THE RELATIVE ABUNDANCE OF RECENTLY-LAUNCHED METEORITES FROM THE MOON AND MARS. J. N. Head[1], Raytheon Missile Systems, P.O. Box 11337, Bldg. 805, M/S L5, Tucson AZ, 85734-1337
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Introduction: It has been known for over 20 years that certain meteorites originated on the moon and Mars. The launch and delivery of these stones is understood qualitatively as a consequence of impact events on those bodies. One of the puzzling features of the sample population is the relative abundance of lunar *vs*. Martian meteorites. One would think that lunar meteorites should be much more common than Martian meteorites. The moon has a much lower escape velocity, meaning many more fragments are launched from a given impact event. Smaller events can launch enough fragments to expect to find one on the Earth; hence, lunar meteorite-liberating events must be much more common than Martian meteorite-launching events. Moreover, the delivery efficiency from the moon to the Earth is higher by a factor of 10 [1]. Finally, the delivery time is shorter, meaning that the liberated lunar material from a given impact arrives at a much faster rate than comparable Martian material [1]. However, the total number of meteorites from the moon and Mars are comparable [2, 3]. The number of source craters represented by these samples appears to be of the same order of magnitude as well. For the reasons cited above, this has been difficult to understand. What I show in this work is that these arguments have missed a significant point and the observed relative abundances of lunar and Martian meteorites are just what one would expect if they are launched in relative small, frequent, impact events.

Method: Recent advances in hydrocode simulation allow the diameter of the source crater to be estimated [4]. In this work I use the SALE 2D hydrocode simulation, modified to incorporate multiple materials and fragmentation [5-7]. I have determined the minimum size crater required to launch meteorites from the moon and Mars. Using the lunar impactor flux, I can estimate the number of source craters that the current population of meteorite samples represent. This estimate can be compared to similar estimates derived from geochemical analyses of the samples in hand.

In order for a crater to qualify as a viable source for these meteorites, the impact must launch a large number of fragments—10^4 for lunar meteorites and 10^7 for Martian meteorites [4]. This is estimated by considering the following: first only of fraction of the fragments launched reach earth in timescales of interest. These corresponding fractions are 5% for Mars and 50% for the moon [1]. Only a small fraction of the earth is efficiently searched for meteorites. I estimate this fraction to be 10^{-4}. While quite uncertain, the minimum required crater size is relatively insensitive to this parameter. Finally, the lifetime of meteorites in the terrestrial environment is limited, approximately 100 ka, based on such ages reported for these stones [2]. One lunar meteorite has a terrestrial age of 500ka, but this is a unique case. The delivery time from Mars is about 10 Ma, hence only a fraction of the Martian meteorites that do arrive are recoverable at any one moment in history. The lunar delivery timescale is much shorter, ~10^4 years. This means it is likely that al of the lunar meteorites that reach Earth from a particular impact are already here. This analysis assumes that all meteorites from a source crater arrive within the stated timescale with no stragglers. Hence, the non-Shergottites and Dhofar 019 are excluded from the analysis. For lunar meteorites, terrestrial age is the limiting factor. Hence all lunar stones launched more than 100 ka are also excluded.

All these fragments must exceed escape velocity, be lightly shocked, have appropriate cosmic ray exposure (CRE) histories, and be physically large enough to account for the known meteorite size plus ablation losses of 50-80%. Impacts into intact (young) Martian terrain are most likely to liberate viable meteorites. Here the minimum required crater diameter is 3 km. Impacts that can launch lunar meteorites are so small that differences in regolith depth play little role and there should be no maria/highland bias in the samples. Hydrocode simulations show that the minimum source crater appears to be 400 m in diameter [8].

Of the ~25 known Martian meteorites, the majority are Shergottites launched in the last 4 Ma in 4 separate impact events on Mars. Of the known ~34 lunar meteorites, 13 have available CRE and terrestrial ages [2]. Seven were launched in the last ~100 ka. The other six were launched between 500 ka and 9 Ma. Thus the samples indicate 4 Martian and 7 lunar meteorite launch events in the sample population least effected by terrestrial weathering.

Results: The number of source craters we expect to have represented in the samples in hand can be estimated as follows. The lunar production curve is estimated to be 10^{-14} craters/km^2/yr for craters 4 km in diameter and larger [9]. Since we are interested in craters somewhat smaller than 4 km, the production function is scaled by assuming a -2 slope. The correction factor R (=0.9) is used to scale the lunar cratering flux to Mars [10, 11]. The timescale of interest is the launch age of the samples. For Shergottites, which dominate the Martian samples, the meteorite-launching events occurred in the last 4 Ma. For the moon, we choose samples launched in the last 10^5 yrs., since those dominate the lunar samples. The surface area on which craters of interest occur are either the entire surface area of the moon or the approximately 10% of Mars that has near-surface materials that date to roughly 400 Ma or less. The number of source craters is then calculated thus: N = flux*size factor*R*Area*f_{del}*t_{CRE}. Using these values, one calculates 5.8 Martian and 7.6 lunar source craters respectively.

Discussion: The analysis of the hydrocode results estimates there should be 6 Martian and 8 lunar source carters represented in the recently-arrived meteorites. Given the uncertainty in the parameters, these numbers are essentially identical. Hence, there should be little surprise that the numbers of lunar and Martian meteorites in hand are comparable. The solution to the lunar/Martian meteorite abundance paradox is that there is no paradox to be resolved. In addition, note that the absolute number of source craters predicted from the hydrocode simulations, using the latest delivery efficiencies and timescales available, matches that derived from geochemical analyses of the samples. For material launched recently enough to be free of the effects of terrestrial weathering, it appears that the small craters model for launch of lunar and Martian meteorites explains all the relevant observations in a consistent manner.

Samples that were launched long enough ago that terrestrial weathering may play a significant role appear to be under sampled [8]. Of the 13 dated lunar meteorites, 7 were launched in the last 100 ka, 4 more in the last 1 Ma, and 2 more in the last 10 Ma. Clearly some process is deleting samples from older launch events from the record, probably terrestrial weathering. Of the Shergottites, all but one were launched in the last 4 Ma. The exception is Dhofar 019, launched about 20 Ma. The small craters model predicts that additional Shergottites finds will yield launch ages between 4 and 20 Ma.

Conclusion: Hydrocode impact simulations suggest that 3 km and 0.4 km craters are large enough to eject meteorites from Mars and the moon respectively. Since the latter form at a rate ~15 times faster than the former, one would expect the flux of planetary meteorites to be dominated by lunar material. However, the number of Martian and lunar meteorites are comparable. Properly accounting for source-crater pairing, delivery timescales, and terrestrial lifetimes predicts that a similar number of source craters should be sampled by the terrestrial meteorite collection. Moreover, the absolute number of source craters predicted by the hydrocode simulations is consistent with that derived from geochemical analyses of the samples in hand. The number of Shergottite source craters and lunar source craters formed in the last 100 kyr should be comparable and hence there is no paradox to be resolved.

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