EJECTA TRANSFER BETWEEN TERRESTRIAL PLANETS

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As meteorites from the Moon and Mars continue to be discovered, it is increasingly clear that impact fragments can escape from large bodies more easily than previously believed. These escaping fragments are then subject to the gravitational perturbations of the planets, allowing them to be transferred to a body other than their parent. The lunar meteorites and SNC meteorites prove the plausibility of this process. Warren (1994) summarizes cosmic ray exposure ages and other properties of the lunar and martian meteorites. Their existence confirms that lightly shocked material can be launched at greater than the escape speed of the Moon and Mars.

We study the transfer dynamics by means of N-body simulations, considering the evolutions of impact ejecta escaping from the Moon, Mercury, and Mars. Impact ejection from Venus and the Earth, with their massive atmospheres, is less likely to be feasible. Particles were launched off the target's surface at a variety of velocities slightly above the escape speed. The lunar case is somewhat different, since often the material has first to be followed through a number of geocentric orbits until the particles escape to heliocentric space [here most ejecta ($> 80\%$) are boosted by close encounters with the Moon to speeds sufficient to escape from orbits bound to the Earth]. In all cases, we track the material that reaches heliocentric orbit using a regularized mixed-variable-symplectic integration package. The particles are followed for between 2 and 40 Myr, until they impact a terrestrial planet, cross the orbit of Jupiter, or evolve to a Sun-grazing state.

The transfer of lunar meteorites to the Earth has been addressed previously by Arnold (1965) and Wetherill (1969) with a Monte Carlo model

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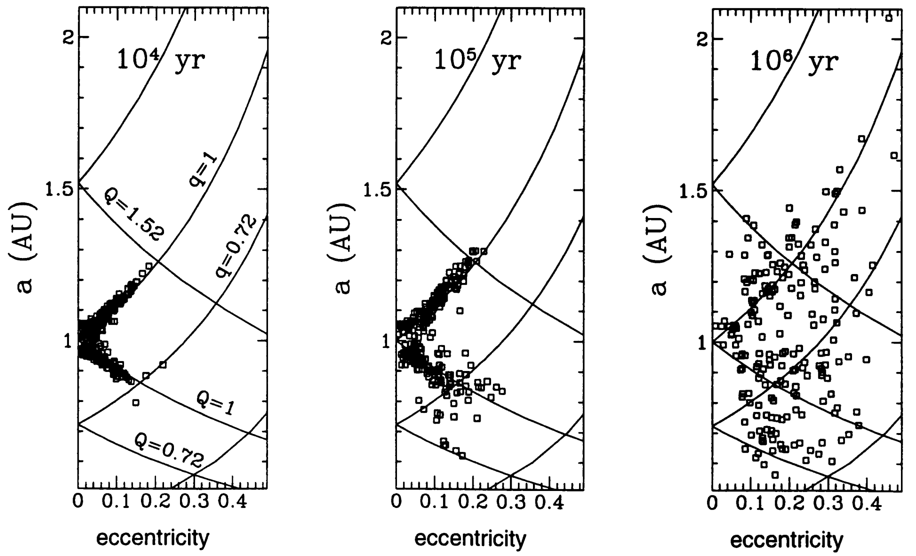

Figure 1. Semimajor axes and eccentricities for particles launched from the Moon at just above the lunar escape velocity. The web of lines marks where the particles' perihelia (q) or aphelia (Q) coincide with the semimajor axes of Mercury, Venus, Earth, and Mars.

using the Öpik collision formulae. Gladman *et al.* (1995) find, as they did, that of the ejecta that just barely escape the Earth/Moon system, about half returns to impact the Earth during 10 Myr. We find that of the Earth impacts that do occur, roughly two-thirds happen within the first 50 000 years, in agreement with the relatively young cosmic ray exposure ages of most recovered lunar meteorites. The early impact rate is very high because the velocities of the escaping particles relative to the Earth are initially low, enhancing the Earth's gravitational cross-section. Within a few Myr, material that does not impact the Earth scatters throughout the inner solar system (see Fig. 1). Over a 10-Myr period the remaining particles continue to collide with the terrestrial planets. Many impacts with Venus, and one with Mars, are observed. After a few Myr, losses commonly occur when orbits become Sun-grazing (with perihelia less than 2 solar radii) as a consequence of entering secular resonances (usually ν_5 or ν_6). Farinella *et al.* (1994) see a similar phenomena for the Near-Earth asteroids.

The transit times of Earth-impacting Martian ejecta may be compared to the age spectrum of the SNC meteorites, which generally have spent less than 15 Myr in space. Yet Monte Carlo simulations (Wetherill 1984) had found a large spread of transfer durations (up to 100 Myr) with only about half being delivered to the Earth in less than 15 Myr. For objects

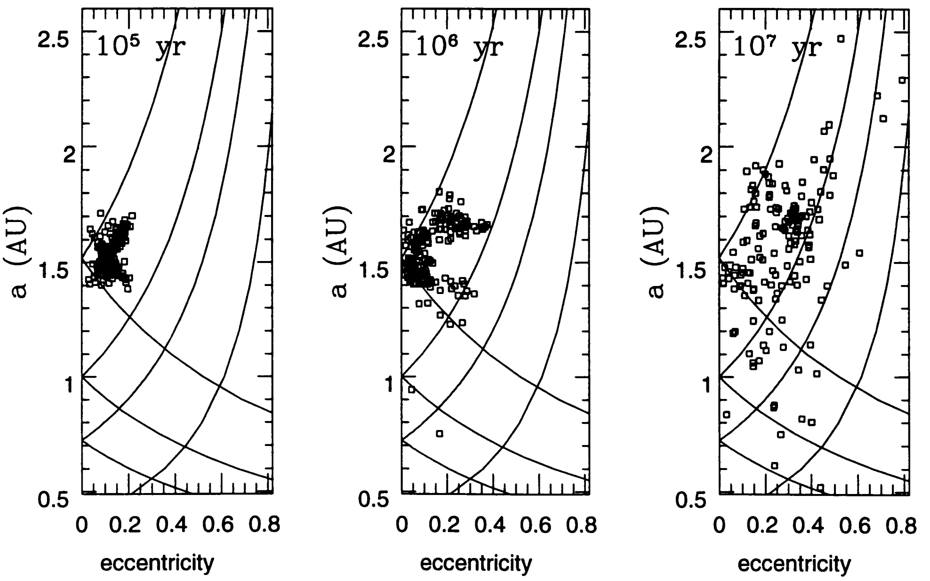

Figure 2. Semimajor axes and eccentricities for test particles launched from Mars at just above the martian escape velocity. The web of lines marks where the particles' perihelia or aphelia coincide with the semimajor axes of Mercury, Venus, Earth, and Mars.

that spend considerable portions of their orbits in the asteroid belt, the Wetherill simulation includes collisional destruction, which might be one way of removing long-lived meteoroids over tens of Myr; however, a decrease in the collisional lifetime by a factor of more than two reduces the yield by only 30%, so apparently collisional destruction is not responsible for the lack of long-lived SNCs. Our numerical integrations (see Fig. 2) show that secular resonances, located throughout most of the inner solar system, are primarily responsible for establishing a relatively short timescale for the delivery of this material to the Earth. They also allow fast transfers even when only very small ejection speeds off of Mars are typical.

We find that, for objects that barely escape Mars (probably the most common case since the amount of ejecta should drop rapidly with increasing velocity), the evolution is divided into three main phases. During the first 2 Myr, roughly 10% of the escaped particles are re-accreted by Mars; after this period few Mars collisions are observed because no longer are the meteoroid orbits sufficiently similar to Mars that the relative velocities (and thus collision time scales) are small. In the second phase, which lasts until about 10 Myr after launch, a variety of removal mechanisms operate: Venus and Earth collisions each absorb 2% of the meteoroids; roughly 1% encounter Jupiter (which we assume removes particles from the system on a short

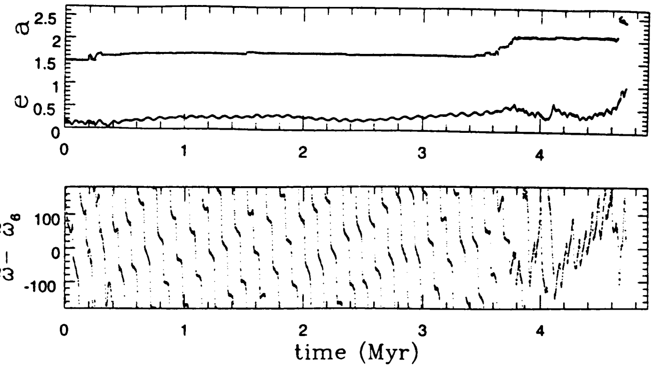

Figure 3. Semimajor axis and eccentricity for a martian ejecta particle that ends its life as a Sun-grazer. Beginning just after 4 Myr from launch the bottom panel shows that the particle is heavily influenced by the ν_6 resonance.

time scale); and the largest fraction (4%) become Sun-grazers (see Fig. 3).

After 10 Myr, the Sun-grazing end-state becomes extremely common, and systematically depopulates the meteoroids, with Jupiter-crossing occurring occasionally, and Earth or Venus collisions happening rarely. By 50 Myr 7%, 7%, and 9% of the initial number of particles particles have struck Venus, Earth, and Mars (respectively), 10% have crossed Jupiter's orbit, and about one third (32%) have become Sun-grazing. Thus perhaps the lack of old SNCs is due to the fact that secular resonances efficiently deplete the remaining meteoroid population by driving them into the Sun.

Three quarters of the material ejected from Mercury is re-accreted by that planet. A small fraction (10%) is driven on Myr timescales to Venus-crossing orbits, where collisions with Venus occur. Transfer of any material to the Earth would require at least 10 Myr, and only a very small fraction, which we estimate should be of order 0.1–1%, of the launched material would arrive (in obvious contrast with the lunar and martian cases). The lack of any discovered mercurian meteorites is thus consistent with what we know about the transfer dynamics.

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