Impact ejecta in the TRAPPIST-1 system

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OVERVIEW

Impact ejecta transfer between planetary bodies could factor in both **chemical cross-incubation** and **biological cross-contamination** (lithopanspermia). The **TRAPPIST-1 system** is an ideal target for study due to its **compact configuration**. Seven planets of masses 0.3–1.4M_{sun} orbit **within 0.06 AU** of an ultra cool M8.2V dwarf of mass ~0.08M_{sun}. Estimates of planetary density and composition suggest that some of the planets have significant volatile envelopes that could indicate **water layers** or **thicker atmospheres**. At least two planets (c, d) are potentially **within the liquid-water habitable zone**[a]. TRAPPIST-1 is therefore an **excellent template for studying impact ejecta transfer efficiencies in compact planetary systems**. Where previous works have utilized simplified flux calculations[b], we choose to use **high-accuracy integration**, which allows a fine-grained examination of the process, the identification of transfer pathways and/or resonance effects, and is adaptable to other system architectures.

Table 1: TRAPPIST-1 Parameters

name	m ($M_\oplus$)	a ($10^{-2} AU$)	e	i (°)	Ω	ω	M	r ($R_\oplus$)
a	2.99×10^5	-	-	-	-	-	-	1.30×10^4
b	1.374	1.154	0	89.728	1	1	320.23	1.116
c	1.308	1.580	0	89.778	1	1	302.03	1.097
d	0.388	2.227	0	89.896	1	1	-421.18	0.788
e	0.692	2.925	0	89.793	1	1	-270.15	0.920
f	1.039	3.849	0	89.740	1	1	-187.20	1.045
g	1.321	4.683	0	89.742	1	1	-136.97	1.129
h	0.326	6.189	0	89.805	1	1	-89.86	0.755

Table 1. Parameters used for simulating TRAPPIST-1[cd]. Longitude of ascending node and argument of pericenter are set arbitrarily to 1, and eccentricities are set to 0 due to essentially circular orbits.

METHOD

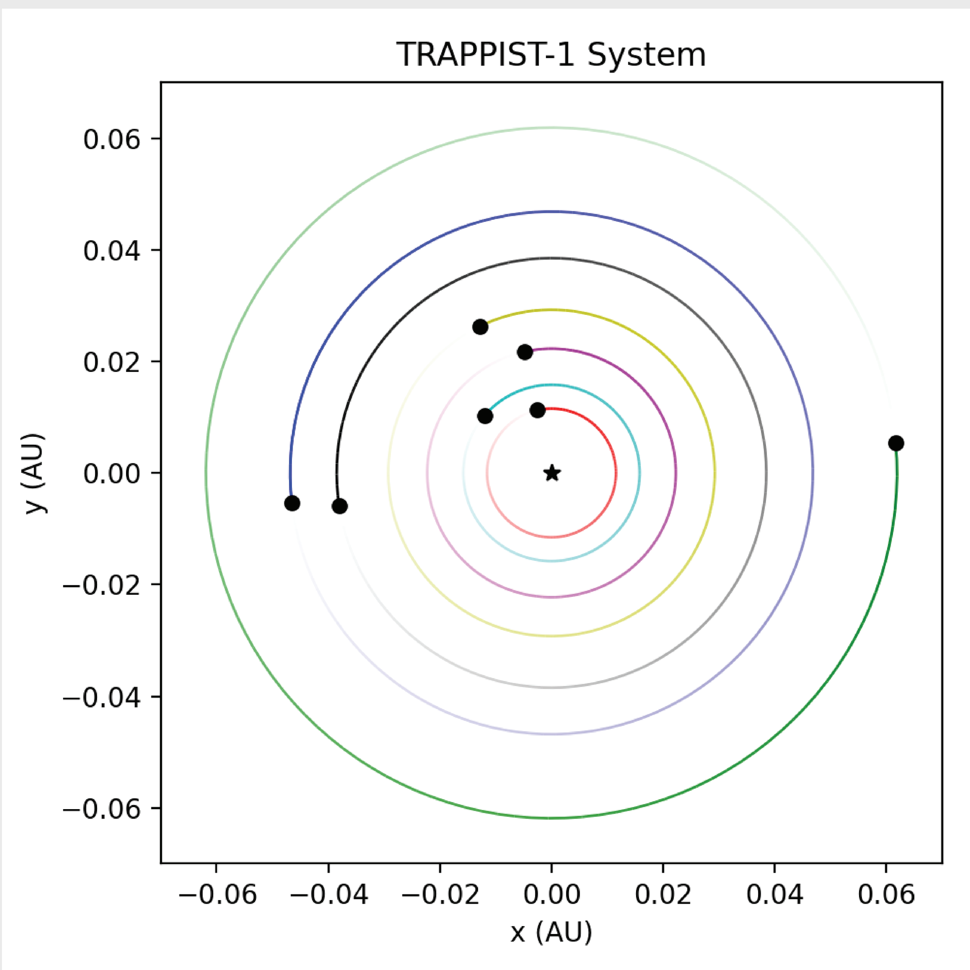


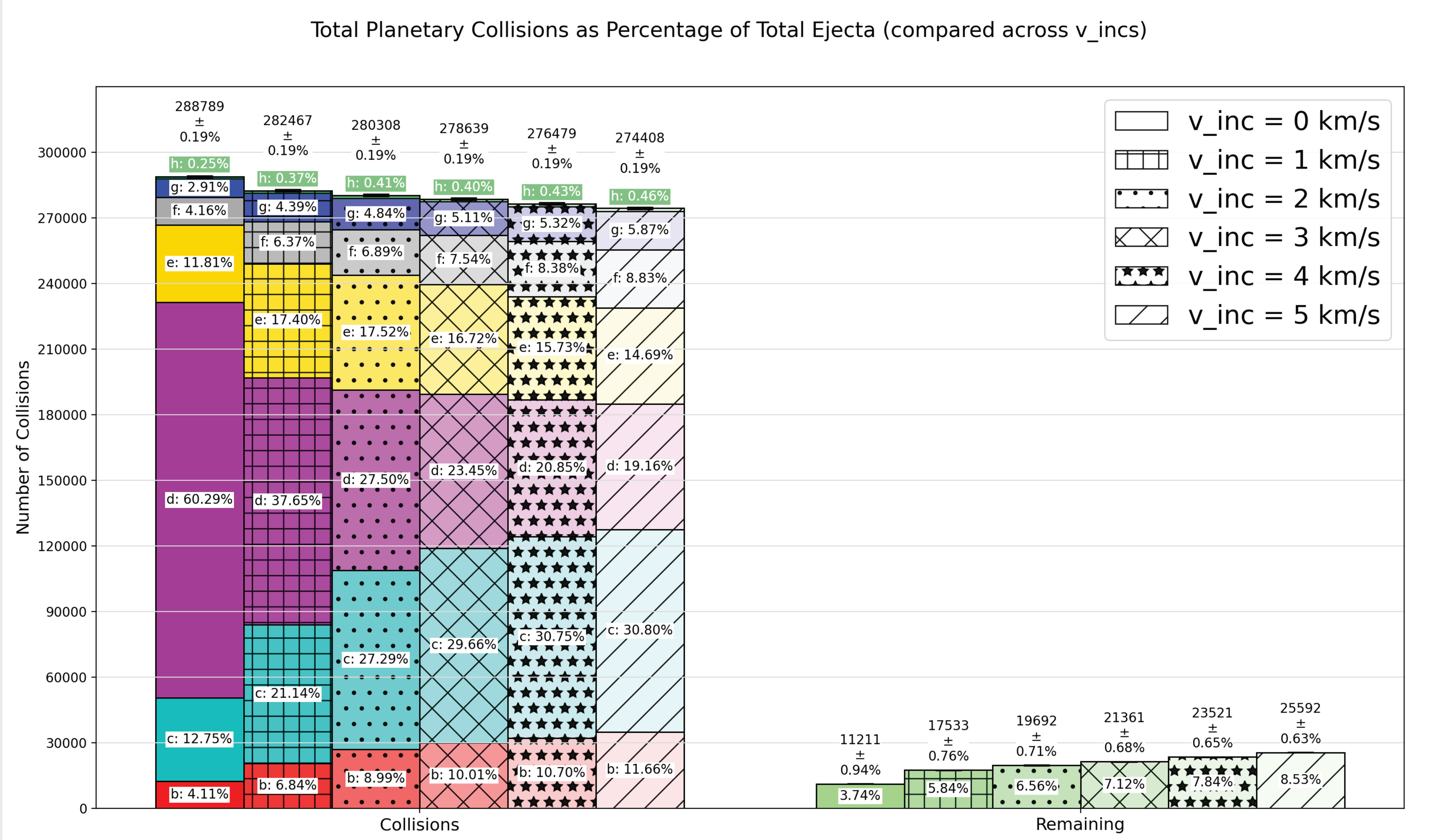
Fig 1. The TRAPPIST-1 system simulated in REBOUND.

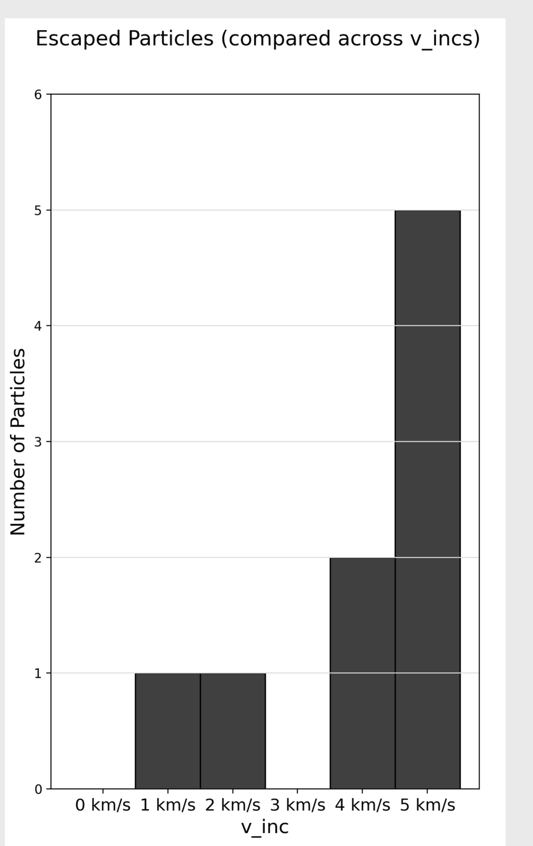
We use Hanno Rein's **REBOUND** N-body integration package[e] with the **MERCURIUS** integrator to simulate ejecta originating from **planet d**. MERCURIUS allows the ejecta to be treated as massless test particles while maintaining accurate dynamics in planetary orbits.

In each simulation, we initialize a **random spherical distribution of 5,000 ejecta at a distance 1km from the surface of planet d**. The ejecta have initial velocities of **v_esc + v_inc** (wrt to planet d) radially outwards, with **v_esc = 7.846 km/s**, the escape velocity at planet d's surface, and **v_inc = [0, 1, 2, 3, 4, 5] km/s**. For each v_inc, we run 60 simulations of 5,000 ejecta each over 2,000 years, using Columbia's terremoto computing cluster. Each aggregated v_inc simulation thus includes **300,000 ejecta integrated over 2,000 years**.

We choose a random distribution of ejecta around the entire surface of planet d to provide a **statistical overview** for all possible impact orientations. After running simulations, the ejecta can easily be separated into specific impact sites for localized analysis.

RESULTS





Figs. 2 & 3. Comparison of ejecta results by percentages across v_incs (categorized by impact with each planet, remaining, and escaped, with escaped particles determined by eccentricity > 1).

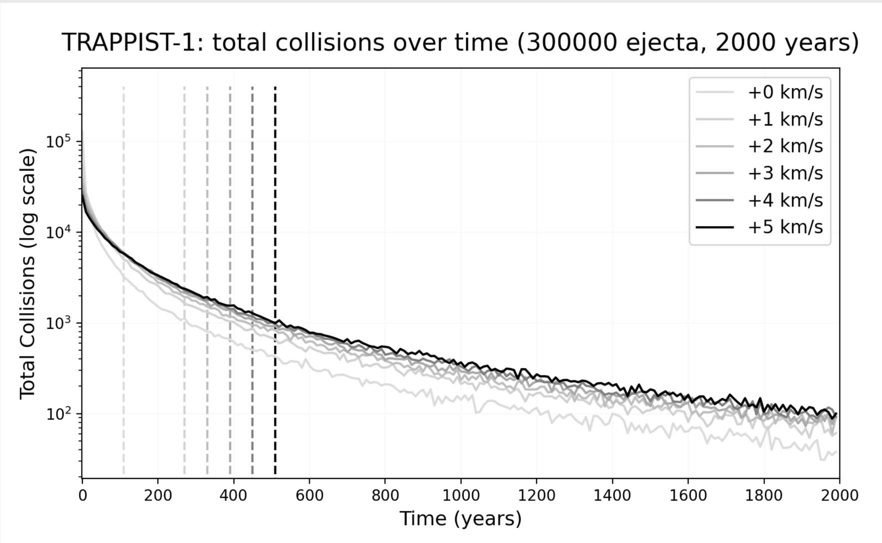


Fig. 4. Comparison of total collisions over time across v_incs, binned in 10-year chunks. Dashed lines show the time at which 75% of all ejecta have impacted.

We find that compact systems like TRAPPIST-1 are **extremely conducive to efficient ejecta transfer**, with **91-96%** of all initial ejecta resulting in impact and **75%** of those impacts occurring within the **first 600 years**. We also find that particles scattered onto interstellar escape trajectories – while statistically insignificant in these quantities – are not out of the question, indicating the possibility to explore **interstellar panspermia** (perhaps with even larger simulations).

With these simulation data, we can rigorously investigate and **parametrize the timescales and efficiency** of ejecta transfer and compare to previous analytic estimates. For example, in Fig. 5 we (roughly) fit the collision vs. time graph for planet b with v_inc = +4 km/s to a double exponential decay.

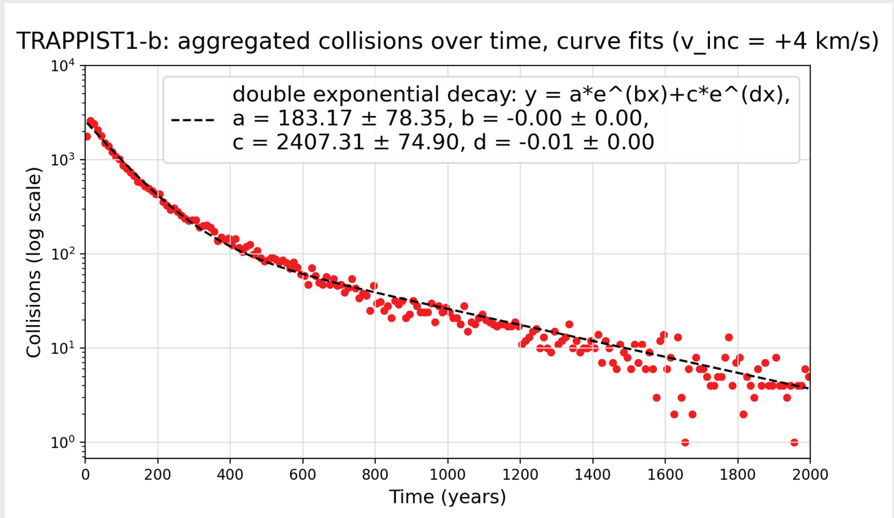


Fig. 5. Double exponential decay fit to the collisions vs. time graph for planet b, with v_inc = +4 km/s, binned in 10-year chunks.

We also investigate patterns in **orbital elements over time**, especially when considering the paths of escaped particles.

Fig. 6.

Fig. 7.

Figs. 6 & 7. QR code links to animations of inclination vs. semi-major axis and eccentricity vs. semi-major axis, respectively, for v_inc = +4 km/s over 2,000 years. All 300,000 ejecta shown, separated by color into planetary collisions/escaped/ remaining.

References:

[a] Lincowski, A.P. et. al. "Evolved Climates and Observational Discriminants for the TRAPPIST-1 Planetary System." ApJ 867 76 (2018)

[b] M. Lingam, A. Loeb. "Enhanced interplanetary panspermia in the TRAPPIST-1 system." Proc. Natl. Acad. Sci. USA (2017 Jun 27); 114(26): 6689–6693.

[c] Gillon, M., Triaud, A., Demory, BO. et al. "Seven temperate terrestrial planets around the nearby ultracool dwarf star TRAPPIST-1." Nature 542, 456–460 (2017).

[d] Agol, E. et. al. "Refining the Transit-timing and Photometric Analysis of TRAPPIST-1: Masses, Radii, Densities, Dynamics, and Ephemerides." Planet. Sci. J. 2 1 (2021).

[e] H. Rein, S. F. Liu. "REBOUND: an open-source multi-purpose N-body code for collisional dynamics." A&A Volume 537 (January 2012)

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