the definition of the shape of the projectile as a theoretical sphere (with a diameter d, Equation (1) [51]), and the mass of this theoretical sphere shape impactor was determined by the use of ρ_iAVG: 3.65 g/cm^3 as its average density, based on the study of Britt and Consolmagno [57] and Hughes [51]. v_e is the speed of ejecta, equivalent to the second cosmic velocity on Earth and Mars, 11.186 and 5.022 km/s, respectively.

Along with temperature, pressure is another critical environmental component during an impact to be considered a potential limitation for microorganism survival. Based on the study of Hazael et al. [58], a microorganism may survive in tens of GPa pressure, and the calculation of Ps0 and Ps0surv allows us to define the characteristics of ejectiles beyond the 1 GPa blast overpressure most likely survivable limit. Ps0 (in Pa; please note that Equation (4) results are in bars) is the maximum (peak) blast overpressure. Along with calculating ejectile characteristics at peak blast overpressure, the pressure limiting factor for life was set to Ps0surv: 1 GPa [5]. Pt is the rock density at the target location: 2.86 g/cm^3 [53], and C_T is the velocity of sound in the target rock: 6×10^3 m/s.

The size of the ejected material during spallation is crucial for the survival of the microbes during the escape from the donor planet, during the interplanetary exchange, and during entering the atmosphere of the recipient planet. Based on Mileikowsky et al. [5], the size of the ejected material needs to be bigger than 0.2 m in diameter to protect the microbes from heat during the impact and the escape phase.

The equation applied by Mileikowsky et al. [5] was used to determine the average fragment diameter expected during spallation:

$$l_{AVG} = \frac{T}{\rho_t \, v_e^{2/3} \, v_i^{4/3}} d \qquad (5)$$

where l_{AVG} is the ejected fragments' average size (diameter in m), and T is the tension fracture, equal to 0.1×10^9 Pa in basalt and other igneous rocks. As it is described in the previous equations, d is the size of the impactor (diameter in km), ρ_t is the density of the rock at the target location: 2.86 g/cm^3 [53], v_e is the speed of the ejecta, and v_i is the speed of the impactor in various, analyzed in multiple cases (v_iE, v_iM and v_io), as it is summarised at the description of Equation (4).

In addition to the average fragment size, possibly ejected from the donor planet, the maximum fragment size was also estimated [5]:

$$l_{MAX} = \frac{m_W + 3}{2} l_{AVG} \qquad (6)$$

where l_{MAX} is the maximum size (diameter in m) of the ejected fragments, l_{AVG} is the average fragment size (in m; Equation (5)), and m_W is the so-called Weibulls constant, which is 9.5 for basalt.

3. Results and Discussion

Some key characteristics of a potential asteroid impact that might be able to eject debris hijacked by living organisms need to be evaluated.

One of the critical environmental components is the peak overpressure wave which appears in the surroundings of the impact. Mileikowsky et al. [5] describe that the pressure caused by the shockwave is zero at the surface, and even the pressure rises, there are near-surface microbes that may survive the impact. Inspired by the works of Melosh [55] and Toon et al. [25], which describe the evolution and effect of the shockwave, namely stress pulse and mechanical pressure, different zones around the impact center were reconstructed. Based on the information about the survivable overpressure found in the study of Mileikowsky et al. [5] and Hazael et al. [58], four zones, namely the "Safe" survival zone, Critical zone, Quasi-sterile zone, and Sterile zone, were separated and calculate. Pressure below 1 GPa was considered safe; pressure between 1 and 10 GPa is critical for certain species, but there are potential survivals of extreme compression (e.g., the length of high-pressure exposure) [58]. The Quasi-sterile zone was defined due to the decreasing number but still existing species that may survive extreme high-pressure exposure (e.g., [59]). The Sterile zone refers to pressure and region where the compression is too big and prevents the survival of known lifeforms.

As it is shown in Figure 2, in the case of a Chicxulub-size impact (with various impact velocities), living organisms even in less than 100 km distance from ground zero may survive the peak pressure of the impact (please note that only the pressure is examined here, without any other components of an impact). The survivability dramatically decreases, e.g., in the case of a 100 km diameter size impactor. The Safe survival zone is located out of c.a. 800–900 km (Earth) and c.a. 700 km (Mars) radius from ground zero and closer than 400 km (Earth) and c.a. 350 km (Mars) from the center of the impact (Quasi-sterile-, and Sterile zone) only a few (or none) possible survival species may be found on the planetary surface.

Regarding the mass and average size of the ejectiles, there are significant differences between the number of ejectiles at various peak pressures, under certain living organisms may survive the impact. In the case of a 100 km diameter impactor, c.a. 10^{33} kg ejectiles are expected in contrast to the c.a. 10^{16}–10^{15} kg mass of ejectiles at the 10 GPa and 1 GPa peak pressure environment, respectively. It must be noted that compared to the estimation of Mileikowsky et al. [5], who used 15 km/s impact speed, in the case of Figure 3a, 30 km/s was used. Setting the impact speed to the velocity of a "planet destroyer" asteroid shows the possible maximum ejected mass and resulted in such extreme ground zero ejected mass results. The estimation of Mileikowsky et al. [5] feels more realistic, e.g., 8.3×10^{14} kg in the case of a 100 km diameter impactor colliding with Mars at the velocity of 15 km/s. As an additional comparison, the mass of Earth and Mars can be listed as c.a. 5.97×10^{24} and 6.39×10^{23} kg, respectively. Despite the extreme values, Figure 3a indicates the significant drop in ejected mass at the Critical pressure zone and Safe survival zone, compared to ground zero.

The average size of the ejectiles was calculated at the two extreme possibilities; one is the already suggested

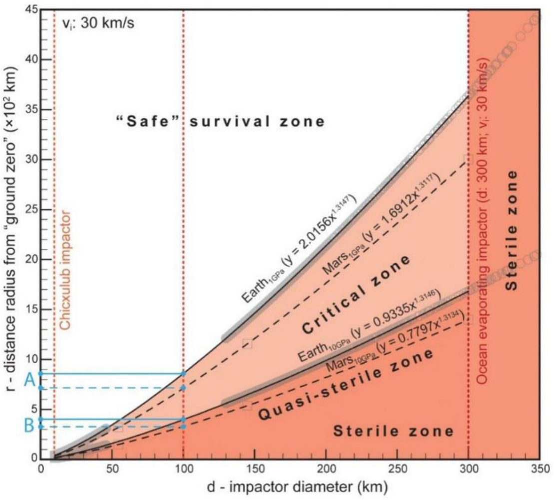

Figure 2. The distance of (non-)survivable pressure zones during a blast wave hit from ground zero of an asteroid impact. The 1 GPa and 10 GPa pressure limits of survivability are based on the study and review of Mileikowsky et al. [5] and Hazael et al. [58]. The blue solid and dashed lines indicate the minimum distance of Safe survival zone (A) and Critical zone (B) from ground zero, in the case of Earth (solid line) and Mars (dashed line), respectively. The solid lines indicate the calculation based on terrestrial impacts and Earth parameters; the dashed lines indicate the calculations based on Martian impact and the various Martian parameters.

maximum expected impact speed, a speed of an asteroid capable of evaporating oceans (Figure 3b, v_i), and the other end, the lowest impact speed which is capable of providing enough energy to transfer the debris out of the gravity well of the planets (Figure 3b, v_{MIN}). Decreasing average grain size can be recognized by the increase in the impact velocity. A collision with a 100 km diameter asteroid with v_{MIN} minimum velocity results in 50–60 m diameter debris ejected from Mars and c.a. 10 m diameter debris from Earth at ground zero. If the same impactor arrives with a 30 km/s impact speed, the size of ejectiles change to c.a. 10 m in the case of Mars and 7–8 m diameter in the case of Earth. Regarding the estimated asteroid size, the roughly 10 to tens-of-meter diameter asteroids feel capable of safely transferring microorganisms between early Earth and Mars. Still, some aspects must be considered during the evaluation of the results.

The comparison resulted in a contradicting result. As may be expected, the calculation of Mileikowsky et al. [5] showed decreasing average grain size by the decreasing impactor size (impact velocity was set to constant), most likely due to the decreasing impact energy with reducing asteroid size. It is also expected that further and further from ground zero, the average size of ejected debris is decreasing due to the decaying impact energy (stress wave) [55]. Example theoretical pressure zones, related to the 30 km/

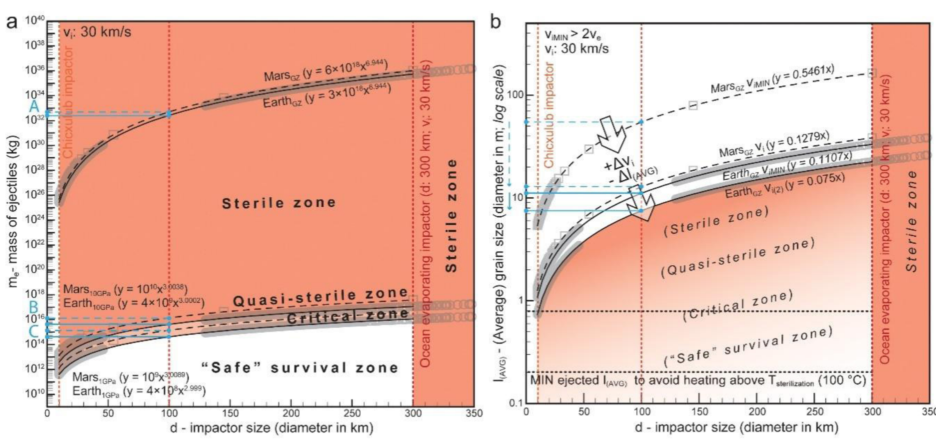

Figure 3. (a) The mass of ejectiles at various distances from ground zero and (b) the estimation of the average size of ejected fragments during various size asteroid impacts. The solid lines indicate the calculation based on terrestrial impacts and Earth parameters; the dashed lines indicate the calculations based on Martian impact and the various parameters of Mars. The arrows in Figure 3b show the decreasing average size of ejectiles. $Earth_{GZ}$ and $Mars_{GZ}$ lines mark the ejected mass and average grains size at ground zero. 1 GPa and 10 GPa indices indicate the ejection mass at the 1 GPa and 10 GPa pressure zones (the distances of those pressure zones from ground zero are summarized in Figure 2). The blue solid and dashed lines indicate the amount of ejected material at ground zero (A), at 10 GPa peak pressure at ground zero and/or at the minimum distance of the Critical zone (B), and at 1 GPa peak pressure at ground zero and/or at the Safe survival zone (C), in the case of Earth (solid line) and Mars (dashed line) respectively. Please note that in the case of Figure 3b, the indication of various zones only serves as a visual aid, indicating the decreasing grain size with increasing distance from ground zero in the case of the v_i = 30 km/s velocity impacts (Section 3 and Section 4; the pressure-mass/size conflict).

s velocity impacts are indicated in brackets (Figure 3b). In contrast, the result in this study demonstrates that impact speed significantly influences the average size of the ejectiles, i.e., higher impact velocity results in smaller size of ejectiles, which variable needs to be considered in further studies.

Along with the impactor's velocity, the size should also be discussed shortly. As an example, the effect of a theoretical 100 km diameter impactor was analyzed. As shown in Figure 3, the mass and average size decrease significantly with the decrease of the impactor size. In the first billion years, the initially high ratio of asteroid impacts reduced considerably [14], along with the estimated size of the impactors (e.g., [48]). Such estimations suggest that the size of potential impactors, which may eject microorganism-containing debris in space when a simple living organism appears on Earth (and theoretically on Mars), was smaller than the example 100 km. Using a 20 km diameter size impactor (such size asteroid was used as maximum size impactor in, e.g., [5], the ejected mass of material at 1 GPa and 10 GPa pressure is around 10^{12}–10^{13} kg, and the average ejectile size is around 1 m diameter (at 30 km/s impact velocity) (Figure 3a).

The minimum ejectile size is the third size-related factor that needs to be considered. Please note that based on the explanation of Mileikowsky et al. [5], if the size of the ejectile is bigger than 0.2 m or 0.8 m diameter, it prevents the inner part from heating up above 100 °C, which would sterilize the debris. Such heating appears at the impact and the time of entering the new planet's atmosphere following the transfer. Regarding the potential transfer between Earth and Mars with their early atmosphere, the 0.2 m or 0.8 m is a crucial minimum size limit, which must be kept in mind, even if the fall through the atmosphere is a relatively short period (few tens of seconds) and a heat shield, a compact, melted layer, forms around the meteorite [5]. In addition, asteroids may break up during the transfer and landing phase, which may endanger the microorganisms' survival in smaller meteorites [5].

The pressure-mass/size conflict

The determination of various pressure zones around the impact site, and their distance from ground zero, all together with the change in the ejected mass (even if the extreme 30 m/s impact velocity and 100 km diameter impactor size were used) and the supposed difference in decreasing average size of ejected debris moving further from the center of impact revealed a dilemma. Such a dilemma is closely related not only to the possible bioaerosol/microbe-containing material exchange between early Earth and Mars but applies, in general, to any case when the escape of microorganisms from terrestrial (Earth-like) planets is discussed.

The size of impactors as a limiting factor during the transfer of microbes to another planet was discussed in detail in Mileikowsky et al. [5]. In the case of Mars-Earth transfer, Category 1 meteorites are too small to provide a safe transfer to microorganisms.

This research adds a factor to the material ejection phase. The distances of the Safe-and Critical survival zone (Figure 2) raised the question that in such distances, there is enough impact energy left to lift big enough size and amount of debris (Figure 3) and eject it into space with possible living microbial content or not (Figure 4). A higher velocity and bigger size impactor certainly provides enough energy to fragment and eject bigger mass and size debris to space. Despite the expected surface and subsurface overpressure conditions, i.e., from 0 to ≤ 1 GPa overpressure [5], the calculation in this study shows that even in the case of a 20 km diameter impactor, zones, where microorganisms may survive the mechanical pressure, are located in c.a. 100 km distance or further. The question is whether the impact has enough energy (regarding, e.g., the propagation and decay of the first stress wave-detached shock [55]) to detach and eject materials into space, located in further distances (along with the non-shocked ejectiles from the neighbour of ground zero), or the ejected material is big enough to protect the microbes via the transfer.

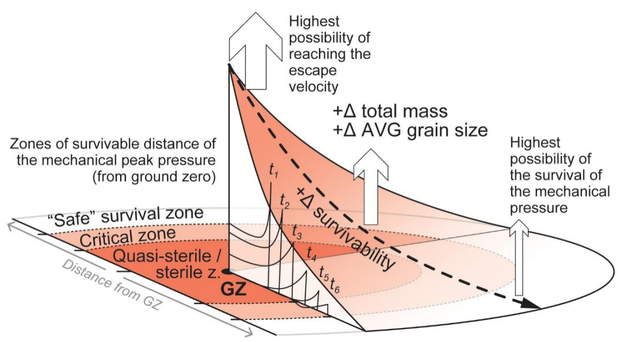

Figure 4. The visual explanation of the pressure-mass/size conflict. t1 to t6 curves indicate the variation of overpressure in the air with the distance at successive times [60], and GZ marks the ground zero.

Similar to explosions, the characteristics of the peak overpressure-related shock front (blast wave) and the dynamic pressure (drag force associated with the strong wind accompanying the passage of the blast wave) at a certain distance from ground zero may be considered critical parameters during the evaluation of surface material detachment, lift and ejection further from ground zero [60,61]. The detailed research of the surface waves, such as incident and reflected waves, and their interaction, including the formation of a single wavefront by merging the two waves (so-called Mach or irregular region), may significantly contribute to understanding microbe-bearing material ejection in space. Still, it is beyond the scope of this study and most likely requires experiment-based complex simulations.

4. Conclusions and Summary

Along with the determination of various zones regarding the (microbial) survivability of the mechanical pressure triggered by the shockwave, the mass and average size of the ejectiles were estimated. The size of ejectiles in the case of a possible exchange between Earth and Mars falls between 10 to tens of km in the case of a 100 km impactor. The extreme ends of such scale represent the scale of various impact speeds, the minimum impact velocity required to trigger enough high escape velocity for the ejectiles, and a maximum high velocity, defined as 30 km/s. The estimated average ejectile size drops to a magnitude smaller size range in the case of smaller (20 km diameter) asteroids, which might be more common around 3.5 Ga ago, during the period when life appeared in the case of Earth and theoretically on Mars. Considering various physical effects on the ejectile, e.g., the potential further fragmentation of the debris during the transfer and landing phase, the smaller size may jeopardize the survival of the carried microbes.

The study of essential characteristics leads to a dilemma, named pressure-mass/size conflict, that is not simply related to the understanding of the possible microbial exchange between the early Earth and Mars, but any panspermia studies targeting asteroid impacts as potential contributors in the escape step of microbial transport.

The pressure-mass/size conflict origins from a contradiction related to the determined zones, indicating the distance where living organisms, most likely microorganisms in the case of early Earth and theoretically Mars, may survive the shockwave-triggered mechanical pressure and the size of the ejectiles which may carry microbes during the transfer between planets. It seems that some impacts with specific impact energy can eject the appropriate size debris, which may be a carrier for microorganisms during the transfer between early Earth and Mars. The only problem is that such impact energy may sterilize the sample by the mechanic pressure, and the zones where the shock wave triggered mechanical pressure is survivable on the surface are far from the impact center. At such a distance, the impact energy may not be enough to accelerate the ejectile speed to reach the escaping velocity and leave the planet's gravity well.

Although solving such a problem is out of the scope of this manuscript, searching for an "ideal" combination of various parameters (e.g., impactor size, impact velocity, and so on) is a possible challenge for future studies. In closing words, at least two alternative ways of material ejection into space by asteroid impact can be considered. The possibly most discussed and known way is material ejection close to ground zero. It guarantees big enough debris to protect its passengers during their travel. Still, the survival rate at/close to ground zero is supposedly low, and the heat and overpressure-related compression may sterilize the material even before "boarding". Another alternative way may provide a higher chance of survival, further from the center of impact. Still, the possibility of the ejectile reaching the escaping velocity and the minimum required size is low. Such ways may represent a scale's extreme ends regarding various factors that may influence the bioaerosol escape during an asteroid impact. One of the focuses of future studies can be the determination of an ideal way, an ideal escaping distance, where all the considered factors are in a setting that supports successful bioaerosol escape.

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Data Availability Statement

Data will be available upon request from the author.

Conflict of Interest

The author declares no conflict of interest.

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