**TOWARDS A SELF-CONSISTENT MODEL OF LUNAR AND MARTIAN METEORITE DELIVERY** Brett Gladman and Joseph A. Burns; Dept. of Astronomy, Cornell University, Ithaca, NY, 14853.

The lunar and martian meteorites present several puzzles: (1) the equal numbers of each group, (2) the much larger average mass of the martian meteorites, (3) the inferred shallow pre-launch depths of the lunar meteorites vs. the deep ones of the martian meteorites, (4) the prevalence of geologically young rocks amongst the SNCs (even though such terrain is relatively rare on Mars), and (5) the $4\pi$ age spectrum of the martian objects terminates at $\sim$ 15 Myr. We have undertaken detailed numerical studies of the orbital history of meteoroids liberated from these bodies. By comparing these results with the age spectrum obtained from cosmic ray exposure studies of the meteorites, we develop a self-consistent model that can explain the above features, although not uniquely since surface properties of the two targets appear to play a major role.

At the start of 1995 11 lunar and 12 martian meteorites had been recovered, with all but one of the lunar meteorites, and half of the martian meteorites, from Antarctica. This presents a problem, since the transfer efficiency (the fraction of escaping meteoroids that reach the Earth) is much larger for the Moon than for Mars ($\sim$40% as opposed to $\sim$3-6%) [1,2]. Moreover, the lower escape velocity from the Moon suggests that more lunar meteoroids should be liberated in any impact of a given size. The total mass of recovered martian material is $\approx$ 38 times that of the lunar meteorites; this difference, along with the cosmic ray exposure (CRE) data indicating deep (> several m) pre-launch depths, has suggested [3] that the martian meteorites originate in larger impacts than the lunar meteorites. The fact that, of all 12 of the martian meteorites, only ALH84001 appears to come from geologically old terrain, even though only $\sim$ 10% of the martian surface is 'young', indicates that the surface properties of Mars are a major factor in determining its meteorite launch rate.

We have approached the problem by trying to understand the orbital dynamics of the transfer of the escaped meteoroids from their launch sites to the Earth. We launch thousands of particles off the body of interest in random directions and track the resulting particles in full N-body simulations of the solar system. Particles are removed when they impact a planet, cross the orbit of Jupiter, or have their perihelion lowered below the solar radius.

We find [4] that the absolute delivery efficiency of lunar material is between 25% and 50%, depending on the launch velocity. A comparison of the arrival time spectrum of the simulated deliveries to the Earth with the CRE data of the meteorites implies that few meteoroids were launched from the Moon at speeds in excess of 3 km/s, indicating that the velocity spectrum of the escaping ejecta must be quite steep. A steep spectrum implies that the lunar delivery efficiency is about 40% (integrated over the 10-Myr lifetime of the oldest lunar meteorite). The time spectrum of the Earth-arrivals is consistent with a purely gravitational delivery in which collisional effects in space are minor, and almost all of the meteorites originate from different, small, source craters.

We now have similar numerical studies of the martian problem which yield an expected delivery spectrum. We find that the secular resonances in the martian region are absolutely crucial to the delivery dynamics [1]. First, the action of such resonances increases the transfer efficiency since more particles are quickly placed on Earth-crossing orbits. Second, they shorten the available time scale for delivery: a large fraction (more than one-third) of the launched meteoroids are driven into the Sun on 50-Myr time scales. This last process helps deplete the meteoroid population, preventing the existence of long-lived meteoroids (which are not observed). Among the simulated martian meteoroids that spend longer than 15 Myr in space, Lunar and Martian Meteorite Delivery: B. Gladman and J.A. Burns

most reside for many Myr with their aphelia in the asteroid belt (while those that arrive in <15 Myr do not); this should result in their collisional destruction. Our best model, assuming a collisional half-life of 2 Myr in the main belt (for decimeter-sized particles), is shown in the Figure. The model is consistent with all of the martian meteorites spending their entire 4-$\pi$ exposure ages in space as small bodies. The model is insensitive to source-crater pairing, since all that is relevant is the length of time spent in space as small bodies. We [1] conclude that a scenario of meteoroid ejection as large bodies (> 1m) from Mars is unlikely to reproduce the observed CRE spectrum.

The issue of the equal numbers of lunar and martian meteorites can be alleviated by realizing that the Antarctic ice sheet has a finite age (almost all lunar and martian meteorites have terrestrial ages < 0.1 Myr). This results in our sampling different portions of the time spectrum of each lunar or martian impact. Also, we presume that larger impacts will generate more meteoroids. Since most lunar meteoroids are delivered *very* quickly (< 50 kyr), only recent impacts (or ancient larger ones) will be delivering meteorites to the ice sheet today. The impact rate onto Mars (for impactors of a given diameter) should be larger than the Moon's by at least the ratio of the surface areas ($\approx 3.8$). Our preliminary modelling shows that, if these effects are taken into account and the correct delivery spectra are included, the lunar/martian meteorite ratio can be reduced to order unity.

**REFERENCES:** [1] Gladman, B., J.A. Burns, M. Duncan, P. Lee, and H. Levison. 1996. The exchange of impact ejecta between terrestrial planets. Submitted to *Science*. [2] Wetherill, G.W. 1984. *Meteoritics*, **19**, 1-12. [3] Warren, P. 1994. *Icarus*, **111**, 338-363. [4] Gladman, B., J.A. Burns, M. Duncan, and H. Levison. 1995. *Icarus*, **118**, 302-321.

**Figure**: Cumulative plot of the time spectrum of martian meteorite delivery.
Dashed line and heavy squares: CRE data from the martian meteorites.
Dotted line: Collisionless N-body model, $v_\infty = 1$ km/s launches from Mars.
Solid line: Inclusion of a 2-Myr collisional half-life for meteoroids *while in the asteroid belt* ($Q > 2.1$AU).
The model provides a good fit to the data.
Errors on the CRE ages are about 10-30%.