LUNAR METEORITE SOURCE CRATER SIZE: CONSTRAINTS FROM IMPACT SIMULATIONS.
J. N. Head[1,2], [1]Raytheon Co., P.O. Box 11337, Bldg. 805, M/S L5, Tucson, AZ 85734-1337, jnhead@west.raytheon.com. [2]Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ 85721.

Abstract: Hydrocode simulations of lunar impact events show that craters as small as 450 meters in diameter are viable candidates for the source of most lunar meteorites. The lunar cratering flux implies that 6 impact events of this size occurred on the moon in the last 0.1 Ma. This is in good agreement with the number of impacts (7) inferred from the geochemical analysis of the samples in hand. The results from geochemistry and numerical simulations diverge for samples with older CRE ages. This is probably a consequence of the delivery timescales and terrestrial weathering.

Introduction: There are at least 12 known lunar meteorites[1]. These samples have been studied in numerous fields, including geochemical analysis (petrology, CRE studies) and celestial mechanics (orbital integration of ejected test particles). It appears that the lunar meteorites are delivered to earth very quickly: approximately 90-95% of the lunar meteorites that reach earth do so in less than 1 Ma[2]. Assigning particular samples to the same source crater (pairing) can be controversial, but it appears that the lunar meteorites represent 11 individual impact events on the moon. Based on geochemical analyses it appears that ten of these impacts probably occurred in the last 1 Ma and 7 in the last 0.1 Ma. It has been estimated from celestial mechanics and CRE data that lunar-meteorite-liberating events occur on a 10^4-year timescale[1]. These data allow one to estimate the size of the source craters for these meteorites. The approach used here is to simulate impact events numerically. The results can be analyzed to set limits on the minimum required crater. It is a minimum requirement that the various approaches must yield congruent results—for example, agreement on the number of source craters—before the problem can be considered well-understood.

Method: I use the SALE 2D hydrocode modified to incorporate multiple materials and fragmentation to simulate impacts onto the lunar surface[3,4]. The impactor and target materials were assumed to be basaltic, using the "gabbroic anorthosite" Tillotson EOS parameters[5]. The impactor diameter studied range from 10 to 100 meters, complementing the 100 to 400 range studied in my work on the martian meteorites. The impactor velocity is 10 km/sec and the implied final crater diameter from π-scaling is 0.45 to 2.71 km. The cell size in the calculation ranged from 0.5 to 2.5 m respectively. The calculation was conducted in two parts: first, an Eulerian calculation with tracer particles generated the input boundary conditions for the subsequent Lagrangian calculation involving fragmentation. Fracture is assumed to occur in tension. This same technique was used to analyze the origin of the martian clan meteorites with good success[6]. The output was analyzed to identify fragments meeting available criteria for the lunar meteorites. The fragment size must be 3-cm or larger, as deduced from the observed size of the meteorites and inferred losses from ablation[7]. The pre-impact depth must be less than 3.2 m (CRE data) and the launch velocity greater than ~2.3 km/sec. Lunar escape velocity is 2.38 km/sec, however, under favorable conditions (full moon at perihelion) material launched at 2.20 km/sec can also escape[7]. The maximum shock pressure allowed ranged from 10 to 40 GPa. The total number of fragments meeting these criteria must exceed a certain value given by the museum efficiency E_m, *id est*, the inverse of the number of particles ejected from a lunar impact required to expect to find one residing in a terrestrial museum. This is defined as $E_m = E_{del}E_{coll}t_{terr}/t_{CRE}$, where E_{del} is the total fraction delivered to the Earth (~50%), E_{coll} is the fraction of the Earth searched with perfect efficiency (estimated to be ~10^{-3}), t_{terr} is the characteristic terrestrial age of the sample (~10 ka) and t_{CRE} is the maximum delivery time (~100 ka for the majority of samples). For this problem E_m is estimated to be ~10^{-4}-10^{-5}. Once an impact event capable of producing the observed lunar meteorites is identified, the number of such events within the time scale of interest (t_{CRE} again) can be calculated from the estimated lunar cratering flux and the surface area of the moon. This estimate of the number of source craters can then be compared to that derived from geochemical analysis.

Results: In earlier work, I determined that martian craters 3 km are larger in diameter produced enough ejecta at 5 km/sec or more to be a candidate martian meteorite source crater[6]. The impactor size in that simulation was 150 meters. Clearly an event of this magnitude is more than sufficient to liberate the lunar meteorites. Indeed, a source crater size of less than 3.6 km was advocated by Warren[7]. I simulated impact events using projectile diameters of 100, 50, 30, and 10 m in diameter (for comparison, the Canyon Diablo meteorite was estimated to be 50 m in diameter) into homogeneous and layered targets. The total number of fragments produced as a function of maximum shock pressure for the two smallest events are shown in Table 1. Even for shock pressures of 10 GPa or less, the number of fragments meeting the selection criteria discussed above is more than enough to make the crater a viable source crater candidate. In addition, the figures in Table 1 for the 30-meter impactor are conservative in that they do not include fragments from a cell where one of the vertices had a spall velocity just below the 2.3 km/sec limit. Only the 30-meter impactor (and larger) produce enough ~10 cm fragments to account for the largest samples amongst the lunar meteorites[7]. The implied crater is 1.1 km in diameter. The smaller event produces relatively few ~10 cm fragments, however it produces enough smaller fragments (3-6 cm) to be the source for those meteorites. Therefore I conclude that craters of this size are viable candidate source craters, and that the minimum required crater may be somewhat smaller.

Discussion: Assuming that the minimum crater is 1.1 km in diameter, the number of individual events is estimated to be ~10 in the last 1 Ma and 1 in the last 0.1 Ma. Since there appear to be 7 impact events represented amongst the lunar meteorites with CRE ages of ~0.1Ma or less, the 1.1 km crater is probably too large. If the lower size limit is represented by 0.45 km craters, the expected number in 0.1 Ma is 6, in good agreement with the geochemically-derived value. In 1 Ma however, one would expect 60 such events.

It is evident from the CRE data that the lunar meteorite collection is dominated by recent launch events[7]. Of the ten events in the last 1 Ma, 70% of them occurred in the most recent 10% of that time span. This behavior is expected from the orbital integration studies of lunar ejecta delivered to Earth—most of the material that eventually arrives on Earth does so very quickly[1,2]. Given the typical terrestrial ages of the samples and the terrestrial environment, the majority of samples from older (~1 Ma) events are not accessible—they have probably been destroyed by erosional processes. Hence, the disparity between my results for 1 Ma and younger events (60 impacts) and geochemical analysis (10 events) is to be expected because there is an unmodeled mechanism removing the samples and consequently, the evidence of those impacts.

When one considers material having terrestrial ages comparable to or less than the launch ages, then the results are in good agreement. Apparently the major factors have been identified and modeled adequately. More detailed modeling of the delivery timescales for lunar meteorites and their survival in the terrestrial environment will probably aid our understanding of lunar meteorite provenance.

An aspect of this problem not studied in sufficient detail is the effect of layering in the target material. The lunar regolith on the maria is estimated to be ~15 meters thick based on Apollo seismic data. A layer of of damaged material, meant to represent the regolith, was added to several simulations. The added layer did not markedly alter the spall velocities and peak shock pressures. In particular, the reduction in spall velocity was insignificant. This is in contrast to my results for the martian meteorites where the physical properties of the target material strongly influenced the spall velocities and hence, the minimum required crater. Since the martian regolith thickness can be related to crater age, the relative abundance of different aged martian samples can be explained. A good regolith model for the moon has not been incorporated in this study to date. Currently I use the same EOS parameters for the regolith and bedrock—the only difference is that the regolith has damage set to 1 at the beginning of the calculation. A better model using appropriate values for density and the elastic moduli may produce different results. My earlier work on the martian meteorites used alluvium EOS parameters to simulate a martian regolith. In that work, the presence of a regolith suppressed the number of fragments launched to more than 5 km/sec, but increased the number launched in excess of 2.5 km/sec. Hence, the presence of a regolith on the moon may have a different effect than is the case for Mars. While better regolith studies are planned, they have a significant disadvantage: the fragment sizes can not be computed since the material, being predamaged, cannot sustain the dynamic tensional stresses from which the fragment sizes are deduced.

Conclusions: The minimum required crater for launching lunar meteorites is less than 1.1 km and is probably smaller than 0.45 km, based on hydrocode studies. The number of source craters implied by the smaller figure is in agreement with that inferred from geochemical and dynamical analysis.

References: [1] Gladman B. J. *et al.* (1996) *Science, 271* 1387-1392. [2] Gladman B. J. (1997) *Icarus, 130* 228-246. [3] Head J. N. (1995) *EOS, 76* F336. [4] Melosh H. J. *et al.* (1992) *JGR 97* 14735-14759. [5] Melosh H. J. (1989) *Impact cratering: A geologic process*, 245 p. [6] Head J. N. (1999) *Ph.D. Dissertation*, U. Arizona. [7] Warren P. H. (1994) *Icarus, 111* 338-363.

Max P_{shock} (GPa)	30 m impactor	10 m impactor
40	10	3
30	4	2
20	2	1
15	1	0.7
10	1	0.6

Table 1. Number of fragments ($x10^6$) meeting lunar meteorite constraints as a function of peak shock pressure.