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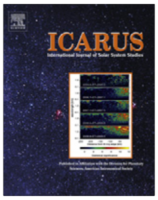

Note

Impact ejection of lunar meteorites and the age of Giordano Bruno

Jörg Fritz [*]

Museum für Naturkunde, Invalidenstrasse 43, 10115 Berlin, Germany

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ABSTRACT

Based on literature data from lunar meteorites and orbital observations it is argued that the lunar crater Giordano Bruno (22 km ∅) formed more than 1 Ma ago and probably ejected the lunar meteorites Yamato 82192/82193/86032 at 8.5 ± 1.5 Ma ago from the Th-poor highlands of the Moon. The efficiency and time scale to deliver ^{3}He-rich lunar material into Earth's sediments is discussed to assess the temporal relationship between the Giordano Bruno cratering event and a 1 Ma enduring ^{3}He-spike which is observed in 8.2 Ma old sediments on Earth.

1. Introduction

The rapidly increasing number of lunar and martian meteorites recovered in hot and cold deserts has revolutionized our understanding of the impact-related transfer of solid rock fragments between planets in the same Solar System (Gladman et al., 1995; Artemieva and Ivanov, 2004; Fritz et al., 2005; Artemieva and Shuvalov, 2008). The suite of available lunar and martian meteorites provide unique samples to investigate the recent impact record of these planets, because absolute ages of the ejection events can be deduced from the cosmic ray exposure history (i.e., Nishiizumi et al., 1991; Eugster et al., 2002). Petrology, geochemistry, and the timescales of delivery and recovery of lunar meteorites are compared with remote sensing data regarding the lunar impact record of the last ∼100 Ma to help identify potential source craters. Here I discuss the age of the lunar crater Giordano Bruno, with implications for recovering its ejecta as lunar meteorites, and for the extraterrestrial ^{3}He preserved in Earth's sedimentary record.

2. Observations of the Giordano Bruno crater

A 22 km ∅ crater just beyond the north-eastern limb of the Moon (36°N, 103°E) is named after an Italian priest, philosopher and astronomer. Giordano Bruno (1548–1600 AD) expanded the helio-centric view of Copernicus by considering that the universe is infinite, that our Sun is a star like other star, and that these other stars host planetary systems populated by intelligent beings (Bruno, 1584).

The Giordano Bruno crater displays a well preserved ray system (Whitaker, 1963). This impact structure is, according to the low spectral maturity level of the ejecta blanket (Pieters et al., 1994), the youngest lunar crater >20 km ∅ (Grier et al., 2001). Hartung (1976) proposed that the Giordano Bruno forming impact was eye witnessed by medieval monks on June 18th, 1178 AD Calame and Mulholland (1978) determined that formation in medieval times would have coincided with the large amplitudes of the free liberation of the Moon. Using Kaguya orbiter data, Plescia et al. (2011) consider a historical age for this crater probable. However, the ejecta blanket of Giordano Bruno shows a 1–10 Ma crater retention age (Morota et al., 2009), which appears consistent with detailed observations using Lunar Reconnaissance Orbiter images (Shkuratov et al., 2012).

3. Number and size of lunar impact ejection events

Impact ejection and the interplanetary transfer of rock fragments is documented by 104 martian and 154 lunar meteorites with individual names (Meteoritical Bulletin Data Base 14. March 2012; http://www.lpi.usra.edu/meteor/metbull.php). Some of these meteorites were ejected together from the Moon (launch paired) or are fragments of a single meteoroid that disrupted during atmospheric entry (fall paired). Launch and fall pairing is disentangled on the basis of petrology and cosmic ray exposure history (Table 1 and Fig. 1). The ejection age is the sum of the cosmic ray exposure during space transit (4π small body) plus the terrestrial residence time. These ages are (besides problems due to complex exposure histories) determined by cosmogenic nuclide abundances (Nishiizumi et al., 1991; Eugster et al., 2002).

Based on ejection ages and petrology, the suite of martian meteorites derives from ∼7 different impact events and each delivered similar lithologies during the last 20 Ma (Christen et al., 2005; Fritz et al., 2007a). Disentangling launch and fall pairing for lunar meteorites is less obvious. The impact gardened lunar surface is covered with regolith composed of a petrologically diverse mixture of rock to dust sized fragments with complex cosmic ray exposure (CRE) histories. The petrologic diversity of lunar meteorites has been used to propose 30–50 different ejection events (Korotev et al., 2009). The CRE age distribution document at least eight different events (Lorenzetti et al., 2005; Fig. 1).

The size of these impact events is constrained by the temporal frequency of the documented ejection events and the lunar crater production rates (and scaled for Mars). It follows that projectiles as small as ∼30 m and ∼200 m can produce lunar and martian meteorites, respectively, and the resulting craters are small in size (∼1 and ∼3 km ∅ on Moon and Mars, respectively; Artemieva and Ivanov, 2004; Fritz et al., 2007a). Based upon surface ages from crater counting, only four lunar craters >20 km ∅ formed during the last ∼100 Ma on the Moon (Morota et al., 2009; Grier et al., 2001).

4. Total mass of lunar ejecta delivered to Earth

The total mass of lunar ejecta delivered to the Earth's upper atmosphere varies from between 0.25 and 2 of the total mass projectiles impacting the Moon (Gladman et al., 1995; Fritz et al., 2007b; Artemieva and Shuvalov, 2008) and may equated to 1 for simplicity. Using the lunar size–frequency distribution (Neukum, 1983) I estimate 6.2×10^9 and 1.8×10^{12} kg of lunar ejecta arriving on Earth's atmosphere

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[*] Fax: +49 30 2093 8565.
E-mail address: joerg.fritz@mfn-berlin.de.

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Table 1
Compilation of literature data for lunar meteorites: T_{space} = irradiation time as a small body in space, T_{terr} = subsequent time interval the meteorite resided on Earth and was shielded by the atmosphere from cosmic rays; T_{eject} = T_{space} + T_{terr}, the time at which the rock was impact ejected from the Moon. All ages are given in million years [Ma]. Thorium [Th] elemental abundance of the meteorite in [ppm]. References [Ref.] for cosmic ray exposure data: (1) Nishiizumi and Caffee (2001b); (2) Nishiizumi et al. (2004); (3) Nishiizumi et al. (2006); (4) Serefiddin et al. (2011); (5) Nishiizumi and Caffee (2001a); (6) Scherer et al. (1998); (7) Nishiizumi et al. (1998); (8) Bartoschewitz et al. (2009); (9) Nishiizumi et al. (2009); (10) Nishiizumi et al. (1991); (11) Nishiizumi and Caffee (2006); (12) Nishiizumi et al. (1988); (13) Eugster (1988); (14) Lorenzetti et al. (2005); (15) Nyquist et al. (2006); (16) Nishiizumi et al. (1996); (17) Thalmann et al. (1996); (108) Nishiizumi et al. (2005); (19) Vogt et al. (1993); (20) Nishiizumi et al. (1999); (21) Nishiizumi and Caffee (1996); and (22) Gnos et al. (2004). Data for Th-concentrations from (A) Korotev (2005); (B) Korotev et al. (2003); and (C) Korotev et al. (2008).

Name	T_{space}	T_{terr}	T_{eject}	Th	Ref.
Thorium-poor feldspatic breccias					
Dhofar 025	>5	0.55 ± 0.05	13–20	0.5	1; A
Dhofar 026	<0.005			0.4	1; B
Dhofar 081/280/910	<0.01	0.04 ± 0.02	0.04 ± 0.02	0.2	2; 3; B
	0.23	0.22	0.4		4
Dhofar 489/908/911/1085	0.004 ± 0.001	~0.3	0.3 ± 0.1	0.07	3; A
Dhofar 1084	0.32 ± 0.06			0.4	5; C
DaG 262	0.5	0.3		0.4	7; B
DaG 400	~1			0.4	6; B
SaU 300	<0.2		0.1 ± 0.1	0.5	8; 4
NWA 482	0.9 ± 0.2	0.09 ± 0.03	0.99 ± 0.23	0.2	5; B
NWA 5000	>0.0013	<0.01		0.7	9; C
NEA 001	0.44 ± 0.08			0.3	3; A
ALHA81005	<0.05	0.04 ± 0.01	0.04 ± 0.01	0.3	10; B
MAC 88104/88105	0.045 ± 0.005	0.23 ± 0.02	0.27 ± 0.025	0.4	10; B
	0.04	0.14	0.18		4
PCA 02007	0.95 ± 0.11	<0.03	0.95 ± 0.14	0.4	11; A
Y-82192/82193/86032	5–11	0.077 ± 0.005	8 ± 3	0.19	12;13;14
			8.5 ± 1.5		15; B
Y-791197	<0.002	0.06 ± 0.03	0.06 ± 0.03	0.3	10; B
QUE 93069/94269	0.035 ± 0.015	0.0075 ± 0.0025	0.04 ± 0.02	0.5	16; B
	0.15 ± 0.02	<0.015	0.16 ± 0.03		17
Mingled breccias					
Calcalong Creek	3 ± 1	<0.03	3 ± 1	4	16; B
Kalahari 008/009	0.00023 ± 0.00009	0.4 ± 0.1	0.4 ± 0.1	0.2	18; C
EET 87521/96008	<0.1	0.8 ± 0.3	0.85 ± 0.35	0.9	19; 20; B
MET 01210	0.9 ± 0.18	<0.02	0.9 ± 0.2	0.9	3; A
	1.4 ± 0.2	<0.03	1.4 ± 0.2		4
QUE 94281	<0.1	0.25 ± 0.1	0.35 ± 0.1	0.9	21; B
Y-793274/981031	<0.025	0.04 ± 0.02	0.045 ± 0.025	1.1	16; B
Th-rich mafic breccias					
SaU 169	<0.34	0.0097 ± 0.0013	0.175 ± 0.175	9	22; A
Mare basalts					
NWA 032/479	0.042	<0.08	0.08 ± 0.02	1.9	23; A
	0.023	<0.02			4
NWA 773	0.03 ± 0.002	0.017 ± 0.01	0.047 ± 0.004	0.6	2; B
Asuka 881757			0.8 ± 0.2	0.4	11; B
LAP 02205/02224/02226/02436/03632	0.35 ± 0.005	0.02 ± 0.005	0.055 ± 0.005	2.2	11; C
	0.04	<0.1			4
Y-793169			0.9 ± 0.2	0.7	11; A

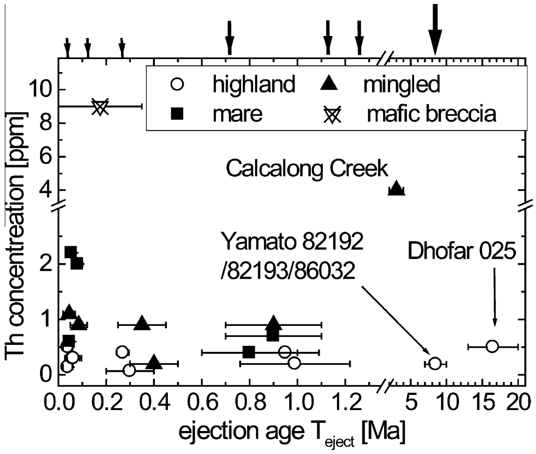

Fig. 1. Cumulative plot of the space residence time ($N > T_{space}$) of lunar and martian meteorites. Literature data for martian meteorites from references in Fritz et al. (2007a), and for lunar meteorites (see Table 1).

in 1 and 10 Ma, respectively. The number of projectiles increases toward lower sizes by roughly a power of 2, but the mass of each projectile increases by the power of 3. Thus, the integrated mass over a given time is dominated by the larges projectile. The Giordano Bruno forming projectile of ~1 km ∅ would deliver ~1.5 × 10^{12} kg, i.e., >80% of the total lunar ejecta during 10 Ma.

5. The delivery through orbital space

Differences in the delivery through space are shown in a cumulative plot of the space residence time ($N > T_{space}$) for martian and lunar meteorites (Fig. 2). A martian impact provides a ~20 Ma period of steady flux of meteorites that travelled on heliocentric orbits to Earth (Gladman, 1997). In contrast, a lunar impact delivers the majority of meteorites on quasi-geocentric orbits to Earth during the initial 0.5–1 Ma (Gladman et al., 1995) following the impact. Compared to 20 Ma on Mars, statistically less and smaller impacts occur during 1 Ma on the Moon. This explains the similar number of lunar and martian meteorites although compared to Mars, the Moon has a lower escape velocity and a more efficient delivery process to Earth (Artemieva and Ivanov, 2004). Compared to martian meteorites the flux of lunar meteorites to Earth is spiky, i.e., briefly dominated by the less frequent larger impacts like the one that formed the Giordano Bruno crater. Remarkably, five different martian meteorites, but no lunar ones, are observed falls (Meteoritical Bulletin Data Base). This supports Withers (2001) arguments that the Earth is currently not exposed to an intense shower of lunar material as would be expected if the Giordano Bruno crater was of medieval age.

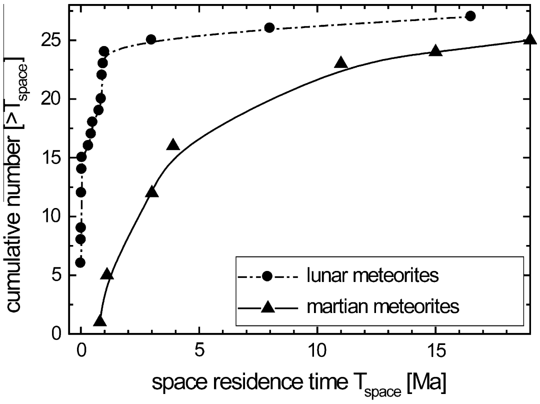

Fig. 2. Th-concentrations and ejection ages of lunar meteorites. Data compiled from references in Table 1. Petrologic types are indicated by different symbols. Small arrow marks a minor ^{3}He excursion in marine sediments and the medium sized arrows show those excursions identified as spikes in the ^{3}He burial flux at ~714, ~1137, and ~1265 ka ago by Patterson and Farley (1998). The large arrow marks the major ^{3}He spike at 8.2 Ma ago reported by Farley et al. (2006).

Withers (2001) arguments can be extended back to the last 1 Ma. Between 40% and 90% of lunar meteorites arrived during less than 0.01 and 1 Ma respectively and only a few% arrived prior to 1 Ma ago (Gladman, 1997; Fig. 2). The recovered lunar meteorites show terrestrial ages of <0.6 Ma (Table 1). A Giordano Bruno impact in the last 1 Ma would certainly have dominated the population of lunar meteorites (see also Section 4). However, there are two primary observations that are inconsistent with such a young age for Giordano Bruno. First, the proportion of basaltic and highland meteorites seems representative for the composition of the lunar crust, such lithological diversity would not be expected for meteorites derived from a single source crater; and secondly, a similar number of lunar and martian meteorites are recovered, whereas there should be considerably more lunar meteorites if a 20 km lunar crater formed within the last 1 Ma. Thus, the lunar crater Giordano Bruno (22 km ∅) is older 1 Ma.

6. Petrology and ejection ages of lunar meteorites

It is quite likely that some of the lunar meteorites that arrived on less efficient heliocentric orbits to Earth (T_{space} > 1 Ma) actually were ejected by the Giordano Bruno crater (~80% see Section 4). A compilation of petrologic grouping, thorium (Th)-concentrations and ejection ages of lunar meteorites (Table 1; Fig. 1) assists in constraining the source regions. The Giordano Bruno crater formed in lunar highlands that are characterized by low (<1 ppm) Th abundances in the global elemental distribution maps (Lawrence et al., 2003). The Th-rich (4 ppm) mingled (basalts and highland lithologies) breccia Calcalong Creek, ejected 2–4 Ma ago, is a poor geochemical match. The Th-poor highland rock Dhofar 025, ejected 14–20 Ma ago, is barely in agreement with a 1–10 Ma age of the Giordano Bruno crater as constrained by crater statistics (Morota et al., 2009; Shkuratov et al., 2012). The Th-poor (0.19 ppm) polymict highland breccia Y-82192/82193/86032 is, based on chemical composition of the bulk rock and individual clasts, from a region distant to the Procellarum KREEP Terrain (PKT) and possibly from the lunar far side (Nyquist et al., 2006). Bulk rock data of the polymict breccias Y-82192/82193/86032 show ejection ages of 5–11 Ma (Eugster, 1988; Nishiizumi et al., 1998). However, different fragments display variations in the amount of several regolith exposure indicators that enable the ejection age to be constrained at 8.5 ± 1.5 Ma (Nyquist et al., 2006). Only this lunar meteorite with published CRE ages matches both the geochemical constraints of the source region and the temporal requirements.

7. Tracing lunar impact ejecta in marine sediments

The Moon's tenuous atmosphere is too thin to decelerate small particles either impacting or escaping the Moon. Thus, the recovery of lunar meteorites implies that sand to dust sized lunar particles are also delivered to Earth via impacts. The composition of the lunar crust means it is not possible to trace lunar impact ejecta in terrestrial sediments using conventional impact indicators such as Platinum Group Element (PGE) enrichments or shocked quartz. However, the lunar regolith is highly enriched in ^{3}He (Cameron, 1992) and this rare noble gas isotope can potentially be used to detect lunar ejecta layers in sediments (Fritz et al., 2007b; Schwenzer et al., 2008, see discussion in Farley (2009)). An efficient delivery of ^{3}He-rich lunar impact ejecta into sediments is thought to explain a variety of independent geochemical data related to the late Eocene projectile shower onto the Earth–Moon system (Fritz et al., 2007b). In contrast to the comet shower scenario (Farley et al., 1998) that can be viewed as a unique event, the intensity of the asteroid shower – lunar impact scenario is constrained by the lunar crater record. Two ~20 km ∅ craters Moore F and Byrgius A have model ages of 41 Ma and 48 Ma respectively (Morota et al., 2009; Grier et al., 2001), that shift to younger absolute ages due to a higher crater production rate during the late Eocene event. The mass of these two projectiles (3×10^{12} kg) is considered a reasonable estimate for the total mass impacting the Moon during the 2 Ma during the late Eocene event (see Section 4). In this model, orders of magnitude smaller craters could efficiently impact eject the upper few meters of ^{3}He-rich lunar regolith to account for the shallow rise time of the double-peaked, hump-shaped ^{3}He anomaly in the sedimentary record on Earth.

The ^{3}He excess in late Eocene sediments may be roughly estimated as 2×10^9 cm^3 STP (cm^3 STP = volume gas at standard temperature and pressure): two times the background flux (0.1×10^{-12} cm^3 STP/cm^2/ka, Farley et al., 1998) multiplied by the total Earth's surface (5.1×10^{18} cm^2) multiplied by 2000 ka. To deliver all excess ^{3}He from lunar ejecta (3×10^{15} g; constrained by the mass of two projectiles that formed Moore F and Byrgius A) requires an average concentration of 6.7×10^{-7} cm^3 STP/g. The calculated average concentration may be compared with values of ^{3}He rich lunar material. Average lunar meteorites host ~4×10^{-7} cm^3 STP/g (Lorenzetti et al., 2005). ^{3}He concentrations in lunar regolith increase with decreasing grain size and increasing Ti concentrations from 5 ppb = 3.7×10^{-5} cm^3 STP/g to 50 ppb = 3.7×10^{-4} cm^3 STP/g (Cameron, 1992). In addition, He concentrations in lunar ejecta dependent on the surface/volume ratio, because solar wind ^{3}He is implanted in the outer few microns during space residence time. In 1 year a solar ^{3}He flux at 1 AU of 1.9×10^{11} ions cm^{-2} year^{-1} (Heber et al., 2009) implants a volume of 1.5×10^{-5}; 7.6×10^{-6}; and 1.5×10^{-6} cm^3 STP/g ^{3}He into dust particles of 5, 10 and 50 μm ∅, respectively.

Small particles (lunar regolith or lunar dust enriched in implanted ^{3}He) host approximately two orders of magnitude more ^{3}He than required for the Late Eocene anomaly, whereas lunar meteorites have slightly lower ^{3}He values. Thus, a few percent of escaping lunar material (either ^{3}He-rich regolith or lunar dust enriched by solar wind implanted ^{3}He) may account for the Late Eocene ^{3}He anomaly.

An efficient delivery of ^{3}He-rich lunar material into Earth's sediments implies a general spikiness of the ^{3}He record. Random lunar impacts large enough (the minimum size being related to the temporal frequency of the ^{3}He-spikes) should produce brief (<10 ka?) ^{3}He anomalies. Indeed continuous-time sampled ^{3}He-profiles of the last 1.8 Ma revealed three brief spikes in the ^{3}He burial flux at ~0.714, ~1.137, and ~1.265 Ma ago (Patterson and Farley, 1998; Fig. 2), and apparently spiky low resolution ^{3}He profiles are observed for the last ~37 Ma (Fig. 2 in Farley et al., 2006). The Necho crater (31.2 km ∅) with a model age of ~80 Ma (Morota et al., 2009) could be temporally related to one of the spikes in the events K1 or K2 (68–85 Ma; Farley et al., 2012). Interpreting the K3 event, characterized by several brief periods of increased ^{3}He flux at 90–93 Ma ago (Farley et al., 2012), as resulting from several lunar impacts would imply that the ^{3}He spike from the Necho crater should be larger. This is because there is no other similar size lunar crater with appropriate crater retention age observed on the Moon (Morota et al., 2009; Grier et al., 2001). So far the lunar crater record seems at least broadly consistent with several features displayed in the ^{3}He profiles of the last 90 Ma.

8. An ^{3}He spike from the Giordano Bruno crater?

However, relating the 8.5 ± 1.5 Ma ejection age of Y-82192/82193/86032 (Nyquist et al., 2006) to the Giordano Bruno crater imparts severe constraints on the efficient delivery of lunar ^{3}He into Earth's sediments. The time interval of 7–10 Ma is covered by a ^{3}He profile with ~100 ka temporal resolution (site 962; Farley et al., 2006). A possible brief (<10 ka?) spike at 7.6 Ma may be confirmed with ^{3}He profiles of higher temporal resolution. However, the main ^{3}He anomaly shows a steep initial rise to four times above background followed by an exponential decay over ~1 Ma. This spike at 8.2 Ma was attributed to a collision that formed the Veritas asteroid family (Farley et al., 2006).

Correlating the 8.2 Ma spike with the Giordano Bruno crater would mean that this single lunar impact produced a ^{3}He anomaly that follows the orbital lifetime of lunar particles larger 1 mm ∅, i.e., those that are mainly affected by gravitational forces. However, relying on the ^{3}He-rich regolith ejected by a single large crater is problematic because for larger craters more material derives from below the few meter thick ^{3}He-rich regolith mantling the lunar surface. Smaller particles that are efficiently enriched by implanted He ions (positive charging) in space might interact with the magnetic field of Earth. They are, however, quickly decelerated by the Pointing–Robertson drag.

To produce a 1 Ma duration ^{3}He anomaly by a single lunar impact possibly requires dust sized particles that are constantly produced during the orbital lifetime of lunar ejecta >1 mm. To some degree lunar dust will be produced by collisional erosion of lunar meteoroids due to the flux of interplanetary particles. The collisional lifetime of a 1 g sized meteoroid at 1 AU is ~10 ka (Grün et al., 1985). The Giordano Bruno crater ejected about 1–4 times its mass into space (~10^{12} kg). Using an average particle mass of 10 g it is estimated that 10^{14} lunar meteoroids dwelled the Hill sphere of Earth, and are collisionally eroded during the orbital life time.

It appears problematic but not impossible that the Giordano Bruno impact is recorded by a 1 Ma enduring ^{3}He-anomaly in late Miocene sediments on Earth. As an alternative this single lunar impact may have only produced a short <10–100 ka spike because a second ^{3}He excursion is not observed at the 100 ka temporal resolution ^{3}He profile of 6–10 Ma old sediments on Earth. Further investigations on the timescales and the efficiency to deliver ^{3}He-rich lunar material is of special relevance for dating the 100 km sized Tycho crater (proposed age of 109 ± 4 Ma; Drozd et al., 1977) in sediments on Earth. This impact delivered about 10^{14} kg to Earth's atmosphere (Artemieva and Shuvalov, 2008). Distributed over 1 Ma (10^8 kg/year) this rivals the total mass of IDP (4×10^7 kg/year) delivered to Earth during that time interval. Tycho should be recorded by ^{3}He in Earth's sediments.

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