Extralunar Materials in Lunar Regolith

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The Scientific Rationale for Searching for Extralunar Materials

The moon has been identified as a potential reservoir for samples from a wide range of inner solar system bodies (Baedecker et al 1973, Brillant et al 1992, Arrhenius and Lepland 2000, Armstrong et al 2002, Crawford et al 2008, Taylor 2008). Because of the lack of weathering and terrestrial crustal recycling, the possibility also exists that some of these samples may be extremely old, or at least older than any meteoritic samples available on Earth. The practical effect of this feature is that extralunar materials in lunar regolith may include a significantly greater diversity of parent bodies and ages than other sample sources such as Earth-resident meteorites and returned samples. Furthermore, extralunar materials may include ancient fragments of the Earth that could shed new light on the evolution of the Earth's surface and atmosphere and possibly on the timing and environmental effects of the origin of life.

Science Enabled by the Study of Extralunar Materials

Meteoroids are dynamically cleared from the inner solar system on relatively short time scales measured in millions of years (Hartmann et al 1999), but the lunar regolith has been collecting material since the Moon's formation. This means that asteroidal samples from long-destroyed asteroids may persist on the Moon, and that samples of currently unsampled bodies likely reside there as well. Likewise, the suite of known planetary materials is probably larger in terms of both parent bodies and ages in lunar-resident samples than in Earth-resident meteorite collections. Infall from carbonaceous bodies should also be preserved, and it may be possible to back-calculate the flux of carbonaceous material delivered to the Moon and Earth in pre-biotic times.

The discovery of terrestrial meteorites themselves in the lunar regolith could provide important insights into the nature of surface and subsurface conditions on the early Earth during the time when life emerged from pre-biotic chemical precursors. On Earth, the geologic record of these critical events has been destroyed by crustal recycling, However, such a record could exist on the Moon as a terrestrial meteorite record (Arrhenius and Lepland 2000). During the Hadean the impact flux from the Earth was very high, such that the probability of encountering terrestrial materials during lunar sampling could be as high as 1:105 (Armstrong et al 2002, Crawford et al 2008). While challenging from an exploration standpoint, the importance of finding a record of the early Earth on the Moon cannot be overemphasized and would open up a whole new approach to understanding the origin and early evolution of terrestrial life (Taylor et al 2008). Note that the scientific returns on analyzing extralunar materials would be improved by the discovery of terrestrial materials but is not solely dependent upon them.

Current State of Understanding

Material is transferred between planets by impact ejection of native rock followed by a period of free flight in solar orbit that results in landing upon another body. The resulting transferred material comprises meteorites and interplanetary dust, which constitute the vast bulk of all extraterrestrial materials currently available for research. Evidence for transfer of large amounts of meteoritic material between planets can be found in terrestrial meteorite collections and in recent observations of meteorites on Mars from Mars Exploration Rover (MER) investigations (Schröder et al. 2007), and they are also predicted from impact rate calculations (Shoemaker 1977, Bland and Smith 2000). In fact, the extralunar component of lunar regolith has been measured as up to ~3.5% in Apollo regolith samples (Baedecker 1992) and 1-2 wt% carbonaceous chondrite materials (Brilliant et al 1992 and references therein) based on bulk trace element analyses, and trace element data has also been used to calculated impactor flux on the moon (Anders et al. 1973, Baedecker et al. 1972).

A number of factors must be considered in developing a successful strategy to locate and investigate such samples, among them: A) survival of particles after lunar infall, B) survival of particles through extended lunar impact processing (gardening), C) the extent to which these particles retain information about the parent body. Additionally, in the absence of surviving rock fragments, what data can be obtained from the disseminated extralunar component, (e.g. composition-based signals remaining from destroyed fragments (Baedecker et al 1973))?

Survivability of Materials on Ejection from their Parent Bodies: One of the major factors influencing the expected variety of extralunar materials involves survival of materials upon ejection from their parent bodies. Parent body mass and atmospheric density serve as the primary limiting factors on survival of material during impact ejection, with ejection from airless bodies simplifying the situation. Meteorite collections on Earth include samples from many asteroids, Mars (with its thin atmosphere) and the Moon, and it is reasonable to expect that masses are ejected from airless Mercury as well. The dense Venusian atmosphere destroys most impactors before they reach the ground (Schaber et al 1992) and also impedes ejection of material such that the likelihood of finding Venusian material is slight but not impossible (Armstrong 2002). While the Earth's atmosphere is not as dense as that of Venus, it is still dense enough to re-capture small masses thrown hundreds of km by impact as attested by the presence of large tektite fields (e.g. King 1977). In this case, the Moon's proximity acts to vastly improve the likelihood of capture of terrestrial materials over material from other bodies, improving the odds that terrestrial material can be found there (Armstrong et al 2002) even if the amount of ejected material is less than on an airless body.

Survivability of Materials on Lunar Infall: Since there is no lunar atmosphere to slow a falling meteoroid, impact into the lunar surface occurs at velocities that commonly fall in the km/s range. This event can be expected to be quite disruptive to the infalling body, but fragments can be expected to survive (Crawford et al 2008). Indeed, there are three examples of extralunar material known so far in the form of the ~1x2.5 mm Bench Crater carbonaceous chondrite found in a Apollo 12 regolith sample (McSween 1976), the 1-2 mm-diameter Hadley Rille enstatite chondrite retrieved by Apollo 15 (Haggerty 1972), and a silicated iron micrometeorite found in Apollo 16 regolith (Jolliff et al 1993). It is also known that phyllosilicates in the Bench Crater carbonaceous chondrite have retained their water content despite infall and impact gardening shock processing (Zolensky

1997), which shows that relatively volatile phases survive and can be collected from the lunar regolith.

Survivability of Materials Under Prolonged Impact Processing ("Gardening"): The lack of an atmosphere on the Moon also means that impactors of all sizes strike the lunar surface directly. Gardening of the lunar regolith will reduce extralunar material in size due to repeated impact. Hörz and Cintala (1984) showed this by subjecting a regolith simulant to repeated light gas gun impacts, showing that grains are relatively quickly reduced to sub-mm size. This implies that impact gardening will preferentially reduce extralunar grains with the longest lunar residence times to very small grains. On one hand, this means that they should be fairly uniformly distributed throughout the regolith, but on the other hand it means that a search strategy should focus on identifying very small grains of material.

As a sum of these processes, Armstrong et al (2002) estimates that terrestrial material exists in the lunar regolith to a concentration of 7 ppm based on a computational dynamics study of impact-driven materials transfer. This equates to "~20,000 kg of terran material over a [cm]-deep, 10x10 [km^2] area". Armstrong et al also points out the estimates of Gladman (1997) and Halliday et al (1989) that 15 100g martian meteorites impact the Earth each year, and when this value is scaled to estimate lunar infall, they estimate a modern value of "180 kg [of martian material] in the same 10x10 [km^2] area".

Potential Strategies for Extralunar Material Identification

Extralunar materials have definitely been delivered to the lunar surface, and the presence of identifiable chondritic meteorite fragments in Apollo regolith implies that additional grains exist. What we need to do is identify the optimal means of characterizing extralunar materials. This process is in its early stages and the information presented here is not a definitive work on the subject, but should be considered an overview discussion.

There are two venues for searching for extralunar material; in terrestrial laboratories with bulk regolith samples and on the Moon as a triaging routine to minimize the amount of regolith returned to Earth for closer examination.

In Situ Regolith Examination: The discovery of extralunar materials is possible in part because of the relatively simple nature of lunar mineralogy (e.g. Papike et al 1982), which should make many extralunar grains appear "unusual" by comparison. Definitive identification *in situ* is complicated by mineral species shared between the Moon and other planets such as quartz, which does exist as a sub-percent component in lunar regolith (Ling et al 2009). Other species such as carbonaceous materials, plagioclase feldspars, phyllosilicates, hornblende and other hydrated minerals are readily identifiable as "unusual" and worthy of closer examination in terrestrial laboratories, however. This mineral list would benefit from discussion and refinement among the scientific community. Bulk methods of analyzing regolith for "unusual" grains would have to balance the need to identify specific minerals, time per analysis, and the capability of separating individual grains for return to Earth.

Examination of Earth-bound Lunar Regolith Samples: Another option is examination of existing (and future) lunar regolith returned to Earth. This option allows for less restriction in the way of equipment size, power, and capability as well as allowing more time for the analysis. The downside is the limited sample suite, but it is highly likely that this is a scientifically useful venture.

In order to process a large volume of regolith in a meaningful time frame, it may be advantageous to rapidly examine individual grains (Fries and Steele 2007). The analytical instrument or suite necessary for this scanning would need to be A) capable of specific mineral identification, B) very rapid in order to analyze a meaningful amount of material in a reasonable amount of time, and C) non-destructive. Some techniques that are potentially applicable for this effort include but are not limited to reflectance spectroscopy, rapid pulsed Raman spectroscopy, fluorescence techniques, and X-ray diffraction. Each of these techniques features attributes and drawbacks, and work is required to define a definitive analysis suite.

Sample Analysis and Expected Science Return

Definitions are required from the scientific community as to exactly what analyses should be performed, and how samples should be allocated, etc., but we can draw parallels to other programs. The NASA Stardust mission, for example, required establishment of new sample handling, sample analysis, curation, and distribution protocols. This was done with considerable input from the scientific community and continues to pay dividends in the continuing analysis of samples returned by this highly successful mission. It is worth noting that Stardust samples are much smaller (~1s to 10s of microns in diameter) than lunar regolith samples (sub-mm) that will probably make up the targeted regolith grain size and yet a broad suite of mineralogical, isotopic, and compositional data are routinely collected from Stardust materials.

In order to obtain scientifically meaningful and contextually constrained information from extralunar materials, we can propose a suite of necessary analyses for cooperative community research such as that employed in the Stardust data analysis program. The following comprises an initial list of measurements that will almost certainly evolve with community input.

Parent Body Identification: It is necessary to ascertain the parent body of extralunar grains, both to place other measurements in context and to initially test "unusual" grains to start with. Meteorite parent bodies are commonly identified using oxygen isotopes and this technique should be applicable to extralunar grains as well. Terrestrial materials are problematic as their oxygen isotope values are indistinguishable from lunar grains. Identification of terrestrial grains may take advantage of elemental or isotopic systems emblematic of the strongly devolatilized Moon, with mineralogy signatures, or other techniques yet to be defined.

Ultimate and lunar residence ages: Temporal context is necessary to define the age and history of a given extralunar grain. The lunar residence age is especially necessary for planetary samples in order to place other measurements in temporal context with respect to evolution of the parent body. For example, samples of the Earth or Mars with well-constrained ages might be used to constrain the evolution of atmospheric oxygen on Earth or the disappearance of surface water on Mars. It would be important to define potential cosmogenic or radiogenic nuclide systems which might allow us to define the formation age, shock age, exposure age or lunar resident age of very small objects. This would be close to detection limits for most methods that are available today such as laser desorption Ar-Ar dating methods, however, we have seen vast changes in methodologies over the last 30-40yr and it is not unreasonable to assume the rapid improvement of technology will continue.

Mineralogy: This analysis is relatively straightforward and will form a central core of defining the formation and history of extralunar grains on their parent bodies. Assessment of oxygen concentration or fugacity through sample mineralogy may prove to be an important probe of environmental conditions present over time on various parent bodies.

Atmospheric Gases: In the event that shock-formed melt dating to original ejection from an extralunar grain's parent body survives, the possibility exists that measurements might be collected of dissolved atmospheric gases in the grain. There is precedence to this concept, as measurements of dissolved noble gases in melt glass were used to definitively identify martian meteorites as originating from Mars (Becker and Pepin 1984).

Summary

There is no question that extralunar materials have bombarded the Moon since early in its history. It is also clear that a small fraction of these materials have survived as shown by the existence of three lunar-resident meteorites found to date and trace elemental evidence of an extralunar component in regolith. Pending work by the scientific community in defining methodologies, instrumentation, and analysis, it is feasible to locate and interrogate extralunar materials in lunar regolith both on the Moon and in terrestrial laboratories. Such grains represent a unique and extraordinarily valuable record of solar system processes and can be expected to yield new insights into the formation and evolution of inner solar system bodies. We strongly recommend inclusion of this research topic as part of an integrated campaign of lunar research.

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