A PANSPERMIA ORIGIN FOR VENUS CLOUD LIFE.

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Introduction: Panspermia is the idea that life can originate on one planetary body and then be transferred to other bodies [e.g., 1, 2]. Impacts are often the suggested method for transfer, as they can eject material containing microbial life into escape trajectories, which can then impact other bodies. Panspermia is perhaps most often discussed regarding the transfer of life between Earth and Mars (in both directions). Here we investigate the (relatively fraught) possibility of delivering Earth-life to the clouds of modern Venus.

Regardless of its destination, organic material must survive its ejection and interplanetary transfer for panspermia to occur. Life experiences several potential sources of trauma, including shock, heating, and radiation. However, past work has shown that all these obstacles are surmountable. Once reaching Venus, microorganisms must be dispersed in or above the clouds if they are to retain the possibility of survival. Izenberg et al. (2021) [3] presented the "Venus Life Equation" as a framework for calculating the probability of modern life as a product of three component probabilities: origination, robustness, and continuity. Panspermia can increase the first term—origination, the probability that life started on Venus. We compute the fate of a bolide that enters Venus's atmosphere, focusing on its ablation, explosion, and fragmentation into pieces that can float in the clouds.

Methods: In this study, we use the pancake model, which treats a bolide as a single body that deforms continuously due to fragmentation and aerodynamic forces. The pancake model is a popular semi-analytic method to describe a bolide's passage through the atmosphere. Starting at the top of the atmosphere, bolides ablate and fragment. Aerodynamic drag spreads these fragments horizontally, forming a "pancake" with an increased effective cross-section, causing rapid deceleration. An airburst occurs when the bolide deposits its highest amount of kinetic energy into the atmosphere. We used our version of the pancake model to explore the outputs from a wide range of input parameters. We tested bolides ranging in mass from 10^2 to 10^{15} kg, assuming a constant density of 3,000 kg/m^3. In comparison, lower-density bolides would have larger diameters associated with a given mass, meaning that they would tend to experience more aerodynamic drag and airburst at slightly higher altitudes.

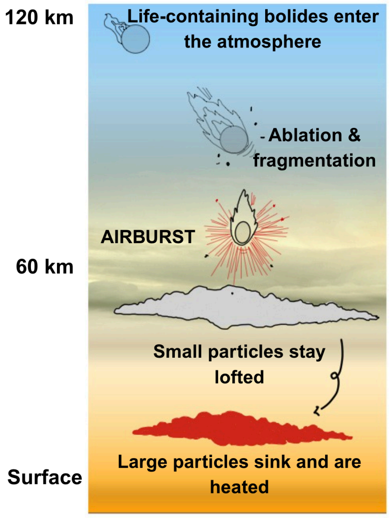

Figure 1: Our cartoon depiction of a meter-sized bolide's journey into the Venusian atmosphere, where it will ablate, fragment, and eventually airburst, causing it to disperse in small particles that can remain lofted in the clouds and potentially disperse life.

Using the output of the pancake model and prior studies, we calculate the total number of viable cells delivered from Earth or Mars to the clouds of Venus:

$$N_{cells} = \rho_{cells} \times m_{Venus} \times f_{cool} \times f_{dispersed} \times f_{survival} \quad (1)$$

Here, N_{cells} is an absolute number of cells delivered over a certain period, while ρ_{cells} is the mass density of cells (i.e., in cells/kg) in the material ejected from the original planet (i.e., either Earth or Mars), accounting for losses during the interplanetary transfer. Then, m_{Venus} is the total mass of material (i.e., in kg) from those planets that reaches Venus without being sterilized during ejection or the interplanetary transfer. Next, f_{cool} (unitless) is the fraction of that mass that ablation does not vaporize during atmospheric entry or heat enough to cause thermal sterilization. The term $f_{dispersed}$ (unitless) is the fraction of the non-ablated mass that is dispersed in pieces small enough to have residence times of at least several days in the clouds. Finally, $f_{survival}$ (unitless) is a critical term with a value between 0 and 1, which describes the cell's potential for adaptation to the new environment of the Venusian atmosphere. We assume $f_{survival} \sim 0.1$ for illustrative estimates. Overall, panspermia is potentially viable if the final value of N_{cells} is very large—and if an analogous calculation suggests that *individual* bolides (meter-sized) can deliver ≥1 potentially viable cells.

Results: Each of the parameters in our equation has substantial uncertainties and requires distinct methods to estimate. This project focuses on atmosphere-impactor interactions, so we adopt values for the first two terms (cell density and mass ejected from Earth to Venus) from prior studies [4], [5]. For our result. We assume ρ_{cells} is $\sim 0.5 - 1 \times 10^9$ cells/kg [4], m_{Venus} is $\sim 8.9 \times 10^{12}$ kg [5], f_{cool} is ~0.4, $f_{dispersed} \sim 10^{-10}$, and $f_{survival}$ ~0.01. With these values, we find

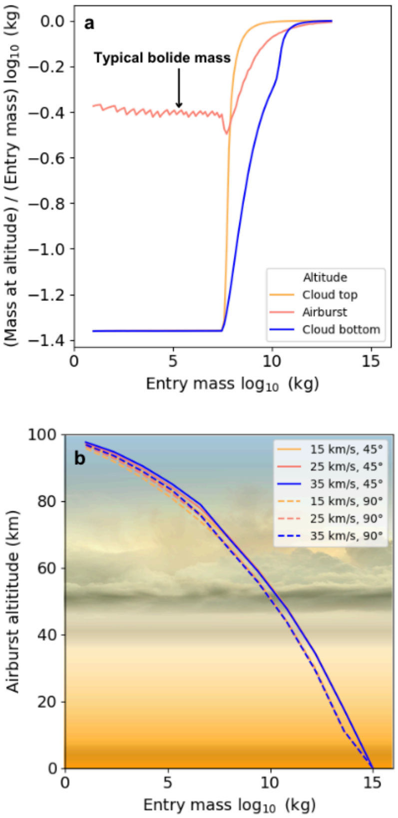

Figure 2: Simulations showing the fate of bolides entering the Venusian atmosphere. Figure 2a shows mass lost to ablation for bolides with densities of 3,000 kg/m^3 with entry velocities of 25 km/s at an angle of 45^o to the horizontal. Each curve represents the fraction of the initial mass that remains un-ablated at a different altitude: the top of the cloud layers (~70 km, yellow), the mass-dependent airburst altitude (pink), and the bottom of the cloud layers (~40 km, blue). Figure 2b shows the altitudes at which these airbursts occur for a 3-meter, 340,000-kg bolide. Illustration of the atmosphere from [10].

that $N_{cells} \sim 2–4 \times 10^9$ cells. In other words, hundreds of billions of cells may have been transferred from Earth to the clouds of Venus. Even if 99% of these cells are unable to reproduce, we estimate that billions may remain potentially viable.

We can express these quantities in a few different ways. For example, our best estimate is an average of ~100 cells dispersed in the clouds per Earth-year, or ~3000 viable cells per 3-m bolide. Alternatively, over 20 billion cells from Earth could have arrived over the average age of Venus' surface (~1 Gyr). Our study shows that panspermia originating from Earth is a possible source of microbial life in the clouds of Venus. Every billion years, roughly a billion tonnes of material is ejected from Earth and delivered to Venus' atmosphere without suffering thermal sterilization. A small fraction of this material dispersed in small-enough fragments that it can stay lofted within the clouds of Venus for at least days. If a future mission finds life on Venus (e.g., [6]; [7]), then there is a chance that it originated from Earth.

Discussion: Our models do not capture every detail of bolide-atmosphere interactions. For example, heat will diffuse inward from the hot surface of an ablating bolide, causing a nonuniform increase in temperature throughout the bolide. This process could reduce the predicted fraction of the original mass that evades high-temperature sterilization, perhaps by a factor of two. Additionally, we assume that one bolide produces a single cloud of fragments. More realistic models could consider more complex histories of fragmentation. Finally, our estimate of the size distribution of bolide fragments after an airburst relied on an extrapolation of measured values for Earth. While a simple power law might indeed apply to a broad range of fragment sizes, this calculation should be benchmarked via studies of other meteorite falls or more complicated 3D simulations. Still, it is not impossible that panspermia may bring life to Venus. Currently, Venus is classified as Category II under COSPAR planetary protection guidelines [8]. Even if the habitability of the clouds were more broadly accepted, we could keep in mind that panspermia may deliver a higher bioload over time than a contaminated spacecraft.

Ultimately, life has never been proven to exist in the Venusian clouds, but our models predict life may exist there for at least a few days per century, courtesy of Earth.

Ongoing, Bonus Work: Models of bolide-atmosphere interactions have diverse applications outside of astrobiology. For example, a recent study argued that Venus must have frequent lightning below the clouds, if the one claimed detection of NO below the clouds is correct [9]. Such activity could indicate an unexpectedly high amount of aeolian activity or explosive volcanism. Beyond lightning, bolides are the other plausible source of NO in the atmosphere. We can easily use our models to calculate the statistical production rate of NO in the atmosphere of Venus because of bolide-atmosphere interactions. However, our preliminary estimates confirm that bolides are unlikely to produce the claimed amount of NO in the lower atmosphere. Given the profound scientific implications, astronomers should aim to reproduce the NO detection to validate or refute it.

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