The Planetary Science Journal, 3:274 (9pp), 2022 December https://doi.org/10.3847/PSJ/aca282

Inconsistency between the Ancient Mars and Moon Impact Records of Megameter-scale Craters

Stuart J. Robbins
Southwest Research Institute, 1050 Walnut Street, Boulder, CO 80302, USA; stuart@boulder.swri.edu
Received 2022 July 2; revised 2022 September 19; accepted 2022 November 8; published 2022 December 16

Abstract

Impact crater populations provide a record of the bombardment history of a planetary body. These craters reveal an intense bombardment history on Earth's Moon that included significant, large impacts, at least four of which created craters larger than ∼1000 km across more than 3.7 Ga. Scaling the lunar impact crater history to Mars using generally well-established scaling rules indicates Mars should have ∼40–80 similarly sized, ancient craters. However, Mars has roughly seven. This is a nontrivial mismatch between observation and expectation. Possible methods to resolve the mismatch are discussed in this work: small number statistics, incorrect scaling laws, heat flow produced larger-than-expected craters, the ratio of Mars:Moon impactors was different in early solar system history, Mars's ancient crater chronology is wrong, and/or Mars has hidden a large fraction of its large impacts. None of these scenarios are mutually exclusive. This work details how the different scenarios could work to bring observations more in-line with the scaling expectations, or vice versa. It is posited that the most likely sources of the mismatch are that the initial bolide rate was different (this is a noncontroversial supposition), that lunar heat flow produced larger craters than expected, and the formation of the Martian Borealis basin could have kept the surface warm enough for long enough to prevent large features from forming for an extended period of time. The primary purpose of this work is to present the issue with possible ways to solve it through future efforts.

Unified Astronomy Thesaurus concepts: Craters (2282); Lunar craters (949); Mars (1007); The Moon (1692); Impact phenomena (779); Lunar impacts (958)

1. Introduction

Understanding the chronology of the solar system is a critical aspect of planetary and dynamical astronomical research. The chronology of planetary surfaces other than Earth are typically based in large part on impact craters: the longer a surface has been exposed, the more time it has had to accumulate craters. Absolute dating ties a crater spatial density to absolute ages from radiometric dating, and a significant amount of work has been done to understand the Moon's absolute crater chronology (e.g., Shoemaker et al. 1970; Neukum 1984; Neukum et al. 2001; Hartmann 2005; Marchi et al. 2009; Robbins 2014; Yue et al. 2022).

Absolute crater-based chronologies are limited to ages <3.92 Ga, based on the maximum age of lunar samples that can be tied to specific surfaces with a given crater spatial density. However, those absolute model ages have been extrapolated further into the lunar past through superposition and modeling. Those superposition rules indicate that the youngest typically thought of as "large"[1] lunar crater is Orientale, ≈940 km across, and formed ≈3.7–3.8 Ga (Stewart-Alexander & Howard 1970; Baldwin 1987a, 1987b; Geiss & Rossi 2013; Yue et al. 2020). There are approximately three identified craters both larger and older than Orientale: South Pole–Aitken, Crisium, and Imbrium (e.g., Spudis et al. 2011).

Transferring the lunar crater chronology to other surfaces encompasses another large body of work (e.g., most recent review by Neukum et al. 2001, or Hartmann & Neukum 2001). The transfer is based on scaling relationships within the inner solar system that are functions primarily of the velocity of impactors, target proximity to the asteroid belt, and target gravity. Based on dynamical arguments, each unit area of Mars should have been hit by impactors at a rate ≈2.7× that of the Moon, at least for the last few billion years (Ivanov et al. 2002). Based on velocity and gravity scaling, those impactors would only form craters ≈75% as large as the Moon. That means a comparison with the Moon for similarly aged craters formed by similarly sized impactors should comprise a search for Martian craters >700 km across. Given Mars's surface area is 3.8× the Moon's, one would expect ≈10× as many craters >700 km on Mars, for a total of ∼40. However, they number only 6–7.

This is far from the expected number, and Orgel et al. (2020) arrived at a similar conclusion for Mercury based on a very different analysis. The mismatch implies any one or combination of the following issues: (1) small number statistics; (2) impactor-crater scaling laws between the Moon and Mars are wrong; (3) nearside lunar craters are abnormally large due to heat flow when they formed; (4) the early Mars:Moon bolide ratio was significantly different than today; (5) the ancient crater-based chronology of Mars is wrong; and/or (6) Mars has managed to completely hide ∼3/4 of its large-crater population *after* that population is preserved on the Moon (discussed extensively in Sections 2.2 and 5.6). Any of these issues present nontrivial problems for the dynamics and/or Mars communities. Some of these issues have been discussed in the literature before, especially the bolide rate changing (see Section 5.4), but a synthesis based

[1] As a nomenclature note, the term "basin" is often used; however, "basin" has no set definition; different researchers use it for craters just >100 km across, others >250 or >300 km across, and others use it for craters >1000 km across. Therefore, in this work, the generic word "crater" is used instead of "basin."

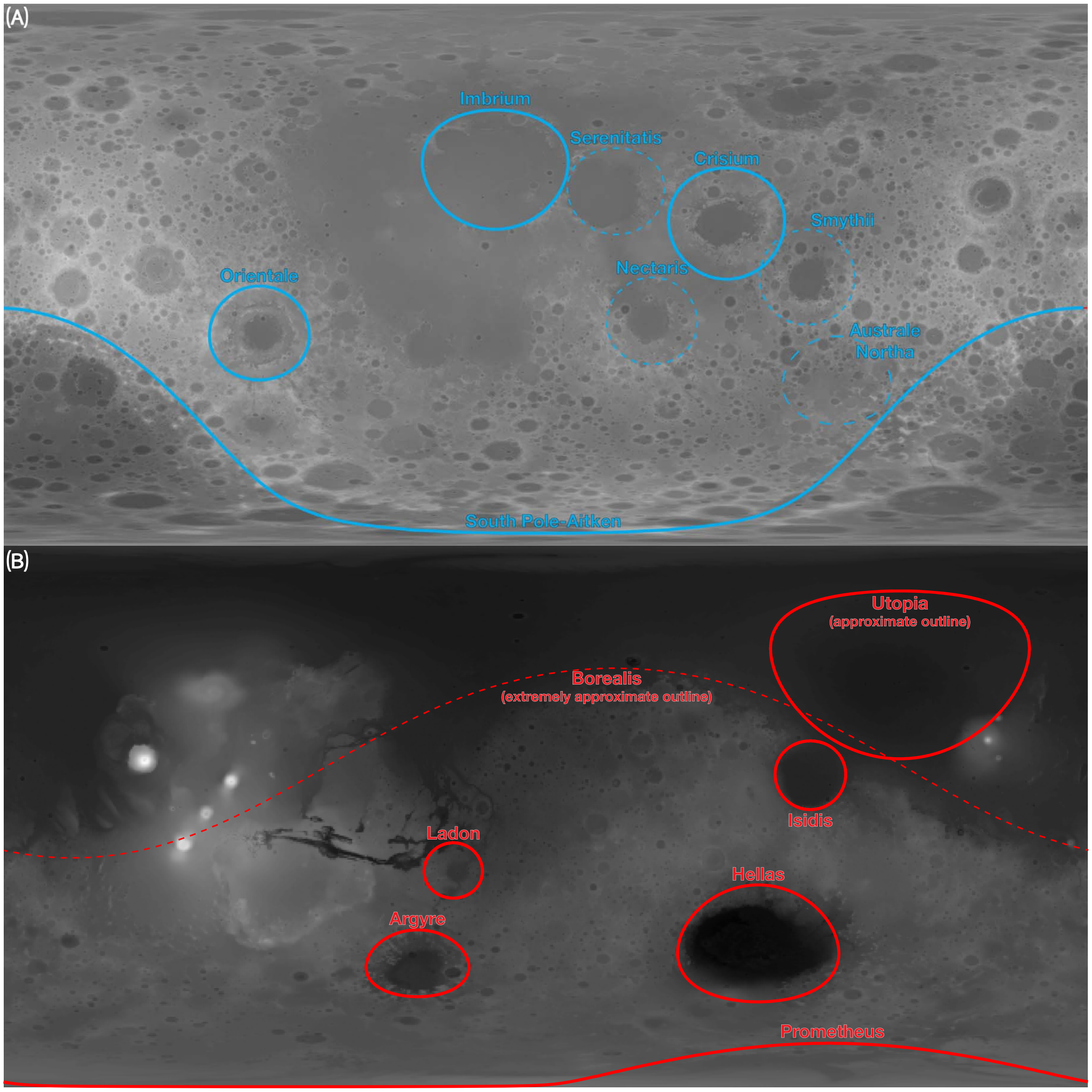

Figure 1. Topographic maps (black = low, white = high) of the Moon (top; Smith et al. 2010) and Mars (bottom; Smith et al. 2001) in equirectangular projection with the impact craters considered in this work overlaid. Short-dashed lines on the Moon indicate possible additional craters based on some uncertainty in their diameters, while Australe Norta is long-dashed because it could not be definitively identified in topography or images (note: maria infill is not necessarily a crater's rim). Short-dashed Borealis on Mars is due to some remaining controversy about whether it is a true impact crater and to indicate its extremely uncertain rim.

on a census of these largest craters and a straightforward crater scaling has not yet been described as it is here.

2. Craters Considered

2.1. Moon Impact Craters

One of the two data sets for large lunar craters used in this work comes from Neumann et al. (2015), who constructed a robust database of the Moon's large-impact craters based on gravity data from the Gravity Recovery and Interior Laboratory (GRAIL) mission. This data set lists four craters of Orientale's size or larger: South Pole–Aitken (SPA; ∼2400–2500 km), Imbrium (∼1100–1300 km), Crisium (∼1100 km), and Orientale (≈940 km).

The Robbins (2018) lunar crater database was produced based on image and topography data, and all craters larger than ∼200 km were compared with other existing databases for possible inclusion, elimination, or other correction. Robbins's database adds Smythii as a ≈955 km crater, while the Neumann et al. work lists it as ≈878 km. Given the different source data and degradation state, it is not surprising that there is some variation in measuring this feature. Orientale postdates Smythii, so its inclusion must be considered. Therefore, one could say that there are 4–5 craters on the Moon that are Orientale's size or larger and Orientale's age or older.

For an expanded crater list, Smythii's diameter in the Neumann et al. database, or larger, could be used instead. Those craters number eight; in addition to the previous five, they add Serenitatis, Nectaris, and Australe Northa. There is also a natural break in diameters in their list between Smythii and the next-largest crater, Humorum, which they measured as 816 km. The Robbins database includes the first two, but not the third, and it similarly lists Humorum after a natural break in diameters. Therefore, an alternative list is that there are 7–8 craters on the Moon with diameters $D > 860$ km which are Orientale's age or older. Figure 1 shows these impact craters on

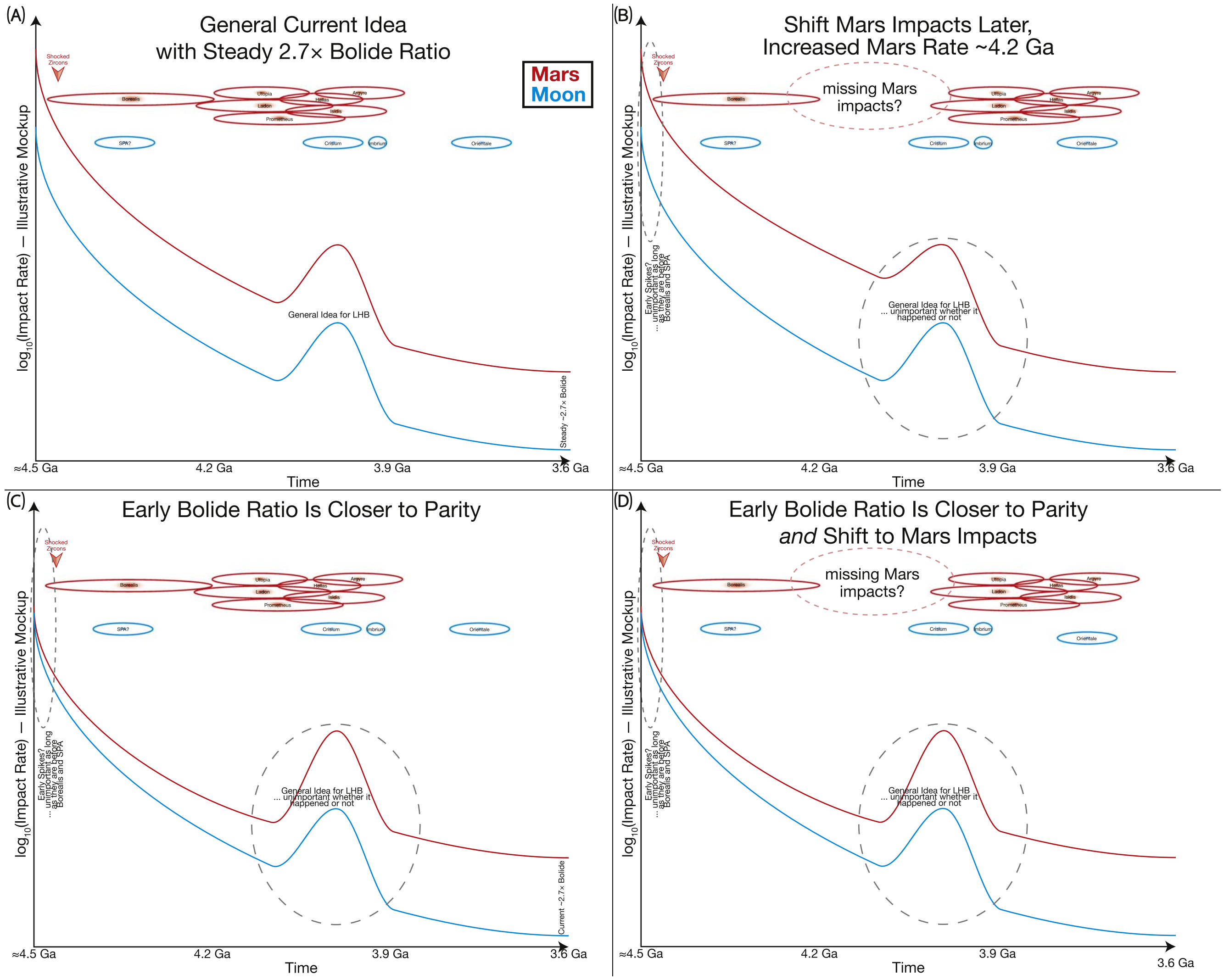

Figure 2. Various scenarios of Moon's and Mars's cratering history presented in this work, where the vertical axes are meant to be illustrative and not precise. The crater ellipses in the horizontal direction indicate uncertainty in their ages based on established, extrapolated crater-based chronologies, while the vertical component is for visibility; crater ages' references are at the end of this caption. Panel (A) represents a typically thought of early solar system, where the LHB is approximate (it might be broader, narrower, shift ~100 Myr in time, or not exist), and the simplest scaling of today's Mars:Moon bolide rate is given. Panels (B)–(D) emphasize that any pre-Borealis or pre-SPA heavy bombardment is not important for this work, nor is the shape (or existence) of the LHB, so long as they happened to both Moon and Mars between the times of Borealis/SPA and Orientale. Panel (B) supposes that there was an increased bolide rate at Mars after Borealis formed, and that the ages of post-Borealis craters are shifted forward in time. That would allow for impacts that would have formed large craters to exist but not have been preserved. Panel (C) supposes that the bolide ratio was much less early in the solar system's history, which would mean fewer early, large Mars craters are expected to form, so does not need as much adjustment to the observational record. Panel (D) merges parts of (B) and (C) together. Ages references: SPA's age is based on it being older than the oldest smaller dated craters while younger than the Moon itself; Crisium's age is based on Baldwin (1987a); Imbrium's age is based on the large number of Apollo samples formed ≈3.92 Ga (Bottke & Norman 2017); Orientale's age is based on Stewart-Alexander & Howard (1970), Baldwin (1987a, 1987b), Geiss & Rossi (2013), Yue et al. (2020). Borealis is set based on Nimmo & Tanaka (2005) and other work discussed in the main text; Utopia on Frey (2004, 2008) and Isidis, Ladon, Prometheus, Hellas, and Argyre are based on Robbins et al. (2013). While there is potentially a large amount of time between Argyre and Orientale, Argyre is the youngest large basin on Mars, the next largest being ~500 km across, so it is not considered in this work.

the Moon overtop topography, and Figure 2(A) shows the first four's model formation ages.

2.2. Mars Impact Craters

Most Martian impact crater databases do not strongly disagree about large, distinct craters, so the database of Robbins & Hynek (2012) in conjunction with the mapping from Robbins et al. (2013) for the largest craters is used here. They—and others (e.g., Barlow 1988)—typically recognize just four prominent, "obvious" large craters on Mars: Utopia (~3400 km), Hellas (~2300 km), Argyre (~1300 km), and Isidis (~1300 km). While size estimates vary considerably when measuring possible visual rims versus crustal thickness cavities (e.g., versus diameters from Bottke & Andrews-Hanna 2017), all would still be included in this sample, so their diameters to even ~±30% accuracy are unimportant for this discussion.

In addition to the above, Prometheus is near the South Pole with a partial rim that forms a crater ~860 km across, and the ancient, peak-ring Ladon crater is ~1100 km across. Figure 1 shows these impact craters on Mars overtop topography. These total six impact craters in the approximate size range of Orientale and larger. The next-largest commonly recognized crater on Mars is Huygens, which has a distinct rim just ≈467 km across, so it is outside of the range of this work, even when scaling impactor-crater size relationships from the Moon (see Section 3) or considering the expanded lunar crater list with diameters larger than Humorum.

In the other size direction, a possible seventh crater is the Borealis crater, or the entire northern plains of Mars. Andrews-Hanna et al. (2008) demonstrated more convincingly than earlier work that it is likely a giant, elliptical impact crater $\sim$8600 × 10,500 km. This is commonly accepted today, though because there is still some controversy (e.g., Ballantyne et al. 2022), it is listed only as a possible seventh large, ancient impact crater on Mars in this work.

The Robbins et al. (2013) work is the most systematic for assigning ages to these impacts so is used here, though their work is in agreement with several others' based on modern imagery (e.g., Werner 2008; Fassett & Head 2011). Using a wide range of crater-based model ages, they concluded that Argyre is the youngest of those craters. The absolute model age of Argyre is somewhere around 3.91 ± 0.03 Ga to 4.00 ± 0.03 Ga (depending on the crater-age model), so Argyre is potentially Imbrium-aged. As this is older than Orientale' age of $\sim$3.7–3.8 Ga, all of the large, identified Mars craters can be treated as the comparison set for this work; Figure 2(A) includes a timeline of their model ages. It should be noted that Frey (2004, 2006, 2008) also date these large craters using superposed—but buried—quasi-circular depressions (QCDs; see Section 5.6 for further discussion of these features). While their stratigraphy broadly agrees with the above, it contradicts the order of Argyre and Isidis based on the superposed crater counts that Fassett & Head (2011), Robbins et al. (2013), and Werner (2008) all independently performed, leading to some questions about its validity.

Beyond these more apparent large-impact craters, numerous other features have been discussed in the literature, both before the availability of global topography (e.g., Schultz & Frey 1990) and after (e.g., Frey 2004, 2006, 2008). For example, the Chryse region of Mars is a broad, circular depression at the outflow of Valles Marineris between Tharsis and Arabia Terra. It is commonly thought of as an impact structure (e.g., the above references, Schultz et al. 1982, and Pan et al. 2019), but others have made a strong case that the gravity data of Mars do not support the conclusion that it is a buried impact crater (Bottke & Andrews-Hanna 2017). From a population standpoint, Frey (2004, 2006, 2008) and several pre-global topography authors have argued that there is a significant population of large craters. However, it is generally the case today that extremely few—if any—of these features are accepted as impact structures, and the work of Bottke & Andrews-Hanna (2017) demonstrated that <12 megameter-scale craters could form after the Borealis event.

Therefore, for the purposes of this section, until the erasure of large craters on Mars is discussed in Section 5.6, Mars has only the above-described 6–7 large craters.

3. Scaling

3.1. Traditional Scaling of Crater Diameters

Scaling the expected impact crater diameter from one large, solid body to another that is composed of similar material can be reduced to two basic variables: the ratio of impact speed and the ratio of surface gravity. While there are other variables in determining the final impact crater diameter, they cancel out under the above assumptions, which to first-order are valid in scaling between Moon and Mars. The Hartmann (2005) treatment of this problem is still valid today, for there has not been any substantial revision of the impactor velocity distributions at bodies in the inner solar system (via Ivanov 2001), and there is no revision to the bodies' average surface gravities, as they are well known.

For velocity, scaling goes approximately as the kinetic energy, E, which from Schmidt & Housen (1987) affects crater diameter as $D \propto E^{0.43}$:

$$\text{velocity: } D_{\text{Mars}}/D_{\text{Moon}} = (10/14)^{0.43} = 0.865. \tag{1}$$

Scaling for gravity from Schmidt & Housen (1987) is $D \propto g^{-0.17}$:

$$\text{gravity: } D_{\text{Mars}}/D_{\text{Moon}} = (3.73/1.62)^{-0.17} = 0.868. \tag{2}$$

Simple multiplication provides a final scaling of

$$\text{total: } 0.865 \times 0.868 = 0.751. \tag{3}$$

A more recent review by Johnson et al. (2016) favored slightly different scaling, pulling equations from Schenk & McKinnon (1985). Here, the final crater diameter is dependent on velocity $D \propto v^{0.5}$, gravity $D \propto g^{-0.25}$, and the diameter of the simple-to-complex crater transition as $D \propto D_{s\rightarrow c}^{-0.13}$. Applying this scaling,

$$\text{total: } (10/14)^{0.5} \times (3.73/1.62)^{-0.25} \times (6/15)^{-0.13} = 0.773. \tag{4}$$

Despite different parameters or exponents, a bolide of a given size appears to produce a crater roughly 3/4 the diameter on Mars as it would on the Moon. Therefore, scaling Orientale's impactor's diameter to Mars, the bolide would likely have produced a crater $D \approx 700$ km on Mars. Using Neumann et al.'s diameter for Smythii at $\approx$880 km, that crater on Mars would be $\approx$660 km. As there is the natural break in identified crater diameters on Mars between 500 and 860 km (Huygens and Prometheus), the lunar minimum diameter for either cutoff does not change the list of Mars craters.

3.2. Fixed Scaling for Expected Crater Number

There are two primary factors affecting the number of craters expected on one body versus another: the impactor flux (bolide/km^2) and the body's surface area. In this discussion, Mars's atmosphere is negligible because it will not significantly affect bolides that would produce multihundred-kilometer craters. Addressing the second factor first, the bodies' surface areas are known quantities, and the ratio is simply evaluated: $\text{SA}_{\text{Mars}}/\text{SA}_{\text{Moon}} = 3.822$.

The bolide ratio is a more complicated issue, and it has been the subject of many dynamical studies (see discussion in Section 5.4). One of the most robust recent efforts to establish a value in the present-day solar system for Mars:Moon bolides is Ivanov et al. (2002), who found 2.7, though there are substantial uncertainties. For purposes of this and the next section, however, a value of 2.7 is adopted, and further discussion of it is in Sections 5.4 and 6.

Combining the bolide ratio and surface area scaling, one would expect $3.8 \times 2.7 \approx 10$ times as many Orientale-sized and -aged impacts on Mars as on the Moon.

4. Results

Putting the numbers from Sections 2–3 together is straightforward. There are 4–5 Orientale-sized impacts on the Moon that are Orientale's age or older (or 7–8 depending on slight adjustments to the lower size bound), and there are 6–7 scaled Orientale-sized impacts on Mars that are Orientale's age or older. The observed Mars number is significantly smaller than the scaling would predict: using the $\approx 10\times$ factor on 4–8 lunar craters, one expects $\sim$40–80 similarly sized and -aged craters on Mars.

5. Methods to Reconcile Observations and Theory

This mismatch between expectation and observation is significant. There are several possible, non-mutually exclusive implications and ways to reconcile these findings, and each is discussed in the subsections below. The purpose of this section is to discuss these different scenarios and give our opinion on which one(s) is or are most likely to yield results that reconcile the mismatch; definitive conclusions are not made because there are none yet.

5.1. Small Number Statistics

With roughly just half a dozen craters on both bodies, the small numbers issue must be considered at least partially responsible for the mismatch. For example, removing just one lunar crater reduces the number required on Mars by 10. However, the observation-expectation mismatch of nearly an order of magnitude is not within any reasonable uncertainty of these small numbers. For instance, attaching a simple Poisson counting uncertainty of $\pm N^{1/2}$ would give a range of 2–11 lunar craters, ergo expecting $\sim$20–110 Martian craters, which is still three times those observed at the lower bound.

5.2. Values in Impactor-crater Scaling are Wrong

Crater scaling is based on fundamental physics, laboratory experiments, and hydrocode simulations. The only variable in the scaling from Section 3.1 that might possibly be uncertain is the velocity distribution of impactors between Moon and Mars $\sim$4 Ga. These velocities would need to be wrong by a factor on the order of $\sim$10,000 to account for the mismatch on their own. Such a large error is extraordinarily unlikely and does not make sense dynamically, where even scattered comets would only have velocities $\sim 5\times$ larger than well-behaved asteroids.

However, scaling very large craters, where "large" is roughly thought of as when the target's curvature becomes nontrivial, is less well constrained than scaling laws for smaller impact events (Stewart 2010, 2012; Davies et al. 2015). Therefore, it must be considered whether accounting for this poorly constrained effect would significantly affect the list of craters for Moon and Mars. While curvature is nontrivial for $\sim$1000 km scale lunar craters, it *is* more trivial for $\sim$1000 km Mars impacts, and estimates of the scaling uncertainty are likely not off by enough to affect these results. Put another way, it is unlikely that Orientale's impactor, if hitting Mars, would produce a crater small enough to not be included in the Mars crater list. Meanwhile, the Huygens crater on Mars would need to be scaled up by a factor of nearly 2 on the Moon to begin to be considered in this work, and it is similarly unlikely that the impactor-crater scaling is off by that much.

5.3. Lunar Nearside Megameter-class Craters are Abnormally Large

A consideration related to the previous subsection is that the nearside lunar craters are larger than they otherwise would be. Miljković et al. (2013) proposed this scenario, motivated by the observation of more large craters on the nearside than farside. Their numerical modeling indicated that large impacts in a crust with more heat flow could form craters up to two times as large as those formed in cooler farside crust from the same impactor parameters.

If true, and if the farside heat flux was more similar to Mars's crust, that would eliminate Imbrium and potentially Crisium from the lunar megameter-scale crater counts. Those eliminations could lower the expected large-crater number on Mars by the linear factor of 2, expecting only $\sim$20. If the larger number of lunar craters were included (Serenitatis, Nectaris, Australe Northa), then 3–4 of the 7–8 craters would be eliminated, again cutting the required Martian craters by half.

However, this analysis also assumes that Mars's crust was cool relative to the nearside Moon and was, instead, more similar to the farside Moon, when these large Martian craters are forming. The timing of exactly when these events happened and the precise cooling model on each body would be critical in exploring this method to reconcile the crater populations.

5.4. The Early Solar System Bolide Ratio was Different

A more likely partial or even full solution to the observation-expectation mismatch is that the bolide scaling value used for today ($\approx$2.7) is not correct for the first several hundred million years of inner solar system history. Indeed, the review by Bottke & Norman (2017) included estimates from $\approx$1.0 to $\approx$5.3, with a discussion that different components of the early impact flux could be substantially different from today (elaborated on below). As the ratio of large impacts scales linearly with this parameter, if it were merely 1 instead of 2.7, that would help significantly to resolve the mismatch (e.g., Figure 2(C)).

This is likely at least part of the solution because it is well known that the dynamics of smaller bodies in the solar system's early days were not the same as they are now (e.g., Bottke & Norman 2017; Morbidelli et al. 2018). Scattering of objects that could become impactors from dynamical rearranging of giant planets and effects within the asteroid belt (e.g., Gomes et al. 2005; Tsiganis et al. 2005; Bottke et al. 2012) could affect the bolide ratio, as could residual planetesimals from accretion or early asteroid belt escapees before they were collisionally evolved (Walsh et al. 2011, 2012; Nesvorný et al. 2017). However, one must be careful about the mixtures of source impactors, for they are somewhat constrained by the crater retention ages—or, at least, the observed number of large impacts—observed on each body (Bottke & Norman 2017); removing the first $\sim$100–200 Myr of those bodies' surface histories—and therefore those as constraints—could help drive the source impactor mixtures to ones more favorable to solving the mismatch (Morbidelli et al. 2018), though other constraints might not allow this (see Section 5.5).

In support of a time-dependent bolide argument, Morbidelli et al. (2018) and others demonstrated that the Mars:Moon bolide ratio is substantially different depending on the impactor source population. Nesvorný et al. (2017) also ran extensive solar system evolution numerical integrations using different possible initial conditions, and they found the ratio might have started at 2.8–2.9, but it evolved to 1.5–2.3 after 400 Myr. If the ratio changed while these large, $\sim$1000 km class craters formed, that would also mean that the Martian crater-based chronology is wrong, moving some ages earlier by up to

≈200 Myr (more time would be needed to account for the same number of craters); implications are discussed in the next subsection. Additionally, dynamical models such as those in Morbidelli et al. (2018) demonstrated that the relative components from different impactor source populations were likely different for the early Moon and Mars, where they estimated that comets accounted for a much larger fraction of impacts on the early Moon than they did on early Mars. Such a difference could invert the early bolide ratio from the roughly 2.8 in the present day to ~0.5 early on.

Additionally, it must be noted that it is possible—even likely—that the bolide ratio is not only time-dependent as a whole, but is dependent also on impactor size that similarly changes as a function of time. A changing size distribution has been discussed before, such as by Strom et al. (2005, 2015), who described the possibility of "Pop 1" versus "Pop 2" impactors pre- and post-heavy lunar bombardment that followed different size-frequency distributions (SFDs). For the earliest times in the solar system, it is likely that small and large impactors followed the same bolide ratio, however, because there had yet to be much dynamical evolution that would have altered the large versus small bodies differently.

Where this becomes potentially important to consider is whether the works quoted above that describe the bolide ratio are describing it for smaller bodies or larger bodies, *if* the SFD has changed: A "bolide ratio" today of 2.4 versus a ratio of 1.0 several billion years ago might apply to objects <10 km across, not to those large enough to create megameter-scale craters. Therefore, the potentially variable bolide ratio as both a function of time and diameter must be considered and better understood.

5.5. Mars's Early Crater-based Age Chronology is Wrong

Orientale is well anchored in the lunar chronology, and the absolute model age is unlikely to be inaccurate by more than ∼100 Ma. This gives ∼700–800 Myr to form Orientale and the other several large craters (Figure 2(A)). However, scaling the lunar chronology to Mars incorporates all of the above uncertainties, the uncertainty in the lunar crater chronology function, and the assumption of a time-invariable bolide ratio between Moon and Mars.

While relative Martian ages can be anchored with Argyre, its age is still a model age. Pushing Argyre to ages significantly older than ≈3.9–4.0 Ga would not solve the mismatch because there are no obvious large younger features. Given that Argyre postdates all known erosion that could remove younger, multikilometer-deep, megameter-scale craters, they likely did not form (such craters should also be present in gravity data, but none are observed (Bottke & Andrews-Hanna 2017)). If Argyre were significantly younger than ≈3.9–4.0 Ga, then the other large craters might be, too (Figure 2(B)). Utopia is commonly dated to ≈4.3 Ga, which is similar to the model age of SPA, considered the oldest preserved large lunar impact. If Argyre *and* Utopia were younger, then that would imply there is a longer stretch of early Mars's impact history that is not preserved today, something favored in dynamical work such as Morbidelli et al. (2018) and Marchi (2021), and supported by the conclusions of observational work by Werner (2014). Under that supposition, one must posit that there were likely many large, Orientale-class craters on Mars for which there is simply no record in the crust or gravity due to Mars's early active surface and heat flow (which could rule out the moon's nearside heat flow as a possible way to reconcile the mismatch). Potentially bolstering this scenario, a different early Mars:Moon bolide ratio necessarily changes the early crater model ages for Mars, for it would not be a simple, linear extrapolation from the Moon (Figure 2(D)).

However, dynamical work (e.g., Marchi 2021) suggests that Mars was only hot enough to prevent crater formation until ≈4.35–4.40 Ga, when the large Borealis basin formed (through a giant impact, mantle plume, or some other mechanism). Morbidelli et al. (2018) also prefer to place Borealis at an age of ≈4.37 Ga, implying <150 Myr of Mars's surface history is missing. In contrast, Werner (2014) argued the first 200–400 Myr of Mars's surface history is missing.

While one might be able to stretch large, non-Borealis impacts (Figures 2(B), (D)) forward in time, supposing Borealis formed more recently is more difficult. Zircons in the Martian meteorite NWA 7034 ("Black Beauty") have evidence of shock dating to the ≈4.4–4.5 Ga time period. These zircons must have been shocked by a major heating event or events, such as the formation of Borealis by an impact (Hu et al. 2019; Moser et al. 2019; Costa et al. 2020; Cox et al. 2022). That we do not have a record of similar shock events in the ∼4.0–4.3 Ga time frame suggests Borealis formed during that recorded shocked zircon record (Bottke & Norman 2017), anchoring Borealis to a time period older than that preferred by recent dynamics work (e.g., Morbidelli et al. 2018; Marchi 2021); this again assumes that Borealis is a crater or it formed from an impact event. However, it is possible that our Martian zircon record is missing a later, major event. It is also conceivable that there was simply a larger time gap between Borealis and Utopia, during which large impacts formed and were not recorded, potentially due to the heat caused by Borealis itself (Figures 2(B), (D)).

5.6. Mars has Hidden ∼80% of its Large, Ancient, Post-SPA-aged Craters

This explanation posits that, somehow, Mars has hidden or destroyed much of its large-impact crater population from the first ≈700–800 Myr of its history. This is possible, at least to a certain extent, beyond the chronology argument above and the hiding of some impacts in a hot, soft Mars between the formation of Borealis and Utopia. The actual mechanisms are unimportant for this discussion, just whether it could have happened and what evidence for or against it exists (e.g., whether aqueous erosion or volcanic overprinting happened does not matter for this discussion, just that *something* happened to remove craters).

One possible way to hide craters is Mars's north–south hemispheric dichotomy: Approximately half of Mars—practically all of the northern hemisphere—has a significantly younger surface age than the other half. These northern lowlands are the Borealis basin. While the true origin of the dichotomy is still debated (though most researchers now consider it to be of impact origin), superposition relationships indicate it is the feature preserved in Mars's crust. Because it contains the Utopia crater, Borealis must predate that feature, so it likely formed at least ⩾4.3 Ga (Utopia's model age). Based on cooling models (see previous section), it is unlikely that Mars's crust could support a ∼1000 km crater prior to Borealis forming, and Borealis almost certainly would have reset the crater retention age of the entire Martian surface.

Approaching this from a *relative* chronology viewpoint and the possibility that the crater-based absolute chronology from Mars is wrong, then if Borealis were an unlikely ∼4 Ga, that could solve the observation-expectation mismatch by simply having ∼30–70 craters that formed earlier be erased by Borealis. The <4 Gyr age would leave $N = 2$ craters on the Moon (Orientale, Imbrium) to scale to Mars for an expected ∼20 large craters. While this is still a factor of ∼3 mismatch, the effects discussed in earlier sections could further change this number, though it may be harder to alter the Mars:Moon bolide ratio at that point in the solar system's history. Conversely, if Borealis and Utopia are older, then this emphasizes the mismatch because the ancient, large-crater record should be well preserved, and the absence of large craters is more certain and cannot be as easily attributed to their not being preserved.

Transitioning to the argument that Mars might be hiding buried impacts, one possible area to hide craters is under the fairly young-appearing Tharsis volcanic province. Tharsis covers ≈25% of Mars, and no impact craters larger than 100 km are visible on it. Tharsis has been uplifted via a static mantle plume, and it contains a dozen large supervolcanoes that have resurfaced the region via volcanic eruptions. Ergo, it is plausible that this region could hide large, ancient impact craters, though Bottke & Andrews-Hanna (2017) found no such large impacts on the buried dichotomy boundary beneath Tharsis. However, using a simple area argument in a thought experiment, Mars's large-crater population could be increased by ∼30% to allow for ∼2–3 buried features to be added to the total. This does not come close to solving the mismatch.

One can expand this discussion to the possibility discussed in Section 2.2, that some researchers have argued for a buried impact population on Mars that is both large in physical size and quantity. With the advent of global topography, this hypothesis is mostly argued for by Frey (2006, 2008). Specifically, Frey (2006) lists 10 additional possible craters $D > 1000$ km, and another nine are visible in their Figure 3 with $D > 700$ km; this work was followed up by Liang et al. (2022) who examined gravity anomalies, though their work was for craters $D < 500$ km. If all of the features identified in Frey (2006) are real impact craters, then there are a total of 23 large, ancient impacts, which is still only *half* as many as are expected from the Moon:Mars scaling described in previous sections.

However, it should be noted that Frey's work is not widely accepted within the impact crater community, and most circular-appearing features they identified have been questioned by later work. For example, Bottke & Andrews-Hanna (2017) demonstrated that the existing gravity data do not support the existence of other large, buried craters (e.g., the gravity data strongly support Utopia being a crater, despite its size and age, but there is no corresponding signal beneath Chryse Planitia, which had often been considered an impact crater nearly 2000 km across). They also performed Monte Carlo simulations and, based on the observation that Isidis is the only observed megameter-class crater to be imprinted on the dichotomy boundary, found that there should be <12 total megameter-sized craters after the Borealis formation event (in contrast with the 6 observed, plus 19 from Frey). Additionally, Frey (2012, and references therein) identified at least six Orientale-sized or larger QCDs on the Moon which were not supported in later work (including by GRAIL (Neumann et al. 2015)). If one accepts the Frey data for Mars, one should consider it for the Moon, ignoring GRAIL, which would double the lunar craters that must then double what is expected on Mars. Ergo, if one includes Frey's work, then the mismatch is actually exacerbated. Therefore, under no reasonably consistent scenario could these features account for the observed mismatch.

With that in mind, one could ask what is the likelihood that the gap in crater diameter between Huygens and Prometheus (∼500 and ∼860 km, respectively) is real, as intermediate-sized QCDs are not being considered? Robbins et al. (2021) provide two potential methods to address this question, and their description of using the cumulative distribution function and solving the binomial probability method is used here. Both their methods require estimating the crater SFD up through Huygens and assuming that that SFD would continue through larger craters. Using the Mars crater population to estimate a power law requires setting a minimum diameter; this was set to 100, 200, 300, and 400 km to test the sensitivity of the results, and Prometheus was the largest crater used in fitting. The most likely number of craters in each case in the 500–860 km range is 2, but it is still a 7%–11% chance that 0 craters would be in that gap. When incorporating the agreed-upon craters >1000 km in the determination of the SFD, the gap becomes more unlikely, approximately 1% chance, with the most likely number of craters in that gap being 4 (≈18%–19% chance, depending on the minimum diameter cutoff). The conclusion from the analysis in this paragraph is that at least a few of the QCDs in the ∼500–900 km range might be real impact craters, and if a few of them are real, perhaps one or two of those >1000 km are also real. However, it is not beyond all reasonable likelihood that the gap is real, especially with the caveat that this method assumes the smaller-crater SFD necessarily extrapolates to craters >1000 km. Regardless, an additional ∼5 craters are not enough to solve the order-of-magnitude Mars:Moon mismatch.

5.7. *Aside: Late-heavy Bombardment versus Heavy Bombardment versus Accretion Tail*

There remains significant debate (e.g., see review by Bottke & Norman 2017) about the nature of the impact flux in the inner solar system's first ∼800 Myr history: Is there a postaccretionary tail of impacts that simply decays with time, where features like Orientale are the last gasps of ∼1000 km causing impacts; was there a late-heavy bombardment spike around 3.9–4.1 Ga (similar to the model ages of most large craters discussed in this study) due to the aforementioned dynamical rearrangements; and/or was or were there earlier spike(s) perhaps as early as 10 Myr (e.g., Clement et al. 2018; Liu et al. 2022) or ∼100 Myr (e.g., Nesvorný et al. 2018; Ribeiro de Sousa et al. 2020) after planet formation? The veracity of these scenarios (or hybrids, or alternatives such as the sawtooth model of Morbidelli et al. 2012) does not matter for the broad observation-expectation mismatch described in this work so long as the same scenario happened on both Moon and Mars.

What might matter, however, is the effect(s) that any spike had on the bolide ratio at each body, and whether that ratio was or was not recorded in the impact crater record. The interaction between the timing of when each surface can begin to record impacts observed today, any spike in impacts, and any different

Mars:Moon bolide ratio could have roles in solving this overall large-crater population issue (e.g., Figure 2(D)).

6. Synthesis and Discussion

The similarity in the number of large (∼1000 km or larger) craters on the Moon and Mars that date to $\gtrsim$3.7 Ga is difficult to reconcile with a simple interpretation of what is known about the history of these bodies and the smaller objects that impacted them. The crater cataloging and straightforward scaling laws indicate roughly 10 times as many impacts should be present on Mars, which is difficult to reconcile with observations, even if several large features on Mars that are often discounted as impact craters actually are impact craters.

Of the six possible ways described above to explain the observation-expectation mismatch, one appears to be the most likely explanation, if not certainly a component of the solution given the modeling that exists in the literature today: The bolide ratio between Earth and Mars today is not what it was when these craters were forming, and especially the *large* bolide ratio that produces megameter-sized craters was different. There are strong dynamical arguments for it to be different, and there are strong dynamical arguments for it to be more complex than a straightforward ratio based on Mars- and Earth-crossing asteroid populations today. If the bolide ratio were smaller, that helps to significantly reduce the number of expected large old craters on Mars.

Beyond the bolide ratio today not being applicable ∼4 Ga, the next simplest way to account for the mismatch is the modeling that indicates half the lunar craters in the sample scaled to Mars might be excluded: If the modeling that suggests those craters would be just half their size if they had formed in the same cool lunar crust as Orientale is true, then that could reduce the number of large craters Mars needs to have by half. However, this must be paired with a realistic cooling model for Mars such that its crust would be similar to the lunar farside rather than nearside, something in between, or hotter than the nearside. If the timing works, then in conjunction with the bolide difference early in the solar system's history, this might be a strong, straightforward component of the solution that neither requires revision to Mars's crater chronology nor requires any different bolide ratio.

After exhausting those two mechanisms, the next-most likely components are for the ancient Martian crater chronology to be revised, and/or for Mars to have hidden large, ancient impacts. While Borealis is either roughly the same age or a little older than SPA (Figure 2(A)), such that pre-Borealis impacts cannot help solve the mismatch, then it is possible that stretching the time between Borealis and Utopia would allow for large impacts to have formed that were then relaxed away by the large amount of heat in the crust. This fits with the argument of Mars "hiding" large impacts, which it also might do to a certain extent under the vast Tharsis volcanic province (though this is more difficult to do based on the dichotomy boundary still being visible under Tharsis in gravity data).

Overall, there does not appear to be a clear, single, simple mechanism to explain the discrepancy of large-impact craters between Moon and Mars that presumably formed within the first ≈700 Myr of the solar system. While there are several possible mechanisms that could explain it, it is likely that the dynamical adjustments to the relative impact rates on both bodies early in their history will bear the most fruit. However, this does not need to be the sole solution. Future, better mapping of Mars's gravity field might help reveal more buried impacts that defy detection today, or follow-up modeling of how large craters form in hot versus cool crust could also be effective.

S.J.R. acknowledges helpful feedback from W.F. Bottke, J.M. Boyce, R.E. Grimm, B.M. Hynek, M.R. Kirchoff, D. Nesvorný, J.D. Riggs, and K.J. Walsh in the preparation of this manuscript, and two anonymous reviewers for helpful and constructive feedback. The author acknowledges significant "free time" for the preparation of this manuscript.

ORCID iDs

Stuart J. Robbins https://orcid.org/0000-0002-8585-2549

References

Andrews-Hanna, J. C., Zuber, M. T., & Banerdt, W. B. 2008, Natur, 453, 1212
Baldwin, R. B. 1987a, Metic, 22, 111
Baldwin, R. B. 1987b, Icar, 71, 19
Ballantyne, H. A., Jutzi, M., & Golabek, G. J. 2022, Icar, in press
Barlow, N. G. 1988, Icar, 75, 285
Bottke, W. F., & Andrews-Hanna, J. C. 2017, NatGe, 10, 344
Bottke, W. F., & Norman, M. D. 2017, AREPS, 45, 619
Bottke, W. F., Vokrouhlický, D., Minton, D., et al. 2012, Natur, 485, 78
Clement, M. S., Kaib, N. A., Raymond, S. N., et al. 2018, Icar, 311, 340
Costa, M. M., Jensen, N. K., Bouvier, L. C., et al. 2020, PNAS, 117, 30973
Cox, M. A., Cavosie, A. J., Orr, K. J., et al. 2022, SciA, 8, 7497
Davies, E. J., Stewart, S. T., Lillis, R. J., et al. 2015, LPSC, 46, 2212
Fassett, C. I., & Head, J. W. 2011, Icar, 211, 1204
Frey, H. V. 2004, LPSC, 35, 1382
Frey, H. V. 2006, JGRE, 111, 8S91
Frey, H. V. 2008, GeoRL, 35, 13203
Frey, H. V. 2012, LPSC, 43, 1852
Geiss, J., & Rossi, A. P. 2013, A&ARv, 21, 68
Gomes, R., Levison, H. F., Tsiganis, K., et al. 2005, Natur, 435, 466
Hartmann, W. K. 2005, Icar, 174, 294
Hartmann, W. K., & Neukum, G. 2001, SRv, 96, 165
Hu, S., Yangting, L., Jianchao, Z., et al. 2019, M&PS, 54, 850
Ivanov, B. A. 2001, SSRv, 96, 87
Ivanov, B. A., Neukum, G., Bottke, W. F., et al. 2002, in Asteroids III, ed. W. F. Bottke, Jr. (Tucson, AZ: Univ. Arizona Press), 89
Johnson, B. C., Collins, G. S., David, M. A., et al. 2016, Icar, 271, 350
Liang, F., Yan, J., Zhao, J., et al. 2022, P&SS, 220, 105532
Liu, B., Raymond, S. N., Jacobson, S. A., et al. 2022, Natur, 604, 643
Marchi, S. 2021, AJ, 161, 187
Marchi, S., Mottola, S., Cremonese, G., et al. 2009, AJ, 137, 4936
Miljković, K., Wieczorek, M. A., Collins, G. S., et al. 2013, Sci, 342, 724
Morbidelli, A., Marchi, S., Bottke, W. F., et al. 2012, E&PSL, 355, 144
Morbidelli, A., Nesvorný, D., Laurenz, V., et al. 2018, Icar, 305, 262
Moser, D. E., Arcuri, G. A., Reinhard, D. A., et al. 2019, NatGe, 12, 522
Nesvorný, D., Roig, F., & Bottke, W. F. 2017, AJ, 153, 103
Nesvorný, D., Vokrouhlický, D., Bottke, W. F., et al. 2018, NatAs, 2, 878
Neukum, G. 1984, PhD thesis, Ludwig-Maximilians Univ.
Neukum, G., Ivanov, B. A., & Hartmann, W. K. 2001, SSRv, 96, 55
Neumann, G. A., Zuber, M. T., Wieczorek, M. A., et al. 2015, SciA, 1, e1500852
Nimmo, F., & Tanaka, K. 2005, AREPS, 33, 133
Orgel, C., Fassett, C. I., Michael, G., et al. 2020, JGRE, 125, e06212
Pan, L., Quantin-Nataf, C., Sylvain, B., & Michaut, C. 2019, NatCo, 10, 4257
Ribeiro de Sousa, R., Morbidelli, A., Raymond, S. N., et al. 2020, Icar, 339, 113605
Robbins, S. J. 2014, E&PSL, 403, 188
Robbins, S. J. 2018, JGRE, 124, 871
Robbins, S. J., & Hynek, B. M. 2012, JGRE, 117, E05004
Robbins, S. J., Hynek, B. M., Lillis, R. J., et al. 2013, Icar, 225, 173
Robbins, S. J., Riggs, J. D., & Parker, A. H. 2021, GeoRL, 48, 93247
Schenk, P. M., & McKinnon, W. B. 1985, JGR, 90, 775
Schmidt, R. M., & Housen, K. R. 1987, IJIE, 5, 543
Schultz, P. H., Schultz, R. A., & Rogers, J. 1982, JGR, 87, 9803
Schultz, R. A., & Frey, H. V. 1990, JGR, 95, 14175

Shoemaker, E. M., Hait, M. H., Swann, G. A., et al. 1970, Sci, 167, 452
Smith, D. E., Zuber, M. T., Frey, H. V., et al. 2001, JGR, 106, 23689
Smith, D. E., Zuber, M. T., Jackson, G. B., et al. 2010, SSRv, 150, 209
Spudis, P. D., Wilhelms, D. E., & Robinson, M. S. 2011, JGRE, 116, 0H03
Stewart, S. T. 2010, LPSC, 41, 2722
Stewart, S. T. 2012, LPSC, 43, 2865
Stewart-Alexander, D. E., & Howard, K. A. 1970, Icar, 12, 440
Strom, R. G., Malhotra, R., Takashi, I., et al. 2005, Sci, 309, 1847
Strom, R. G., Malhotra, R., Zhi-Yong, X., et al. 2015, RAA, 15, 407
Tsiganis, K., Gomes, R., Morbidelli, A., et al. 2005, Natur, 435, 459
Walsh, K. J., Morbidelli, A., Raymond, S. N., et al. 2011, Natur, 475, 206
Walsh, K. J., Morbidelli, A., Raymond, S. N., et al. 2012, M&PS, 47, 1941
Werner, S. C. 2008, Icar, 195, 45
Werner, S. C. 2014, E&PSL, 400, 54
Yue, Z., Kaichang, D., Wenhui, W., et al. 2022, NatAs, 6, 541
Yue, Z., Yang, M., Jia, M., et al. 2020, Icar, 346, 13804