MARTIAN METEORITES AND COSMIC RAY EXPOSURE: CONSTRAINTS ON THE ROLE OF IN-SPACE BREAKUP EVENTS.
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Introduction: The differing cosmic ray exposure (CRE) ages derived for the Martian meteorites (MMs) have been interpreted as the dates of either in-space break-up events [1,2,3] or launch from the Martian surface [3,4,5]. A theoretical analysis of the amount of ejected material that would be expected to exhibit either single-stage (CRE was from 4π steradians) or two-stage (CRE was from 2π, then 4π) can be compared to the CRE observed in the recovered MMs. MM CRE appears limited to single-stage within detection limits [1,4,5]. Note that CRE for EET79001 may be too short—about 0.5 million years (Myr)—to generate a detectable two-stage history (Bogard, pers. comm.).

Three scenarios for CRE initiation are considered here. First is the in-space environment where break-up events generate fragments with different CRE ages by exposing previously sheltered material. Second is launch from the Martian surface, where most ejected material (deeper than 1-2 meters) is sheltered from CRE. Finally, the combination of the two is considered. To bound the study, the largest crater of interest was estimated by requiring the wait time for such a crater to occur on Shergottite-aged terrain to be comparable to the oldest CRE age for any MM, 20 Myr (Dhofar 019) [6]. Applying the lunar flux to Mars in the manner of [4], the crater size with this characteristic wait time is 10 km in diameter, roughly the size of Zunil [7].

Analysis: The approach taken here is a geometric analysis of the material launched from Mars via impact from which the recovered MMs are random samples. It is assumed that cosmic rays (CR) penetrate exactly 1 meter (or 2 meters) into the material either in space or on Mars [3,4,5]. This is a simplification over the observed 150 g/cm^2 mean interaction length. The relative volume of 2π and 4π CR exposed material is calculated, as is the likelihood that a random draw of 10 or 20 fragments will only show 4π exposure.

In-space breakup. Assume that the different CRE ages are solely consequences of in-space breakup events. In order for there to be different CRE ages for fragments from the same parent meteoroid, the interior must be exposed to CR flux after a sheltered period. Therefore, the less-exposed (younger CRE age) fragments must originate from a depth of at least one (or two) meters, and hence the parent fragment must be at least 1 (or 2) meter(s) in radius. In such a large fragment the outer 1 (or 2) meter rind will exhibit 2π exposure as well as 4π exposure after the breakup event, generating a two-stage CRE history similar to that observed in lunar meteorites. Hence, the ratio of material with two-stage CRE as opposed to single-stage exposure (4π only) can be calculated as a function of parent fragment size; it is inversely proportional (Figure 1). The volume of two-stage exposed material is greater than that of single-stage material unless the parent fragment is greater than 5 m (1-m CR penetration) or 20 m (2-m CR penetration) in diameter. The likelihood that random draws of 10 and 20 samples would only collect single-stage CRE histories is 0.04 and 0.001 for 20 meter parent fragments (Figure 2) and is much less for smaller parent fragments.

Launch. Assume that the different CRE histories are due solely to individual impact events. The surface of Mars and therefore MMs from the shallow subsurface (upper 1 meter) is subject to CR bombardment. Assume that all MMs from the upper one meter will have 2π CRE akin to the lunar meteorites and that all other MMs will have only 4π CRE exposure in the space environment after launch. Previous work [4,8] indicates that the maximum depth of the spall (launch) zone for MMs is 1/20 the impactor diameter. Since craters are roughly 20 times the diameter of the impacting body, the fraction of 2π material can be computed as a function of crater size (Figure 3). For a cylindrical spall zone (which underestimates the proportion of two-stage material), the probability that the first 20 MMs would have single-stage CRE is ~0.45 for 10 km source craters and less for smaller craters. However, the Martian surface is not bedrock, but is covered by a regolith unsuitable for ejection as intact MMs. Assuming that the regolith contains 10% blocks [9], and is 1 meter deep, the probability that the first 20 MMs will have 4π-only exposure rises to 0.82 for 4 km source craters and to 0.92 for 10-km source craters (Figure 4).

Combination: The in-space breakup scenario carries the implicit assumption that none of the material had two-stage exposure until launch. Surface exposure has the effect of increasing the portion of material with two-stage CRE; therefore, the combination increases the proportion of MMs with two stage CRE histories at the expense of single-stage histories.

Discussion: In this analysis it appears that in-space breakup events will produce a large proportion of MM material with two-stage CRE histories and that the likelihood that the recovered MMs are a representative sample of such a population is ~10^{-3} for ~10-m diameter parent fragments and far less for more plausible fragment launch sizes. The results of [4,9,10] show that the most common fragment size from a 3-km Martian crater is ~10-15 cm with a 1-m maximum and that the fragment and crater sizes scale nearly linearly. If the largest likely source crater is 10 km in diameter, then the most numerous fragments are less than 1 meter across and hence unable to shelter material from CRE to produce multiple CRE ages within a single parent fragment. Only rare, maximum size fragments (~3 m [3]) from the largest plausible source craters (10 km) could shelter material from CRE.

A surface exposure model can match the MM data well, though not uniquely, by choosing plausible values for regolith thickness and block abundance. For example, if we desire the first 20 samples to have a 95% probability of displaying only 4π CRE, a 1-m regolith and CRE penetration depth, coupled with a block abundance of 2% to 7%, will be sufficient (the range in block abundance is related to source crater size).

Conclusions. Unless a selective mechanism delivers MMs to earth, it is difficult to reconcile an in-space breakup model with the observed CRE, constraining the role of such events in generating the observed CRE ages. If the MM samples are indeed representative, their CRE history can be satisfactorily, though not uniquely, explained by 2π CRE on a Martian surface with a plausible regolith thickness, CR penetration depth, and block abundance. In this case, CRE for most material is initiated at launch and thus is indicative of the number of launch events. This result is insensitive to the range of published values for CR penetration depth and therefore warrants additional analysis.

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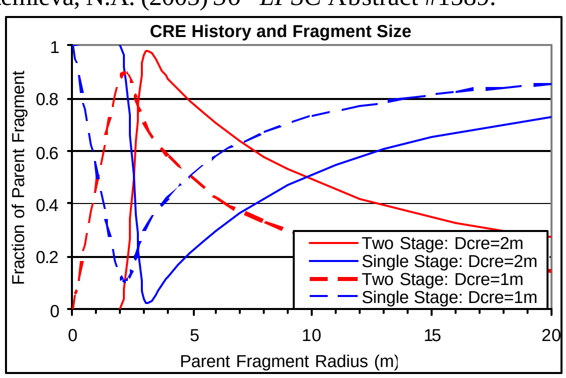

Figure 1. In-space break-up favors production of two-stage CRE MMs for small parent fragment sizes.

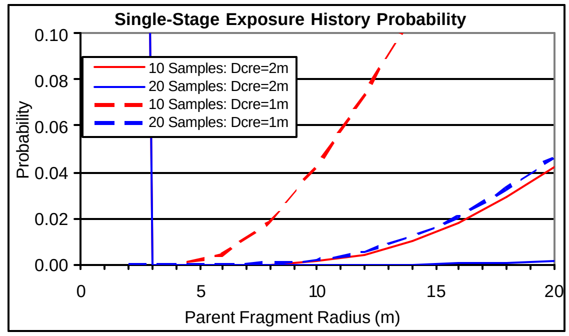

Figure 2. If in-space break-up is responsible for the different CRE ages in MMs, it is highly unlikely the recovered samples would display only single-stage CRE unless the parent fragments were unreasonably large. Note scale.

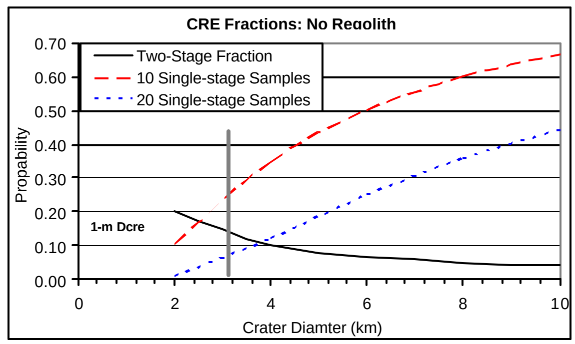

Figure 3. A no-regolith surface exposure model appears unlikely to produce the CRE history observed in the MMs. The estimated minimum required crater is indicated by the gray bar [1]. Source craters larger than 10 km are unlikely to have formed in the last 20 Myr, equivalent to the greatest known MM CRE age.

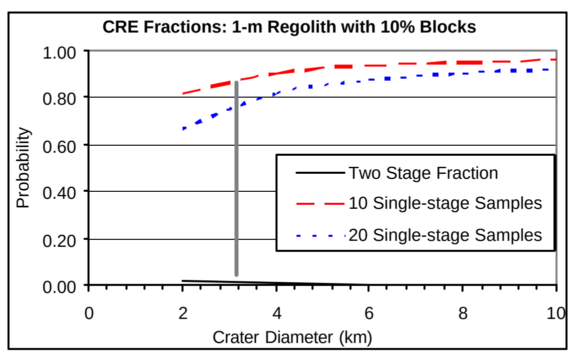

Figure 4. Surface exposure for a 1-m regolith with 10% blocks and 1-m CRE penetration depth appears likely to produce CRE histories close to that observed in the MMs. Adjusting the regolith depth, CRE penetration depth, and block abundance within plausible limits can produce better, though non-unique matches.