Modelling panspermia in the TRAPPIST-1 system

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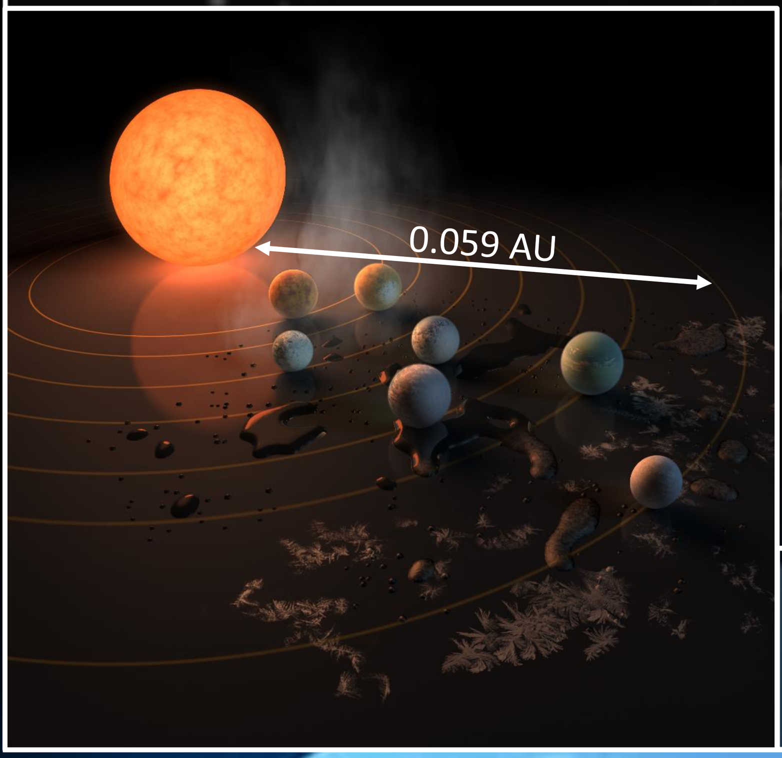
1. What is panspermia?

Panspermia ('seeds everywhere') is the theory that seeds of life exist all over the Universe and can transfer from one location to another. This study focuses on the process of lithopanspermia, where comets and asteroids provide the mechanism for this transfer. Initially proposed by Lord Kelvin in 1871, it is by no means a new idea. However, the recent ground-breaking discovery of seven Earth-sized planets orbiting within the TRAPPIST-1 system has sparked a renewed interest.



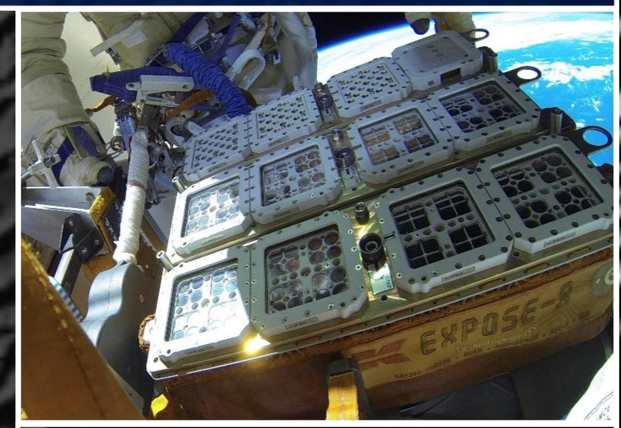
A Python script was created to simulate panspermia in compact planetary systems like TRAPPIST-1, making use of an N-body integrator to investigate its efficiency and success-rate. The program tracks the stellar flux throughout the simulation; an in-depth review of space microbiological literature has been undertaken to convert this to an informed measure of survivability.

An artist's representation of the TRAPPIST-1 system. It's compact, coplanar nature makes it an exciting testbed for the process of lithopanspermia.

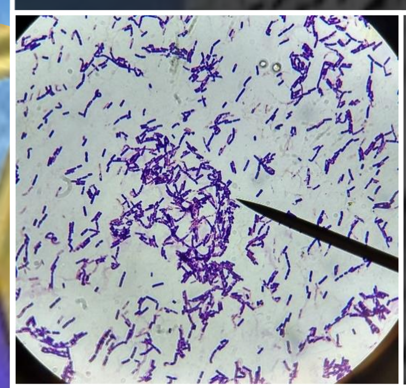
2. Micro-organisms in space

Since the dawn of spaceflight, one of the key questions tackled by astrobiologists has concerned life's resilience against the harsh conditions that exist in outer space. From temperature extremes to radiation with both a stellar and cosmic origin, microbial life would need to withstand a number of damaging factors to survive through the three stages[1]:

1. **Ejection from the original planet;**
2. **Interplanetary transit through space (this work);**
3. **Atmospheric entry upon reaching the new planet.**



The EXPOSE-R facility, providing 22 mths of exposure aboard the ISS (2009 – 2011).



Bacterial spores

- The *bacillus* species of bacteria (among others) is able to form spores, resistant to extreme conditions.
- A survival rate of around 70 % was observed after 6 yrs of exposure in NASA's Long Duration Exposure Facility, when immersed in protective glucose[1].

Lichens

- Composite organisms comprising of symbiotic interactions between fungi and cyanobacteria.
- A full photosynthetic recovery was observed when *X. elegans* and *R. geographicum* were exposed for 14.6 days in the Biopan 5 and 6 facilities[1].

Animals

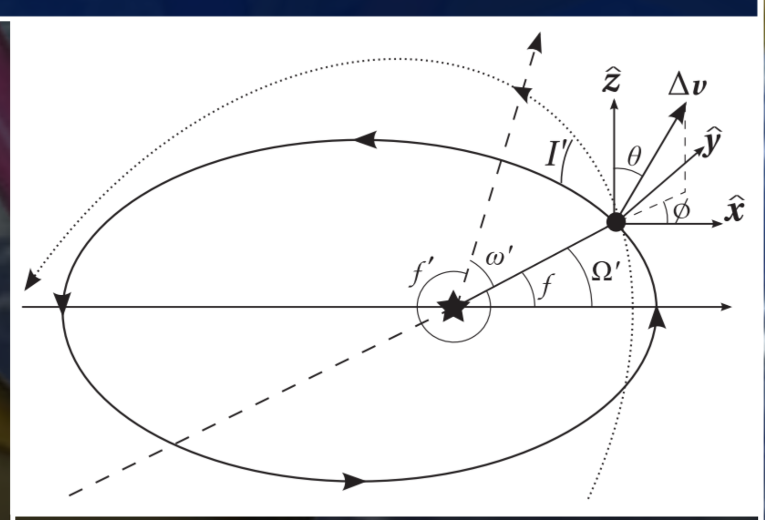
- Tardigrades can withstand large radiation doses up to 5000 Gy.
- Tested in the Biopan 6 facility[1].
- 68 % survived when exposed to the space vacuum for around 10 days, protected from solar UV.

3. Ejecta from an impact event

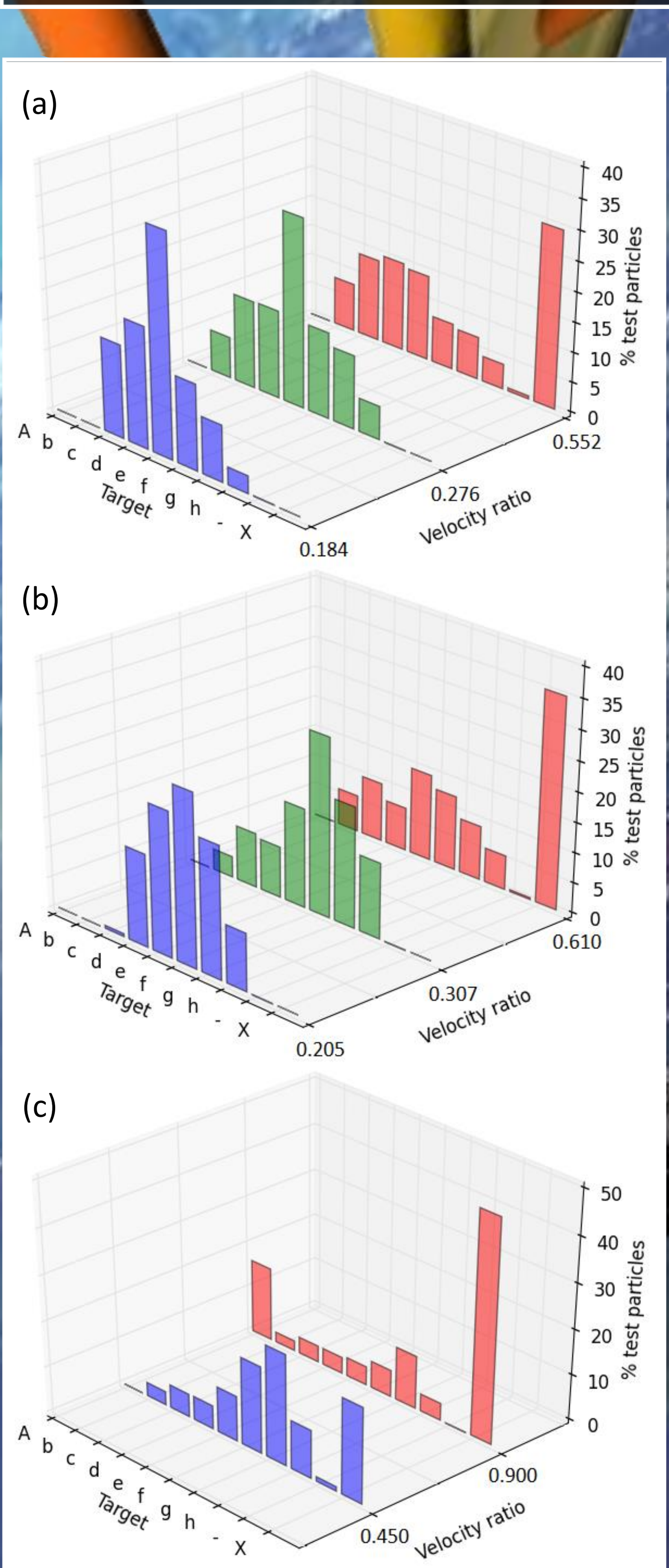
The properties of ejecta orbits that can result from a velocity kick Δv, such as that generated by an impact event, may be derived from the conserved equations[2]

$$\frac{1}{a} = \frac{2}{r} - \frac{v^2}{G(M+m)} \quad | \quad e^2 = 1 - \frac{h^2}{G(M+m)a},$$

with a the semimajor axis, r the distance from star, v the particle velocity, e the eccentricity, h the angular momentum, M and m the masses of the star and particle. The kick is defined by angles (θ,ϕ) – see right.



Orbit of a particle before (solid) and after (dotted, primed) a velocity kick Δv[2].

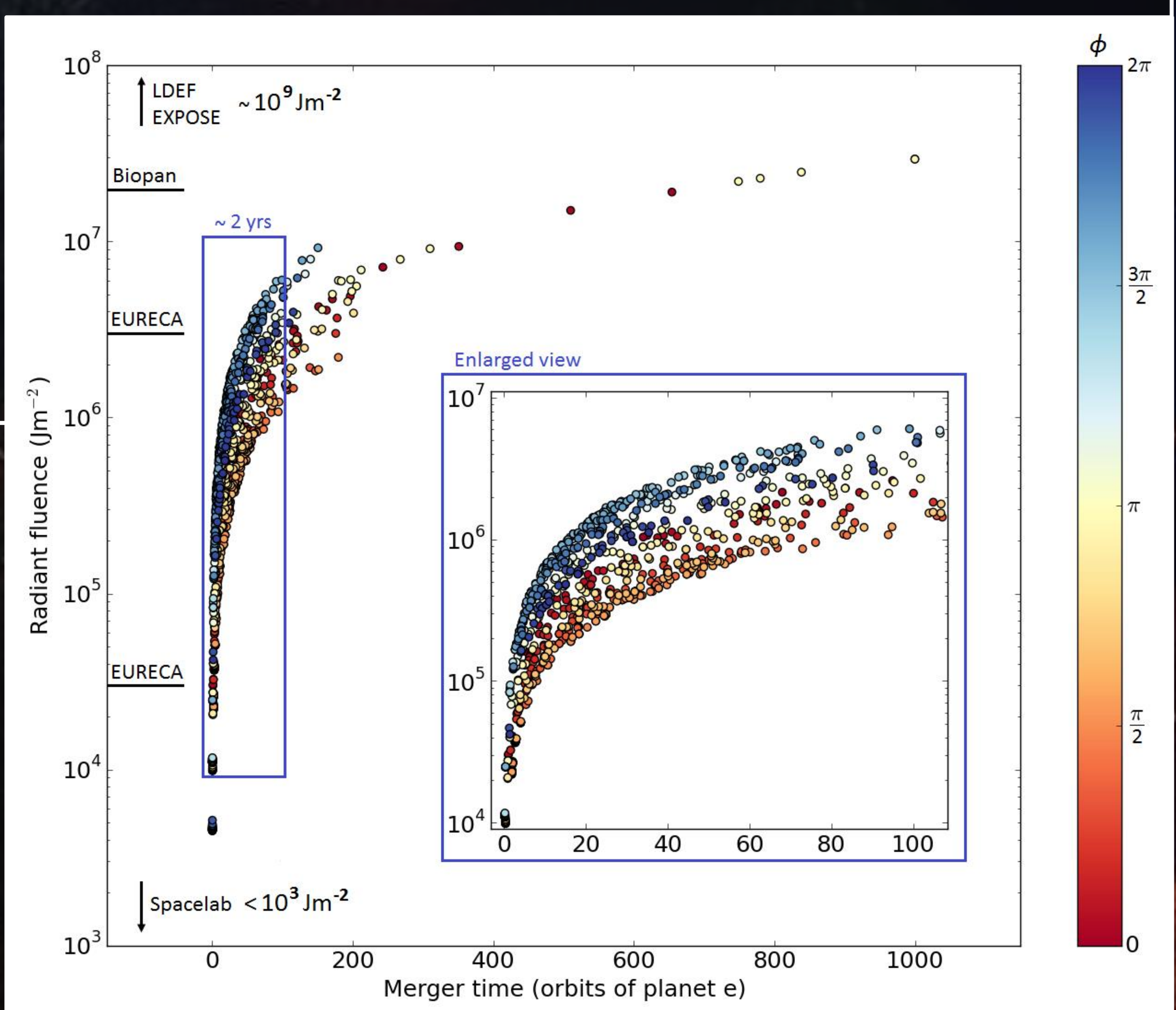


The final destinations of ejecta from (a) planet e, (b) planet f and (c) planet g of TRAPPIST-1 after 1000 orbits of the impacted planet. By this time, the vast majority of particles had either collided or escaped. Target 'A' refers to a collision with the star, whilst 'b' – 'h' refer to a collision with a planet. Escape from the system was defined as reaching one Earth-Sun distance and denoted 'X'. Finally, a target of '-' denotes particles that are yet to collide or escape. The velocity ratio refers to $\Delta v/v_k$, for a Keplerian velocity v_k. All ejecta orbits were coplanar with those of the planets.

4. Results of the simulation

The N-body simulation was run for a number of cases, investigating different ejection sites and kick speeds. Focus was placed on the three 'habitable zone' planets (e, f, g), whilst the speeds used are identical to those considered recently in a study of lithopanspermia in TRAPPIST-1 by Krijt and coworkers, for ease of comparison[3]. In each simulation, 1000 test particles were released from the vicinity of the impacted planet. The simulation currently only concerns itself with ejecta orbits that are coplanar with those of the planets (θ = 90°), as these are most likely to undergo fast lithopanspermia.

At each timestep, the distance of each particle from the star was stored, allowing the stellar irradiance to be determined from the dwarf star's spectrum. A merger would take place if the particle-planet separation fell below the Hill radius of the planet, defined as $a(m/3M)^{1/3}$. The fates of the test particles for each case investigated are provided (left). For low-velocity ejection from planet e, the radiant fluence is shown as a function of merger time and angle ϕ (right).



The radiant UV fluence (100 – 400 nm) received by each particle for the case of ejection from planet e at a velocity $\Delta v/v_k$ = 0.184, where v_k is the Keplerian velocity. It is clear that the vast majority (approx. 95 %) of particles collide within the first two years of the simulation. Markers signify the UV doses measured in the following astrobiological experiments[1]:

- Spacelab 1 | *B. subtilis*, survival rate (SR) 10^{-2};
- EURECA ERA | *B. subtilis*, SR 10^{-3} (low dose) or 10^{-6} (high dose);
- Biopan 1 – 3 | *B. subtilis*, SR 10^{-6} (full UV) or 0.5 – 0.97 (shielded);
- Biopan 5 | *X. elegans*, SR 0.83, *R. geographicum*, SR 0.71;
- Biopan 6 | *Milnesium tardigradum*, SR approx. 0.01;
- LDEF | *B. subtilis*, SR approx. 0.7 in presence of glucose and shielded;
- EXPOSE-E | Plant seeds (various), SR up to 0.44.

Test particles are plotted as a function of time taken to merge with a planet (x axis) and ejection angle ϕ (colour scale).

5. Further work

With the simulation in place, other aspects of panspermia in compact exoplanetary systems can now be investigated, such as:

- **generalising the equations to account for eccentric, non-coplanar orbits,**
- **tracking the effects of other damaging conditions, like the space vacuum or cosmic ray radiation,**
- **taking into consideration absorption by typical meteorites,**
- **analysing the effect of asteroid rotation on radiant exposure.**

Acknowledgements

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[1] G. Horneck, et al., *Microbiol. Mol. Biol. Rev.* **74**, 121 (2010)
[2] A. P. Jackson, et al., *MNRAS* **440**, 3717 (2014)
[3] S. Krijt, et al., *ApJ* **839**, L21 (2017)