# Space dust collisions as a planetary escape mechanism

Arjun Berera\*

School of Physics and Astronomy, University of Edinburgh, Edinburgh EH9 3FD, United Kingdom

It is observed that hypervelocity space dust, which is continuously bombarding the Earth, creates immense momentum flows in the atmosphere. Some of this fast space dust inevitably will interact with the atmospheric system, transferring energy and moving particles around, with various possible consequences. This paper examines, with supporting estimates, the possibility that through collisions, the Earth-grazing component of space dust can facilitate planetary escape of atmospheric particles, whether they be the atoms and molecules forming the atmosphere or bigger sized particles. As one interesting outcome, floating in the Earth's atmosphere are a variety of particles containing the telltale signs of Earth's organic story, including microbial life and life essential molecules. This paper will assess the ability for this space dust collision mechanism to propel some of these biological constituents into space.

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## I. INTRODUCTION

A huge amount of space dust enters the Earth, on the scale of  $\approx 10^5$  kilograms per day, that is composed of dust particles of varying masses from  $10^{-18}$  to 1 gram and enters the Earth's atmosphere at very high speeds  $\approx 10-70 \text{km/s}$  Carpenter et al. [5], Flynn [11], Kyte and Wasson [23], Love and Brownlee [24], Plane [30]. This hypervelocity space dust forms immense and sustained momentum flows in the atmosphere. For particles that form the thermosphere or above or reach there from the ground, if they collide with this space dust, they can be displaced, altered in form or carried off by incoming space dust. This may have consequences for weather and wind, but most intriguing and the focus of this paper, is the possibility that such collisions can give particles in the atmosphere the necessary escape velocity and upward trajectory to escape Earth's gravity. Two types of particles that will be considered are either light elements/molecules that form Earth's atmosphere or bigger particles capable of harboring life or life essential molecules. The former possibility implies an exchange mechanism of atmospheric constituents amongst widely separated planetary bodies. The latter, and perhaps most interesting possibility, addresses basic questions about the origin of life, with similarities to the Classical Panspermia mechanism Arrhenius [1], except space dust rather than radiation scrapes up life in the upper atmosphere. One should approach the application of this space dust collision mechanism to panspermia cautiously, since there are several complicating factors and they will be considered in this paper. However the prospects are intriguing and so worth exploring. Earth harbors the greatest, perhaps only, concentration of life and its biologically produced molecules within this local region of our Galaxy. The idea that microbial life and its constituents are exchanged between planets would gain further scientific footing by establishing that natural processes on Earth send out its biological constituents into the Solar System.

Realizing gravitational escape for small particles presents a few difficulties. First it requires upward forces that can accelerate these particles up to escape velocity level. On the one hand, if this is done at too low an altitude, the stratosphere or below, the atmospheric density is so high that drag forces will rapidly slow fast moving particles. Moreover these particles will also undergo immense heating to the point of even evaporating. For these reasons, even though wind, lightning, volcanoes etc... all would be capable of imparting huge forces at these lower altitudes, they would not be able, even in principle, to accelerate particles intact up to escape velocity. On the other hand, at very high altitudes, at the upper part of the mesosphere and into the thermosphere, particles moving at escape velocity levels would not suffer such great drag and heating effects and so could escape the Earth's gravity and cruise into outer space. As such, only in the higher atmosphere would it even be possible that the atoms and molecules found there could be propelled into space by space dust collisions. As for larger particles capable of harboring biological constituents, the most likely scenario for thrusting them into space would require a double stage approach, whereby

<sup>\*</sup>Electronic address: ab@ph.ed.ac.uk

they are first hurled into the lower thermosphere region or higher by some mechanism and then given an even stronger kick by fast space dust collision, which eventually leads to escape velocity and an exit from the Earth's gravity.

#### A. Drag force and surface temperature

Consider the forces that act on a particle of mass m at an altitude z above sea level. First there is the downward gravitational force, which for altitudes within a few hundred kilometers of sea level, can be approximated as just a constant mg with  $g \approx 9.8 \text{m/s}^2$ . Second is the drag force in the direction opposite the motion of the particle,

$$\frac{dv}{dt} = -\frac{3\Gamma\rho_a}{4\rho r}v^2 \,,$$
(1)

where v is the speed of the particle,  $\rho_a$  is the atmospheric mass density,  $\rho$  is the particle mass density, r is the particle radius, and  $\Gamma \approx 1$  is the atmospheric drag coefficient. The atmospheric density Brekke [4], Havens et al. [14], Picone et al. [29] as function of altitude z is  $\rho_a(z) \approx (1.2 \times 10^3 \text{g/m}^3) \exp{(-z/7.04)}$ , which is valid to within approximately a factor 2-3 and up to an altitude around 150km. Third a particle at speed v will get heated from collisions with the molecules in the air as

$$\alpha \frac{1}{2} \rho_a 4\pi r^2 v^3 = 4\pi r^2 \sigma T^4 \,, \tag{2}$$

where the LHS is the rate of energy gained by the particle from the kinetic energy of the molecules in the air and the RHS is the blackbody rate at which the particle radiates the energy, leading to a surface temperature T. Here  $\sigma$  is the Stefan-Boltzmann constant and  $\alpha$  is the fraction of the total kinetic energy of the air molecules that stick to the moving particle, which we will set to  $\alpha = 1$ . There can also be a heat capacity term on the RHS of Eq. (2), but for small particles of micron size or a couple of orders of magnitude bigger, this term can be ignored Whipple [45]

#### II. ESTIMATES

Let us first make some estimates on the speed that small particles, whether they be the space dust or particles sitting in the atmosphere, are able to achieve in the atmosphere, accounting for drag and gravitational forces and surface temperature levels. For atmospheric elements and molecules, the scenario proposed in this paper is that as the space dust moves through the atmosphere, some of the atoms and molecules that it is made of get stuck to the space dust. Since these atoms and molecules will be of negligible mass compared to the space dust, after collision the space dust will simply maintain the same speed it had. For bigger particles capable of harboring microbial life, the collision dynamics can range from a simple elastic collision, to the small particle sticking to the space dust particle, to fragmentation/vaporization of one or both particles in the collision. Note however this paper focuses on interplanetary space dust which has a velocity range when coming to Earth of  $\approx 10-70 \text{km/s}$ . Collisions between small grains in this velocity range have been shown in Borkowski and Dwek [3] to not completely destroy them. Some percent of the colliding grains do undergo fragmentation/vaporization, but some portion also remains intact. At the same time, since the velocity range for the fast space dust is still some factors higher than escape velocity, provided the incoming space dust particle is the same or bigger size than the small particle in the atmosphere it collides with, both the case of elastic collision and where the atmospheric particle sticks to the incoming space dust particle will result in a final velocity still around the same as the incoming velocity of the space dust. Although some fraction of the two colliding particles may fragment or vaporize Borkowski and Dwek [3], given the huge energy being transferred in this process, it still is plausible that portions of the two colliding particles ultimately emerge with high velocity, capable of escaping the Earth's gravity.

## A. Speed and altitude

To make some estimates, for the space dust, it has typical density  $\rho_s \approx 2 \times 10^6 \mathrm{g/m^3}$ . The small atmospheric particles struck by this space dust may contain life related quantities, such as bacteria, viruses, fungi, life related molecules like DNA, RNA, etc... For example a typical bacteria has a mass around  $\sim 10^{-12} - 10^{-13} \mathrm{g}$  and and a length around  $r \approx 10^{-6} \mathrm{m}$ . Other biological constituents will have approximately similar density. The small atmospheric particles will be approximated as spherical and have a density  $\rho_p$  the same as the space dust.

Focusing first at higher altitudes, the speeds of interest here are near escape velocity, so in the km/s range, or within an order of magnitude around this. As the interest is in vertical motion, atmospheric densities experienced

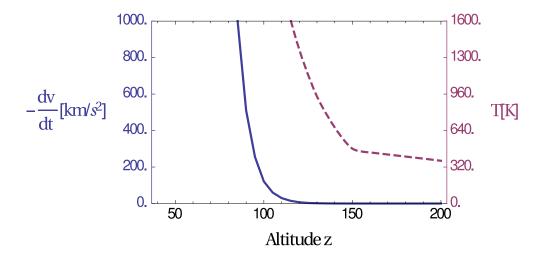


FIG. 1: Deceleration due to atmospheric drag forces and surface temperature as function of altitude for a particle of radius  $r = 10^{-6} m$  moving through the atmosphere at speed of  $20 \mathrm{km/s}$ 

by these fast moving particles at these speeds will change substantially within timescales of around a second. The effect of the gravitational acceleration is in the  $m/s^2$  range and so can be ignored, since it will be a small effect on particles of km/s speeds. For a particle of radius  $r=10^{-6}$ m and speed 20km/s, the results for the deceleration from Eq. (1) and surface temperature from Eq. (2) are shown in Figure 1. In particular the deceleration from atmospheric drag at altitudes 110,130, and 150km from Eq. (1) respectively is around (in km/s<sup>2</sup>) -30,-2, and -0.1, as shown in Figure 1. These expressions scale quadratically with speed, so for every factor two less in speed, these expression decrease by a factor four. Moreover they scale inverse with the radius, so for every order of magnitude increase in r these expressions decrease by an order of magnitude. Estimating also the surface temperature from Eq. (2) at the same speed of 20km/s for the same altitudes 110,130, and 150km, gives respectively  $\approx 2000,1000,500$  K as shown in Figure 1. These expressions scale to the 3/4th power with speed and are independent of the particle radius. So for example at 150km altitude, if the speed is around a factor two smaller, so just around escape velocity 11.2km/s, the surface temperatures will be within the range where biological life can be sustained. From these simplified expressions, it suggests the minimum altitude of around 150km above which a single collision to escape velocity can allow a particle to cruise free of the Earth's gravity, unhindered by atmospheric drag and heating effects.

At much lower altitudes, our estimates show it is very difficult to accelerate particles to any substantial speed. For example at an altitude of 20km, where micron and larger sized particles are known to be found in the atmosphere with some containing microbial life, the drag force and surface temperature remain adequately small only for speeds at most  $\stackrel{<}{\sim} 20$  m/s and the particle radius needs to be in the millimeter or larger range. This speed is low enough that the gravitational force is relevant, and will pull such particles down unless they experience frequent upward forces to maintain this upward speed. At around 50km altitude, drag forces and surface temperature are small for particles with speed  $\stackrel{<}{\sim} 30$ m/s and radius larger than around  $10^{-5}$ m. At around 85km, which is approximately the highest altitude that particles from volcanic eruptions are believed to have reached *Ludlam* [25], *Self and Rampino* [38], *Verbeek* [43], drag forces and surface temperatures become small for speeds  $\stackrel{<}{\sim} 0.5$  km/s and particle radius larger than  $10^{-6}$ m.

## B. Flux of hypervelocity space dust with grazing trajectories

Next we need to consider what is the rate at which fast moving space dust collides with particles in the atmosphere. We are interested in collisions that accelerate particles upward to higher altitude and eventually escape from the Earth's gravity. Space dust is bombarding the Earth from all directions. Although much of of this dust will get pulled down by Earth's gravity and fall to the ground, given the high entry speeds of this dust in the order of and even much bigger than escape velocity levels, some of the dust that enters the Earth's atmosphere will then graze through it. For larger sized meteorites, such phenomenon is well known and is visible in spectacular fireballs that streak through the sky, sometimes accompanied also with meteor showers. Some fraction of the lighter space dust will also simply pass through the Earth's atmosphere. For a space dust particle that is grazing past the Earth, just beyond the point where

it moves exactly parallel to the ground beneath it, this space dust will be moving with an increasing upward incline relative to the ground immediately below it. It is beyond this point that if it collides with particles in the atmosphere it will give them an upward force, accelerating them to higher altitudes. At very high altitudes around 150km and higher, we saw from the above estimates that at escape velocity level, drag and heating effects are not significant. Above this altitude, fast moving space dust will not heat up significantly and will continue to move fast. Anticipating that the chances of space dust hitting small particles in the atmosphere is a rare event, which will be verified below, it will be assumed that a given atmospheric particle may have at most one or two collision with space dust. If this is to provide adequate momentum to the particle, the fast space dust needs to be at least the same or greater mass than the particle it hits. In such collisions, by momentum conservation, a considerable portion of debris after collision will then leave with about the same speed and direction as the incoming fast particle that initially hit it. If such a collision by a fast moving space dust particle with some upward velocity happened at high enough altitude, then the struck particle, whether attaching itself to the incoming space dust particle or scattering elastically/semi-elastically, could be accelerated to escape velocity level. If that small particle contained any biological constituents, these would be thrust out into space, free of the Earth's gravity.

Alternatively at lower altitudes, where atmospheric drag forces and heating effects prohibit particles from moving very fast, space dust with some upward momentum colliding with particles in the atmosphere would accelerate them to sub-escape velocity levels, but possibly still high enough to push the particles substantially further up in the atmosphere. Once higher up, a second collision could then serve to propel the particle out into space. This possibility at lower altitudes is by no means the only mechanism for elevating particles upward and may not even be a significant mechanism to achieve this. Other forces are known to provide particles with upward velocity from lower altitudes such as weather phenomenon, atmospheric electric fields during thunderstorms Dehel et al. [7], Pasko et al. [28], gravito-photophoresis Rohatschek [35], mesospheric and thermospheric vertical wind Eswaraiah et al. [10], Kurihara et al. [22], Rastogi and Bowhill [33], Rees et al. [34], Woodman and Guillen [47] and volcanic eruptions Ludlam [25], Tupper et al. [41], Wilson et al. [46]. Nevertheless since the effects of collisions with fast moving space dust is being examined, for completeness this process at lower altitudes is also considered.

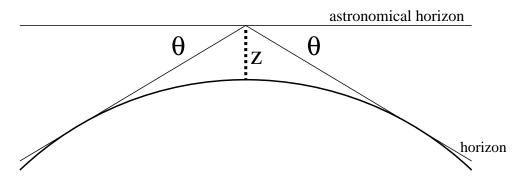


FIG. 2: Earth-grazing space dust approaches point at altitude z from within angle  $\theta$  and has some upward component of momentum

In order to estimate the chance of occurrence of space dust collisions with particles in the atmosphere, it requires the flux of space dust moving upward away from the Earth at a given point that is a normal distance z above the ground, as shown in Figure 2. At this zenith point consider the plane that is parallel to the Earth's surface just beneath it, also known as the plane defined by the astronomical horizon around this point. Space dust particles coming to this zenith point from beneath this plane will have some upward component of momentum. From this zenith point, lines extending tangent to the Earth's surface, thus to the true horizon, in all directions define a cone. The region between the astronomical horizon plane and this cone section, as shown in Figure 2, is the maximum region in which Earth-grazing space dust approaching this zenith point will have some upward component of velocity. The angle between the astronomical plane and this cone is  $\theta \equiv \sqrt{2z/R_e} \ll 1$ , where  $R_e \approx 6400 \mathrm{km} ~(\gg z)$  is the radius of the Earth. The space dust flux that can pass this zenith point from all directions forms a solid angle region of  $2\pi + 2\pi\theta$ . Assuming a uniform distribution of space dust flux from all directions heading to this zenith point, then the approximate fraction of this flux with some component of upward velocity is  $\approx \sqrt{2z/R_e}$ .

Space dust that is not moving upward can still impart transverse momentum on an atmospheric particle during a collision that could have some upward component. Also for space dust moving toward the point z within an angle  $\theta$  above the astronomical horizon plane, a forward collision of it with an atmospheric particle will give it an Earth-grazing trajectory which initially moves downward with respect to the ground beneath it but eventually will move upward. Another possibility is when the fast space dust collides with atmospheric particles, they could fragment from the high impact collision. Given that the space dust speed can be many factors higher than the required escape

velocity, even if the collision results in a fragmentation of the atmospheric particle, there is adequate kinetic energy present in such collisions that some emerging fragments could still be capable of having speed at escape velocity level. For the order of magnitude estimates of interest here, all these details will not be treated.

There has been considerable work in determining the amount and mass distribution of space dust bombarding the Earth Carpenter et al. [5], Flynn [11], Kyte and Wasson [23], Love and Brownlee [24], Plane [30]. Measurements show that the Earth receives roughly  $10^7 - 10^8$  kilograms per year of space dust. Estimates from ground and satellite measurements also show that the flux to the Earth is in the neighborhood of about  $10^9$  grams of space dust per year for each decade of particle mass from  $10^{-9}$ g to  $10^{-2}$ g Flynn [11], Kyte and Wasson [23], Love and Brownlee [24], Plane [30]. Based on the arguments given above, the fraction of this space dust flux that will have some upward velocity is for example at z = 20km,  $\sqrt{2z/R_e} \approx 0.08$ , whereas at z = 150km it is  $\sqrt{2z/R_e} \approx 0.2$ .

#### C. Planetary escape of small particles in the higher atmosphere

Examine a particle sitting high in the atmosphere at altitude 150km with mass  $10^{-11}$ g. Assuming a typical matter density of 2g/cm<sup>3</sup> this implies a particle radius  $r_p \approx 10^{-6}$ m. This mass and size correspond to, for example, a collection of several bacteria or some bacteria packed in some dirt or water. If a fast moving space dust particle that is grazing the Earth at this altitude with mass at or above that of this small particle, collides with it, the result will be this small particle then emerges with approximately the same speed and direction as the incoming space dust particle. Using the measurements of space dust flux by Carpenter et al. [5], Flynn [11], Kyte and Wasson [23], Love and Brownlee [24], Plane [30], space dust with radius  $10^{-6}$ m,  $10^{-5}$ m,  $10^{-4}$ m, and  $10^{-3}$ m have particle flux, f, in  $m^{-2}s^{-1}$  of order  $10^{-3}$ ,  $10^{-6}$ ,  $10^{-8}$ , and  $10^{-12}$  respectively. Based on our above estimates, at the altitude of 150km, these numbers need to be multiplied by 0.2 to obtain the corresponding flux,  $f_u$ , of space dust particles with some upward velocity. The rate at which this upward fast moving space dust will collide with a particle in the atmosphere is  $R = \sigma f_u$ , where  $\sigma = \pi (r_p + r_s)^2$  is the classical hard sphere cross section between the particle p and the space dust s. Calculating, we find at 150km altitude the collision rate is dominated by space dust particles of radius at or below  $r_s \approx 10^{-4}$ m, with  $R \approx 2 \times 10^{-15} {\rm s}^{-1}$ . To put this value for the rate in perspective, if there was one atmospheric particle with radius at or less than  $\approx 10^{-6}$ m within each meter squared column of the atmosphere all around the Earth at or above this altitude, it would lead to about one such particle being accelerated upward to escape velocity every second. To see this another way, if we ask what is the smallest number of such atmospheric particles that need to be found at this altitude at any given time, so that there is a chance that at least one particle attains upward speed around escape velocity level within the course of one year, we find this requires as little as one particle in every  $10^7 \mathrm{m}^2$ surface area of the atmosphere at or above this altitude. Note that for atmospheric particles up to radius  $r_p \lesssim 10^{-4} \mathrm{m}$ the estimate for the rate R goes down by only a factor two or so. For atmospheric particles bigger than this, the rate then decreases by a few orders of magnitude for each order of magnitude increase in radius. This is because the particle flux of space dust of radius bigger than around a millimeter decreases significantly.

In the above analysis, the focus was on small sized space dust in the micron to millimeter range, but the same basic idea will extend to other sized space dust and meteoroids. For example there will also be on roughly a daily basis the few larger centimeter to meter sized meteoroids grazing past the Earth Flynn [11], Plane [30]. For those grazing above  $\approx 150 \,\mathrm{km}$ , such meteoroids could collide with particles in the atmosphere and send them out into space. Its possible in such cases that the atmospheric particles may even attach to the grazing meteoriod, adding the bonus of further protection once in the harsh space environment. Also sizeable space dust flux has been measured down to nanometer and smaller sizes Carpenter et al. [5], which could impart momentum on similar or smaller sized particles, such as molecules or tiny microbes, in the higher atmosphere.

## D. Planetary escape of atoms and molecules comprising the higher atmosphere

Hypervelocity space dust also has a role in the collection and exchange of chemical constituents amongst planetary atmospheres. This has similarities to the impact ejection mechanism de Niem et al. [9], only here for smaller scale fast dust particles. At altitudes above where it can abalate,  $\approx 130 \, \mathrm{km}$ , an Earth-grazing space dust particle can collide with the elements and molecules in the atmosphere, which could stick to it and get carried out to space. At lower altitude, the space dust will abalate or fall to the Earth, releasing all its content, amongst which the lighter elements collected from that dust particle's journey to Earth will disperse into the atmosphere. To get some idea of scale, for a space dust particle of radius  $r_s$ , if it travels a distance d at altitude around z through the atmosphere of density  $\rho_a(z)$ , it will sweep through an amount of mass  $\Delta m = \alpha \rho_a(z) 4\pi r_s^2 d$  in the air, where  $\alpha$  is the fraction of the atmospheric elements and molecules that stick to the space dust particle. The maximum mass will be swept where  $\rho_a(z)$  is largest, thus at the lowest possible altitude safe from abalation, so somewhere around  $130-150 \, \mathrm{km}$ . Moreover

once above around 150km, the atmospheric density requires an altitude increase of around 50km to decrease by an order of magnitude Brekke [4]. As such, most of the mass swept from the atmosphere by space dust will occur in the altitude range between around 130-200km. Evaluating the density at  $\rho_a(150\text{km})$ , setting d=50km, and  $\alpha=1$  gives  $\Delta m = \rho_a(150\text{km})4\pi r_s^250\text{km}$ . Multiplying by the flux of space dust with some upward velocity over the surface of the Earth at this altitude,  $f_u 4\pi R_e^2$  and adding up the contribution over all sizes of space dust, we find the mass of air collected by space dust and escaping to space is around  $10^{-2}$ g every second. This can maybe increase by another order of magnitude by estimating at a slightly lower altitude like 130km or extending the distance d.

The thermosphere region dominantly contains oxygen, nitrogen and helium, so these will be the main elements that will be swept up by space dust. The amount escaping is much less than the approximate 3 kilograms of hydrogen escaping every second, but for these heavier elements this space dust mechanism would be competitive or even dominant to Jeans escape and other mechanisms *Hunten and Donahue* [20], *Zahnle and Catling* [50]. Escape via space dust will propel these elements at high speed into space. Eventually they could reach other terrestrial bodies, thereby providing an exchange mechanism for atmospheric elements amongst planets. During the long transit time through the Solar System and beyond, space dust will also collect the light elements, mostly hydrogen, that are present in dilute quantities in space. The space dust will then deliver all these light elements/molecules to the host planetary object it eventually crashes into at journey's end. One possible consequence is smaller terrestrial bodies may beable to sustain their atmospheres longer because the incoming space dust keeps reintroducing light elements.

### E. Discussion of mechanisms pushing small particles from lower to higher atmosphere

For small, micron sized particles, there are several mechanisms that have been discussed in the literature that can push them from the lower atmosphere up to the higher attmosphere, where a collision with fast dust conceivably could then thrust them into space. We will review some of these possibilities. However first, let us explore another such mechanism which so far has not been explored, following the same theme, that of space dust colliding with particles at lower altitudes and pushing them upward. From our earlier estimates of allowed particle speeds, we see at lower altitudes drag and heating will inhibit small sub-millimeter sized particles from acquiring anything even close to the escape velocity range. Equivalently, fast space dust, as it comes down into the lower atmosphere will also heat up and slow down. The heating will cause this dust to fragment. Detailed estimates of ablation show than once the radius of the fast moving space dust is below around  $\approx 10^{-6}$ m, the particle becomes efficient enough to radiate its heat and it seizes to ablate Correira et al. [6], Hughes [19], Plane [30], Whipple [45]. If it is assumed the entire flux of space dust by the time it reaches the lower altitudes below 100km has fragmented into particles of radius  $10^{-6}$ m, based on the flux data in Carpenter et al. [5], Flynn [11], Kyte and Wasson [23], Love and Brownlee [24], Plane [30] we estimate the flux below this altitude would be  $0.1 \text{m}^{-2} \text{s}^{-1}$ . This is a crude model, but it should allow us to make some initial estimates. For altitudes around 50km or below, atmospheric drag forces will prohibit particles from gaining speeds beyond tens of m/s, thus attaining very little increase in altitude and quickly succumbing to the downward force of gravity. At or above 85km our estimates on drag and heating show that a single collision with space dust could thrust a small atmospheric particle of radius  $\approx 10^{-6}$ m up to 150km. This is interesting, since up to this altitude there are mechanisms such as volcanic eruption that at least in rare cases are known to propel particles, and its an altitude at which small particles are observed such as those helping to form noctilucent clouds Ludlam [25]. At 85km altitude  $\sqrt{2z/R} = 0.16$ , so the upward flux of the space dust we estimate to be  $f_u \approx 2 \times 10^{-2} \text{m}^{-2} \text{s}^{-1}$ . If the number density of atmospheric particles of radius  $\approx 10^{-6}$ m at altitude a few kilometers thickness around 85km were  $\approx 1/\text{m}^3$ , then our estimates show the space dust collision mechanism could push enough particles up to altitude 150km to attain the minimum density up there to allow, based on our earlier calculation, for the chance of a second collision to propel at least one such particle free of the Earth's gravity in a year.

To make further progress with these estimates, a better understanding of the distribution of small particles in the atmosphere is needed. Up to the middle of the stratosphere, so altitudes up to 35km, various measurements have shown there are small particles of radius within an order of magnitude range of a micron and in concentrations within a couple of orders of magnitude of one per cm<sup>3</sup> Heintzenberg et al. [15], Rosen [36], Ursem [42], Xu et al. [48], Yin et al. [49]. Measurements have even shown that amongst the particles are bacteria Griffin [13], Ursem [42], Wainwright et al. [44]. At the upper end of the troposphere at around 10km altitude after hurricanes, bacteria number concentrations were found to be as high as  $0.1 \text{cm}^{-3}$  DeLeon-Rodriguez et al. [8]. Even higher up at 41km, bacteria have been detected Ursem [42], Wainwright et al. [44]. Further up noctilucent clouds at altitudes of 80 - 100 km provide evidence that small particle matter must reside, although the origin of particles this high up is argued both as terrestrial and from space dust Dehel et al. [7], Ludlam [25], Rohatschek [35], Ursem [42], Wainwright et al. [44].

There also are various mechanisms that to varying degree are known capable of sending small particles high up into the atmosphere. Hurricanes and other strong weather activity can thrust particles up the troposphere. Volcanoes can thrust ash well into the stratosphere *Tupper et al.* [41], *Wilson et al.* [46]. From the powerful eruption by Krakatao

in 1883 Self and Rampino [38], Verbeek [43] there are suggestions that dust from the volcanic ash diffused up to 85km and has been regarded as a source for noctilucent clouds that appeared at the time Ludlam [25]. Blue jets and sprites from the tops of thunderclouds in the troposphere have speeds in the thousands of meters per second so offer a powerful source to thrust particles upward into the stratosphere or higher Pasko et al. [28]. The process of gravito-photophoresis, arising from irradiation of particles by sunlight, has been shown can elevate micron scale particles to altitudes upward of 80km Rohatschek [35]. Mesospheric and thermospheric upward vertical winds have been measured in the tens to hundreds of m/s Eswaraiah et al. [10], Kurihara et al. [22], Rastogi and Bowhill [33], Rees et al. [34], Woodman and Guillen [47]. These mechanisms along with space dust collisions in the lower atmosphere seem suggestive that some micron sized particles can get pushed up well into the thermosphere.

#### F. Shock pressure during collision

Another concern for this mechanism is, if atmospheric particles are thrust into space by a hard collision, if any microbes are present in those particles can they withstand such powerful hits. The possibility for such atmospheric particles to to be destroyed through processes like fragmentation and vaporization are not too significant up to collision speeds of interest here  $\stackrel{<}{\sim} 50 \mathrm{km/s}$  Borkowski and Dwek [3]. However the shock pressure created during such collisions is a concern, with studies showing that bacteria can survive collisions with shock pressure at least up to 50GPa Price et al. [31], Stöffler, et al. [39]. For an initially stationary atmospheric particle or radius  $r_p$ , if it is impacted by another particle at velocity  $v_s$ , the collision time would be approximately the time it takes the impinging particle to travel the size of the initially stationary particle,  $\Delta t \sim r_p/v_s$ . If the stationary particle emerges from this collision with velocity approximately the same as the incoming particle, then the force from this collision would be  $\Delta p/\Delta t = m_p v_s^2/r_p$ , where  $m_p = 4\pi r_p^3 \rho_p/3$  is the mass of the stationary particle and  $\rho_p$  its density. So the approximate shock pressure on the particle would be  $\sim 4\rho_p v^2/3$ . For a particle emerging at velocity 11.2km/s and  $\rho_p = 2 \times 10^6 \text{g/m}^3$  this leads to a shock pressure of  $\sim 3 \times 10^2$  GPa, which is less than an order of magnitude higher than the survival limits tested so far. If imparting only the velocity needed to reach an orbit around the Earth  $\approx 7.8$ km/s is considered, it leads to a shock pressure  $\approx 10^2$ GPa, which is within a factor two of the survival range from the tests that have been done. If the particle is already moving fast and just needs an increase in velocity of a few km/s to reach escape velocity, then the shock pressure would be well below 50GPa. Also if the collision is with a particle containing many microbes packed together, some may absorb the main impact of the collision, while leaving others intact. Moreover if the organisms undergoing the collision are in an anhydrobiotic state, they would better withstand the shock pressure and in addition would be greatly reduced in mass, so also making it easier to accelerate them to high speed. From these considerations we find that the impact shock is a key limiting factor in controlling the amount of microbial life that will be able to escape the Earth from fast space dust collisions.

#### III. DISCUSSION

Should some microbial particles manage the perilous journey upward and out of the Earth's gravity, the question remains how well they will survive in the harsh environment of space. Bacterial spores have been left on the exterior of the International Space Station at altitude  $\approx 400 \, \mathrm{km}$ , in a near vacuum environment of space, where there is nearly no water, considerable radiation, and with temperatures ranging from 332K on the sun side to 252K on the shadow side, and have survived 1.5 years Horneck et al. [17]. Other experiments with bacteria Horneck et al. [18] and lichens Sancho et al. [37] have shown survival of these organisms also openly exposed to the vacuum of space, with its radiation and extreme temperatures. A small invertebrate animal, the tardigrade is even more resilient, surviving extreme temperature, heat, pressure, and radiation Horikawa [16] and has been shown to survive in space Jönsson et al. [21]. Thermophiles are known to survive in temperatures reaching up to 400K Takai et al. [40]. Thus for microbes that manage the hypervelocity escape from the Earth, it seems some would be hardy enough to also survive in the region of space nearby Earth. If these microbes continued to journey further out in the Solar System, radiation levels would decrease but temperatures would get much more cold down to 40K at the outer part of the Solar System. Tardigrades have been tested and shown to survive at liquid nitrogen temperatures 77K Ramlov and Westh [32] and even near absolute zero Berquerel [2]. Note that further tests of microbes at very low temperatures and for long duration could be done at the Large Hadron Collider facility at CERN, which has a functioning cryogenic unit containing liquid helium cooled down to 1.9K.

If biological constituents have been escaping the Earth continuously, even in tiny amounts, over its lifespan, then it would suggest floating out in the Solar System there is information about the evolutionary history of microbial life over the time of the Earth's existence. Once a particle escapes from Earth, it could circulate around the Solar System, possibly eventually landing on another planet or even returning back to Earth. Such a particle would have

a much better chance for survival if upon escape, it was quickly swept up by an oncoming comet, asteroid or other near Earth object. Even if the escaped particle only contained organic molecules or microbes that were killed on their journey out of Earth, such complex organic systems may still act as blueprints in suitable environments to speed up the development of life through assisting self-replication, self-organization, abiogensis and various other potential mechanisms.

Once atoms, molecules or even bigger sized particle escape from Earth, they could still remain within the gravitational bound of the Solar System and circulate around, possibly eventually landing on another planet or even returning back to Earth. Another possibility is the particle gains enough speed to leave the Solar System altogether. Since the Earth is rotating at  $\approx 30 \text{km/s}$  around the sun, a particle escaping the Earth generally would emerge with speed in the tens of km/s. If the speed exceeds around 42km/s, it would be fast enough, if unencumbered and headed in the right direction, to escape the gravitational bound of the Solar System. Upon emerging from the Solar System, such a particle could still have a speed in the same order of tens of km/s, so that over the lifespan of the Earth of four billion years, particles emerging from Earth by this manner in principle could have travelled out as far as tens of kiloparsecs. This material horizon, as could be called the maximum distance on pure kinematic grounds that a material particle from Earth could travel outward based on natural processes, would cover most of our Galactic disk, and interestingly would be far enough out to reach the Earth-like or potentially habitable planets that have been identified. As such, these estimates show the exchange of atoms, molecules and even small biological constituents amongst these distant Earth-like planets, can not on kinematic grounds be entirely excluded. Numerical studies show it would be extremely improbable for a meteorite originating from a planet in one solar system to fall onto a planet in another Solar System Melosh [27]. The same conclusion is likely to follow for the small particles propelled into space by the space dust collision mechanism we are considering in this paper. Moreover the long time spent in the harsh space environment in such distant journeys would lead to considerable exposure to radiation and cosmic rays that most likely would destroy any biological life. It is possible that some of the organic molecules contained in these small particles may survive. Their unique sequences coming from different stellar systems could therefore intermix and have some influence in the development of biological processes amongst distant solar systems.

Collisions of huge meteorites with the Earth are a well known mechanism for raising large amounts of material from the Earth out into space, some of it possibly containing microbial life Gladman et al. [12], Melosh [26]. Although this is a potential mechanism for throwing microbial life into space, it occurs very rarely, on geological time scales. This microbial life once in the harsh space environment would have the best chances of survival if around the time of the impact other near Earth objects, like asteroids, comets etc..., in the Solar System were also sweeping past the Earth and collected the microbial debris, thus helping to protect this life and facilitate its transfer to larger planetary bodies. In contrast, the mechanism suggested in this paper at best could propel only a small amount of Earth's biological constituents into space. However the influx of space dust is continuous, so the process of expelling particles could occur more frequently and so possibly increasing the chances that some of it is collected by an asteroid, comet or other near Earth object as it comes past the Earth. Note that if this space dust collision mechanism succeeded to propel just one small particle containing life from a planetary system like Earth into space even just every several thousands of years, that still implies that many such events would have occurred over geological timescales. The key estimate made in this paper is that even for a vanishingly small concentration of small particles harboring microbial life in the upper atmosphere, the space dust collision mechanism still provides the possibility for several escape events over geological timescales.

Huge amounts of microbial life need not have to escape from Earth, but what is equally important is that they escape at the right time, so as to be collected by a body that can allow that life to flourish and multiply. Also the space dust collision mechanism proposed here is as likely to be occurring in the present as in the past. As such it can be tested as it occurs in the present rather than requiring the modelling and assumptions needed for testing huge meteor strikes from the distant past. However for both mechanisms, whether huge meteor stike or space dust collision, there is the common concern whether microbial life can survive the impact of the collision. Just as many investigations have gone in studying the meteor mechanism, much more investigation will be needed for the space dust mechanism proposed in this paper. This paper has made order of magnitude estimates. For the application to the escape of atoms/molecules forming the atmosphere and the escape of bigger particles, better modelling of Earth-grazing space dust flux would improve our estimates. In addition, for the application to the escape of larger particles, more information is needed about the density of small, micron sized and larger, particles in the mesosphere and higher. Direct measurement of the density of such small particles in the higher atmosphere, into the mesosphere and above, would benefit not just the further development of this mechanism but would provide further knowledge about the constituents making up the atmosphere, which may be useful elsewhere such as climate science. Collecting particles by high altitude balloons, sounding rockets, or higher up at 400km by the International Space Station are possibilities. Conceivably the vast amount of man-made space junk orbiting around the Earth, primarily at altitudes around 750km, would contain useful information about both the incoming flux of space dust and outgoing flow of small particles from Earth. Since some of this debris has been orbiting for decades and the over million objects are distributed all around the Earth, they contain long time and spatially well distributed information. Possibly microbes have even become housed in some of it, albeit in a dormant state, or complex organic molecules can be found there. Remote analysis of this space junk and conceivable retrieval of some of it in the future would allow assessing its science content.

The influx of hypervelocity space dust creates huge and sustained momentum flows in the planetary atmosphere. This paper is the first to observe that fast space dust particles inevitibly will sometimes collide with particles residing in the atmosphere and cause them to be moved around and may thrust some out into space. Hypervelocity space dust is a unique entity in planetary systems like our Solar System, which is able to go past and enter the atmosphere of planets, collect samples of those planets and deposit samples of other planets. The entire system of fast space dust in a planetary system thus contains the atoms, molecules and possibly even microbial life, from all the planets and provides a means to mix them up amongst the different planets. For collecting atoms and molecules that form atmospheres, the mechanism proposed in this paper is fairly straightforward. For collecting life and life related molecules this mechanism has interesting features, but many detailed issues would still need to be studied. The violent collisions involved in this mechanism could make it difficult for life to remain intact. There are several possible collision scenarios that would all need to be explored to get a definitive answer to this problem. But even if life itself does not remain intact, it could still permit the complex molecules associated with life to get propelled into space, and that is also interesting for the panspermia process. Since space dust is ubiquitous all over the Solar System and is believed to exist in interstellar and probably intergalactic space, the mechanism proposed in this paper for propelling small particles into space could provide a universal mechanism both for the exchange of the atomic and molecular constituents between distant planetary atmospheres and for initiating the first step of the panspermia process.

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