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Abstract

Meteoroids are known to impact the Moon although the smallest size fraction is unconstrained due to the difficulty in observing faint impact flashes. Here we present observations of lunar impact flashes from NASA's Artemis II crew during their lunar flyby on 7 April 2026 UTC. Five impact flashes were observed on the lunar farside during a total solar eclipse. These observations indicate meteoroids impacting the Moon with a lower limit of ~4.65 cm in diameter. The energy of each impact was equivalent to ~0.64 lbs of TNT and created a new lunar crater less than 1 meter in diameter. This information is used to supplement risk assessments for impact debris on lunar infrastructure which is critical as NASA plans to develop a sustained human presence on

the lunar surface. Artemis II flew outside of any major annual meteoroid streams, and thus these observations place a lower bound on the impact flux at the lunar surface. With these observations, the Artemis II crew set a record for the smallest meteoroids ever optically observed to impact the Moon.

Main

The cis-lunar environment is dynamic with new, fresh craters forming on the Moon in the present-day from micrometeoroid impacts. The meteoroids themselves are naturally-occurring fragments of comets, asteroids, and planetary impact debris that travel through space. When these meteoroids encounter the Earth, our atmosphere reduces the velocity of the meteoroid and most material ablates and/or disintegrates before reaching the ground. The Moon, however, lacks such an atmosphere and so these meteoroids impact the lunar surface directly. The kinetic energy of the impact works to heat the impacted material, produce an ejecta plume, and excavates an impact crater which also creates a seismic signature in the lunar interior (*1-3*).

These impact events create a visible flash on the lunar surface as the vaporization of material produces light emission (*3*) and hence can be observable from both the Earth and the Moon (*4*). There are at least three instances of Apollo astronauts observing impact flashes from lunar orbit (one reported impact flash on Apollo 16 and two flashes on Apollo 17; *5-6*). These impact flashes observed during Apollo were all observed on the unilluminated portion of the Moon but not during a total solar eclipse. Over 450 impact flashes have been detected in the last several decades by Earth-based telescopes through a variety of observing campaigns (*1*), and new surface impact features have been documented by the Lunar Reconnaissance Orbiter (LRO) spacecraft (*1, 7, 8*). The Artemis II crew had scheduled time during the lunar flyby to look for impact flashes on the non-illuminated lunar surface. Observations of impact flashes (or a lack thereof) aid in characterizing the lunar impact environment and determining the scale of what may be visible from cis-lunar space.

The observation of impact flashes on the Moon provides one of the best mechanisms to characterize the lunar dynamic environment. Given the unique vantage point of Artemis crew and their close proximity to the Moon, they had the opportunity to observe impactors that may be too small to be detectable by observations from Earth, where light is attenuated by the greater distance and scattered through Earth's atmosphere, thereby decreasing the sensitivity to low-light flash events. Additionally, the Artemis II crew was monitoring the farside of the Moon, providing a novel dataset that can be compared with the known rate from Earth-based nearside observations.

Observations

NASA's Artemis II mission was the first crewed mission to the Moon in over 50 years. The Space Launch System (SLS) rocket launched the Artemis II crew onboard the Orion vehicle from NASA's Kennedy Space Center (KSC) on 1 April 2026. As shown in the mission profile (Fig. 1), the Orion vehicle conducted a lunar flyby on Flight Day 6 (7 April 2026 UTC), bringing the astronauts within their closest approach of the Moon at 6,545 km above the lunar farside surface. This trajectory afforded the crew a unique view of the farside of the Moon at relatively close proximity. The launch and subsequent flyby date also occurred during a yearly minimum in

meteoroid flux activity in the Earth-Moon system and outside of any major annual meteor shower (*9, 10*), meaning that any observed meteoroids during the Artemis II mission and the associated lunar impacts place a lower constraint on lunar impact flux, representing the ever-present sporadic background population of impactors.

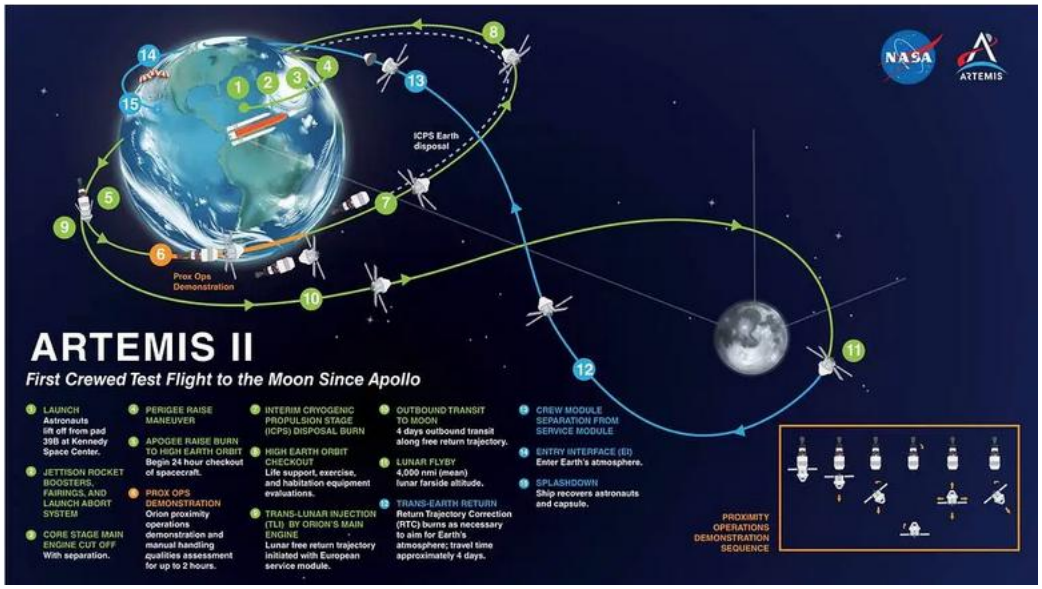


Figure 1. Artemis II flight path showing launch and orbit around the Earth followed by the flyby around the lunar farside. Scientific observations were specifically planned for the period of the lunar flyby, enabling observations during the closest approach to the Moon. Image credit: NASA.

The Artemis II astronaut crew conducted a dedicated lunar science campaign during their lunar flyby around the farside of the Moon on Flight Day (FD) 6 (April 7, 2026 UTC) of the Artemis II mission. The trajectory of the Orion spacecraft brought the crew within their closest approach to the Moon during the flyby which thus afforded the crew optimal viewing conditions to collect lunar observations. The crew utilized a Lunar Targeting Plan (LTP) that was created by NASA's Artemis II Lunar Science Team for strategic observing targets and was timed to optimize science return (*11*). The LTP included guidance for the crew to collect targeted imagery and verbal (audio) descriptions of scientific targets. Crew members were trained to observe the dark portion(s) of the Moon to visually monitor for impact flashes and record any observations via audio recordings on their PCDs (Personal Computing Devices) and/or through written PCD annotations (*12*). The crew was equipped within the Orion spacecraft with two Nikon handheld cameras, although these were not utilized for lunar impact flash monitoring due to the transient nature of impact flash phenomena. Additional data was collected via SAW (Solar Array Wing) camera imagery from the SAW cameras mounted on the exterior of the Orion vehicle. The SAW cameras were GoPro devices and were not able to unambiguously detect impact flashes primarily due to limited frame rates.

Observations of impact flashes were collected during the total solar eclipse period of the Artemis II lunar flyby. The sunset end/full eclipse start time was at 00:34:28.4 UTC on 7 April 2026 and the sunrise start/full eclipse end was at 01:28:54.4 UTC for a total solar eclipse duration of 54 min 26.0 sec. A portion of the Moon was in Earthshine during the eclipse, hence we calculate, at five minute intervals during the eclipse, the lunar surface area and fraction of the

lunar surface within the field of view of the Orion spacecraft that was in complete darkness (e.g., no direct solar illumination and no Earthshine), resulting in the values shown in Table 1. The average lunar surface area that was in darkness during the eclipse period was 11,768,763 km^2.

Eclipse time (UTC)	Lunar surface area (darkness), km^2	Surface area fraction (darkness)
0:35:00	12436673	0.3279
0:40:00	12286780	0.3239
0:45:00	12142731	0.3201
0:50:00	12004338	0.3165
0:55:00	11871395	0.313
1:00:00	11743688	0.3096
1:05:00	11620997	0.3064
1:10:00	11503104	0.3033
1:15:00	11389790	0.3003
1:20:00	11280843	0.2974
1:25:00	11176056	0.2946

Table 1. Values shown in 5-minute intervals for lunar surface area (center column) and fraction of the lunar disk (right column) in darkness (no direct sunlight or Earthshine) during the total solar eclipse of the Artemis II lunar flyby.

The Artemis II crew reported five impact flashes visible on the lunar surface during the period of the total solar eclipse (see Fig. 2). All impact flashes were observed where the lunar surface was not directly illuminated by the Sun and no impact flashes were observed in the portion of the Moon illuminated by Earthshine. Furthermore, no impact flashes were observed outside of the total solar eclipse time period (e.g., when the Sun and/or Earth were in the field of view from the Orion vehicle). An impact flash was reported by the crew as a “pin prick” of light, lasting less than one second, with no observable color associated with the flash. In addition, multiple crew members reported observing the same impact flash (both in the PCD audio files as well as the annotation, Fig. 2), lending more credence to the robustness of the flash observations. We assume the five impact flashes is a lower limit on the number of impactors as the crew reported several other ‘possible’ flashes with less certainty, and thus we only consider the five unambiguous flash detections in this work.

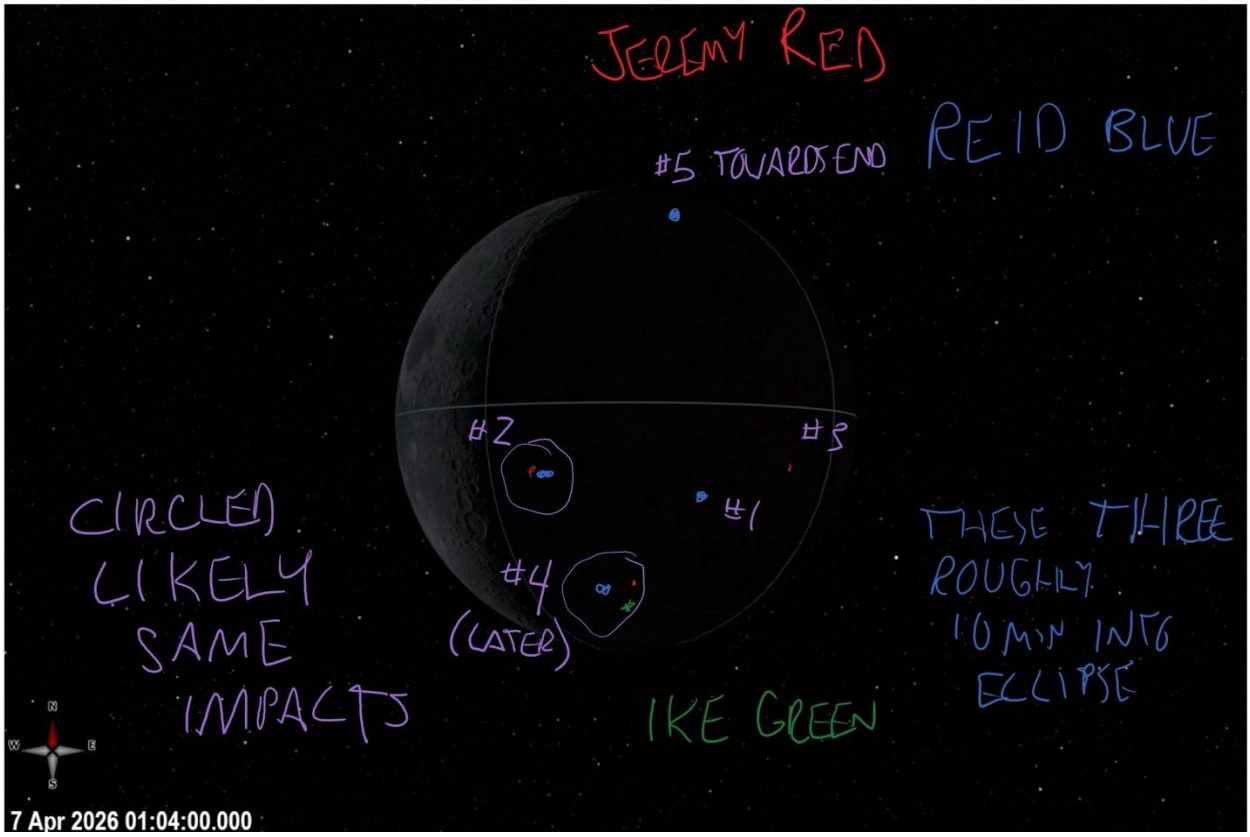


Figure 2: Artemis II crew annotation showing locations and observers of impact flashes observed during the total solar eclipse of the lunar flyby. All observations occurred on the unilluminated farside of the Moon with no flashes observed in Earthshine (left portion of the Moon in this image). Flashes observed by R. Wiseman are in blue, J. Hansen are in red, and V. Glover are in green. Impacts labeled #2 and #4 are circled, indicating that these flashes were observed by multiple crew members. Observations by C. Koch are not annotated with geolocation data although audio data from the Artemis II flight indicates C. Koch observed at least one of the same impact flashes as R. Wiseman (likely flash #5).

The impact flash observations reported by the Artemis II crew are considered true flash detections and are not radiation-induced light flashes, which is a well-known phenomenon experienced by astronauts during spaceflight (*13-16*). Approximately 80% of astronauts who travel in space experience sudden phosphenes, commonly called light flashes (LF). Although the detailed physiological process is still not known, the LFs are typically streaks of light observed by crew members, often during sleep periods, and are caused by particles in the cosmic radiation field. The Artemis II crew specifically addressed this issue during the post-flyby crew conference with the NASA Science Officer in NASA's Mission Control and confirmed that the impact flashes, (which were all similar in duration, intensity, and color), were distinguishable from the LFs, which are longer visible streaks and occurred during the mission including at sleep time. This description is consistent with the observations reported by Apollo 17 astronaut Harrison Schmitt who observed a lunar impact flash while in lunar orbit and also reported that this phenomenon was distinct from an LF (*5, 6, 17*). The Apollo 17 flash description was consistent

with that of the Artemis II flashes, e.g., less than one second duration, described as a “pin prick” of light, and no color.

Micrometeoroid impact flux constraints

Constraining impactor size

We use the relative size distribution of lunar microcrater data (lunar flux) to estimate the size of the observed Artemis II lunar impactors. This approach compares the measured flash flux with an external meteoroid-flux model that has been determined from relative crater size distributions and the Pegasus spacecraft datasets, supported by Explorer 16 and 23 datasets as well as optical and radar meteor data (*18-20*). During the Artemis II total solar eclipse, we calculate a detectable-flash flux of Φ flashes/km^{2}-hr as the lunar surface experienced N detectable impact flashes over an area-time product of AΔt, where N is 5, A is 11,768,763 km^2, Δt is 54 min 26 sec, resulting in Φ equaling 4.7X10^{-7} flashes/km^{2}-hr. Fig. 3 shows the impactor flux rate as a function of impactor size based on Grun et al. 1984. Using the known values for number of observed impactors from Artemis II, the average area of the lunar surface that was in complete darkness (no Earthshine) during the total solar eclipse of the Orion capsule lunar flyby, and the duration of the eclipse, we constrain the lower limit of the particle mass producing the observed impact flashes. The five observed impact flashes collected during this observation period suggest a limiting impactor mass of 8.5 grams. Assuming an average density of 2.5 g/cm^3 for typical meteoroid material (*21*), the average volume of these impactors is 3.4 cm^3 and the diameter is d=s X cuberoot (3V/4*pi) where d is the diameter and V is the volume, yielding a spherical particle of ~4.65 cm diameter (1.83 inches).

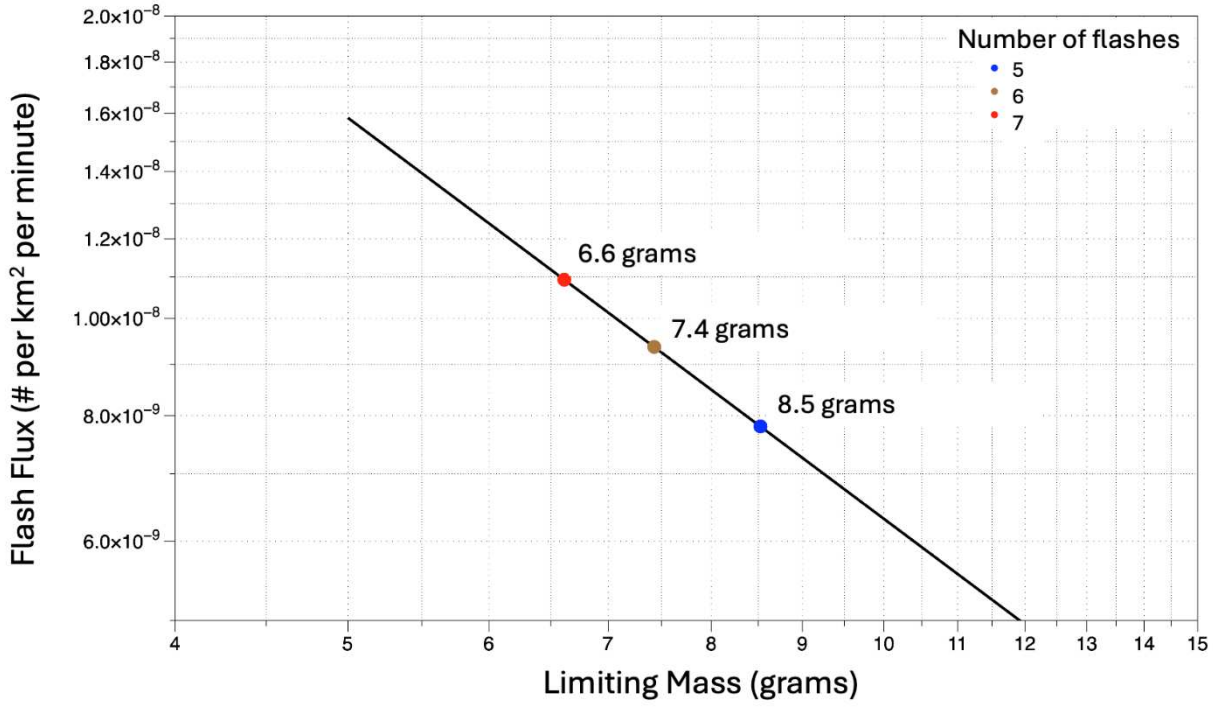


Figure 3. Impactor flash flux places a lower bound on the impactor mass (flux curve based on *20*). Five observed impact flashes during the Artemis II lunar flyby yields a limiting impactor mass of ~8.5 grams.

Given a bound on impactor size, we can determine the limiting energy of the impactors as well as the smallest size of the resulting craters. The energy (E) of the impact scales as $E=1/2*mv^2$ where m is impactor mass and v is impactor velocity. The typical velocity of sporadic meteoroids is 17 km/sec (*17*), which coupled with the impactor mass yields a lower limit on the impact energy of ~1,228,250 Joules, or the equivalent of 0.29 kg (0.64 lbs) of TNT. Using typical scaling laws for lunar impact crater formation with the assumption of an impact angle of 45°, the smallest crater produced on the lunar surface by these meteoroids would be ~0.8 m in diameter (*22-26*). The continuous ejecta blanket expected from these craters would extend ~2 m from the crater rim (*27*). The crater itself is below the detection limit of the Lunar Reconnaissance Orbiter (LRO) high resolution LROC camera (*28*) and so would not be observable from this platform. The proximal ejecta blanket would theoretically be within the resolving power of LROC. However, we do not anticipate being able to directly observe these new craters from lunar orbit since the geolocation data (Fig. 2) does not have the accuracy to target such small features.

Parameter	Value
Number of impacts	5
Observing duration	54 min 26 sec
Observing area (lunar surface) in darkness (avg, km^2)	11768763
Impact flash flux	3.5×10^{-9} # km^{-2} min^{-1}
Impactor limiting mass	8.5 g
Impactor limiting diameter	4.65 cm
Limiting Kinetic energy	~1,228,250 Joules (0.64 lbs TNT)
Smallest crater diameter	~0.8 m

Table 2. Summary of Artemis II impact flash observation parameters.

Impact probabilities for lunar surface infrastructure

As humanity moves towards a sustained human presence on the Moon and NASA develops Moon Base infrastructure, it is of interest to quantify impact probabilities for these cm-sized, megajoule particles, as they represent the smallest meteoroids observed to impact the Moon as of this date. For surface structures, the impact probability of these meteoroid impactors can be calculated as

$$P_{\text{impact}} = \frac{S_{\text{impact}}}{S_{\text{total}}} f_{\text{app}}\, t,$$

where S_{impact} is the effective impacting surface, S_{total} is the total surface of the sphere (e.g., Moon) with a radius equal to that used to derive the respective calculated appearance frequency of the meteoroids f_{app} (meteoroids / hour), and t the time of the mission (*3*). Here we use S_{total} as 37.9×10^6

km^2, f_{app} as 6 (scaling the Artemis II total solar eclipse observations to one hour), and an assumed initial mission timeline of two weeks (336 hours) for early Artemis flights. We consider the HLS (Human Landing System) vendors of Blue Origin and SpaceX for notional sizes of initial human-rated landers for the early Artemis flights. Blue Origin's Mark-2 lander is designed to fit inside a 7 m fairing (3.5 m radius) of the New Glenn rocket, therefore here we use a maximum footprint of 3.85×10^{-5} km^2. The SpaceX Starship vehicle that is designed to land humans on the Moon has a diameter of 9 m (4.5 m radius), therefore we use an areal footprint of 6.36×10^{-5} km^2.

Using the values derived from the Artemis II impact flash observations, we present these impact probabilities for various scenarios in Table 2. Small infrastructure footprints (such as the HLS landers) have a very small probability of being hit by a megajoule impactor during a short-duration early Artemis mission timeframe. Larger-scale infrastructure (e.g., size of a FIFA World Cup soccer field) which may be more representative of the footprint for a sustained human presence on Mars (e.g., NASA's planned Moon Base) has a higher, yet still relatively small, impact probability.

Such impact probabilities are design-dependent, however, and may vary based on the sizes, shapes, and spacing of surface infrastructure components. We also note that the International Space Station (ISS) shielding is designed to protect against impacting particles of 1-1.3 cm in diameter (kinetic energies of 1.5-4.5 x 10^5 joules) with a required probability of no penetration of 0.98-0.998 per critical element over 10 years (*30*). Therefore, the impact probabilities presented here based on the Artemis II observations are for a particle size and energy well beyond the design limits of current spaceflight hardware. Fortunately, the impact probability for these larger impactors (8.5 cm diameter class) is relatively low, and thus the threat to surface infrastructure and crew from this population of meteoroids is minimal.

Infrastructure Element	Infrastructure Size (km^2)	Time period	Impact Probability
HLS- Blue Origin Mark 2	1.54×10^{-3}	2 weeks	8×10^{-8}
HLS - SpaceX Starship	2.54×10^{-3}	2 weeks	1.35×10^{-7}
Moon Base	0.00714	10 years	9.9×10^{-5}

Table 2. Impact probabilities for multiple lunar surface infrastructure elements and mission durations. HLS landers have an incredibly small probability of impact from a meteoroid having a kinetic energy larger than a megajoule. Larger-scale infrastructure (e.g., Moon Base) when considered for a decade of operations has a higher, yet still low, probability of impact.

Conclusions

The Artemis II crewed lunar flyby mission provided an opportunity to collect a scientifically unique and valuable dataset to understand the dynamic lunar impact environment. The astronauts' close proximity to the Moon, view of the lunar farside, and observation period during the extreme darkness of a total solar eclipse afforded the crew the opportunity to observe short duration, faint impact flashes on the lunar surface. Observations of flashes were confirmed through multiple sightings of the same flash by different crew members during the flyby. These are likely the faintest impact flashes observed to date since they were only observed during the

total solar eclipse with no other illuminated sources (Earth or Sun) or sunlit lunar terrain visible in the field of view while viewing from the Orion spacecraft at the Moon. These observations, which were collected outside of any major annual meteor showers, indicate that the crew was observing the background flux of sporadic meteoroids in the lunar environment. The Artemis II astronauts observed flashes created from the impact of ~4-5 cm diameter and larger meteoroids hitting the Moon. The smallest of these impacts had an energy of less than a pound of TNT. These impacts created craters less than a meter in diameter which is below the imaging detection limit of LRO, although the proximal ejecta blanket could in theory be resolved with LRO except we lack sufficient location data for imagery targeting. Data-informed risk assessments suggest that the probability of a high-energy sporadic meteoroid impact on Artemis lunar surface infrastructure is non-zero but relatively low.

Future missions are planned to further constrain the meteoroid flux as a function of time at the Moon. The Lunar Meteoroid Impact Observer (LUMIO) mission (*31, 32*) is scheduled for launch in 2026–2027. LUMIO will be equipped with two cameras attached to a dichroic beam splitter and will observe in the visible and near-infrared bands with a frame rate of 10–20 fps. LUMIO will continuously observe the Moon for approximately 15 days per month, when the lunar illumination phase is less than 50%. China's Moon Flash orbiter will also observe impact flashes. Moon Flash is scheduled for launch in 2028 and is a 12U cubesat planned for a lunar polar orbit and consists of an optical telescope designed for impact flash observations (*32*). Future Artemis missions will also contribute to lunar meteoroid science as Artemis IV, V and beyond are planned with lunar orbital crew members who will be in a position to observe for impact flashes during their flight. The Artemis II SAW cameras on the exterior of the vehicle could be upgraded as science cameras with increased resolution and streaming video to detect impact flashes. In addition, Artemis astronaut crew members remain a valuable source of data, as human observations of impact flashes from the Moon have provided a key dataset to constrain the dynamic lunar environment providing critical knowledge for both science and understanding the meteoroid flux in the cis-lunar environment as well as to inform future human exploration and safety planning for the Moon. The Artemis II crew members have set the record for the smallest meteoroids observed to impact the Moon to date.

Data Availability

All Artemis II data reported here is publicly available within NASA's Planetary Data System (PDS). The PDS is a long-term archive of flight data and products from NASA planetary missions which undergo peer-review and include documentation for access and use of the data. [*Direct links to these data in PDS will be provided upon PDS release on 7 Oct 2026*].

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Author Contributions

J.L.H., W.C., B.A.C., and K.Y. developed and designed the science investigation plan for this work. J.L.H., B.A.C., J.R., A.D., A.C., K.D., M.H., and K.Y. planned the impact flash observations as timelined crew activities for the Artemis II flyby. E.W. provided scientific visualizations and quantitative predictions and analysis of lunar phase, timing, and lunar illumination conditions. J.L.H., B.A.C., J.R., M.B., A.T., A.C., C.E., D.,H.-B., A.D., A.C., D.N., J.G., J.H., M.B., K.D., M.H., and K.Y. conducted post-flight data analysis and synthesis of Artemis II crew audio, imagery, video, and annotation files.

Competing Interests

The authors declare no competing interests.

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