

Delivery of Lunar Meteorites to Earth. Brett Gladman, Joseph A. Burns, and Pascal Lee, Dept. of Astronomy, Cornell University, Ithaca, NY, 14853.

As more and more meteorites from the Moon and Mars are discovered, it is increasingly clear that impact fragments can escape from large bodies more easily than previously believed. For the case of the lunar meteorites Warren [1] has concluded that few, if any, common source craters are plausible; thus at least a half-dozen separate lunar launch events must have occurred in the last million years. Since the terrestrial inventory of lunar meteorites is undoubtedly incomplete, one can argue for a reasonably large injected flux of lunar material into the near-Earth environs. We study the transfer dynamics by means of numerical simulations. We attempt to construct a self-consistent model of lunar meteorite delivery that takes into account the impactor flux, the delivery efficiency, and the statistics of meteorite finds.

To estimate the delivery efficiency, we undertake a detailed examination of the dynamical evolution of escaping lunar ejecta through the use of numerical simulations. We study the evolution of the geocentric orbits (Stage 1) and in then the orbital evolution of particles that escape to heliocentric orbit (Stage 2). In Stage 1, the Moon is randomly bombarded with impactors that eject material at various velocities above the lunar escape velocity (2.38 km/s). A small fraction of this material is delivered directly to the Earth while 80 – 90% escapes (in less than a few decades) to heliocentric orbits, confirming the results of previous work [2]. Depending upon the launch speed and direction, the launched material can impact the Earth or Moon, exit immediately to heliocentric orbit, or barely escape the Earth/Moon system after repeated lunar scatterings.

We track the material that reaches heliocentric orbit (Stage 2) using a regularized mixed-variable-symplectic integration package developed by Levison and Duncan [3]. Of the ejecta that just barely escapes the Earth/Moon system, slightly more than half returns to impact the Earth during 10 million years. For ejecta launched at higher speeds, the fraction of material returned to the Earth in 10 million years drops to about one-quarter. Regardless of the ejection speed, 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 of the recovered lunar meteorites. The rate of impacts is very high early on because the velocity of the escaping particles with respect to the Earth is initially low, enhancing the Earth's gravitational cross-section.

Our simulations show that lunar meteorites strike with equal probability all over the Earth's surface. In the absence of post-landing disturbances, lunar meteorites should be uniformly distributed on the Earth. Hence, the fact that 9 of the 10 recovered lunar meteorites were found in Antarctica reflects a selection bias, not a dynamical effect that would preferentially deliver meteorites to polar regions. The average entry velocities (at the top of the Earth's atmosphere) begin to rise significantly for lunar meteoroids returning after 1 Myr, making later objects somewhat less likely to survive atmospheric entry and be recovered.

Within a few million years, the material that does not re-impact the Earth scatters throughout the inner solar system, as illustrated below. Particles begin on very Earthlike orbits ($a \simeq 1$ AU, $e < 0.1$, $i \simeq 0$) and gradually diffuse through repeated close encounters with the Earth (many colliding in the process). Initially the particles remain on orbits

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which have either their perihelion or aphelion at the Earth's orbital radius because of approximate conservation of the Tisserand invariant. After several hundred thousand years, once the particles begin crossing the orbits of other planets, this behavior is disrupted. After 1 Myr, the surviving particles are roughly uniformly scattered throughout the inner solar system. 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.

Having acquired this understanding of the transfer process, we are now estimating the lunar meteoroid launch rate, at least in the last few hundred thousand years. With some reasonable assumptions, the Antarctic meteorite record reveals what fraction of the incoming meteoritic flux in the 1-1000 gram range is lunar. Combining this with the Canadian camera network data [4] we may estimate the amount of lunar material delivered to the top of the atmosphere. Our dynamical results allow us to convert this into a launch rate of escaping ejecta from the Moon.

Our work supports the idea that, once impact ejecta escape a planet, meteoritic material is redistributed relatively easily amongst the other planets. There are likely pieces of the Moon in near-Earth asteroid orbits, on both Venus and Mars, and beyond.

REFERENCES: [1] Warren, P. 1994. *Icarus*, **111**, 338-363. [2] Gault, D.E. 1983. *LPSC XIV*, Session on meteorites from the Earth's moon, 8-9. [3] Levison, H., and M. Duncan. 1994. *Icarus*, **108**, 18-36. [4] Halliday, I., A.T. Blackwell, and A.A. Griffin. 1989 *Meteoritics*, **24**, 173-178.

Figure: Semi-major axes and eccentricities for the surviving test particles after launch from the Moon at just above the lunar escape velocity. Those that escape to heliocentric orbit first have their random velocities (and hence eccentricities) increased by repeated scatterings by the Earth, until after about 10^4 years they begin to cross the orbits of Venus and Mars. After several million years the surviving particles are spread throughout the terrestrial planet zone. The web of lines marks where the particles' perihelia (q) or aphelia (Q) coincide with the semi-major axes of Venus, Earth, and Mars.

