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The Potential Danger to Satellites due to Ejecta from a 2032 Lunar Impact by Asteroid 2024 YR_4

Paul Wiegert[1,2], Peter Brown[1,2], Jack Lopes[1,2], and Martin Connors[3]
[1] Department of Physics and Astronomy, The University of Western Ontario, London, Canada; pwiegert@uwo.ca
[2] Institute for Earth and Space Exploration (IESX,) The University of Western Ontario, London, Canada
[3] Centre for Science, Athabasca University, Athabasca, Alberta, Canada
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Abstract

On 2032 December 22, the 60 m diameter asteroid 2024 YR_4 has a 4% chance of impacting the Moon. Such an impact would release 6.5 MT TNT equivalent energy and produce a ∼1 km diameter crater. We estimate that up to 10^8 kg of lunar material could be liberated in such an impact by exceeding lunar escape speed. The current overall probability is about 1% that the asteroid will impact the Moon at a location such that more than 10% of the ejected material would accrete to the Earth on timescales of a few days. If this were to occur, the lunar-ejecta-associated particle fluence at 0.1–10 mm sizes could produce up to several years of equivalent background meteoroid impact exposure to satellites in near-Earth space late in 2032. Our results demonstrate that planetary defense considerations should be more broadly extended to cislunar space and not confined solely to near-Earth space.

Unified Astronomy Thesaurus concepts: Solar system (1528); Natural satellites (Solar system) (1089); Small Solar System bodies (1469); The Moon (1692); Asteroids (72); Near-Earth objects (1092)

1. Introduction

Asteroid 2024 YR_4 is a 60 m diameter asteroid (A. S. Rivkin et al. 2025) that is confidently expected to miss the Earth but that as of this writing has a 4% probability of striking the Moon at 13 km s^{-1} on 2032 December 22. Here we report on the amount of lunar material potentially injected into cislunar space should that impact occur and the implications for Earth's satellite constellations in particular. Of primary concern are ejecta particles above the impact hazard threshold (0.1 mm) for satellites. This is the size range identified by NASA (W. Cooke et al. 2017) as being at the limit of causing substantial damage to satellites, with particles smaller than this size normally leading to surface degradation alone.

Our goal in this work is to provide an order-of-magnitude estimate of the expected short-term effect of lunar ejecta on near-Earth space from a potential impact of 2024 YR_4 in late 2032 December. We emphasize that there exist order-of-magnitude uncertainties in the following analysis. This is particularly true in regard to ejecta size–frequency distributions (SFDs) at small sizes and the mass fraction of ejecta able to exceed lunar escape speed.

To assess the particle population that might reach Earth should 2024 YR_4 impact the Moon, we need to estimate the following:

1. The size of the crater produced in the impact
2. The amount of material ejected in the impact that has speeds above lunar escape
3. The SFD of the escaping ejecta
4. The range of locations on the moon where an impact might occur
5. The delivery efficiency of escaping ejecta to near-Earth space.

This Letter is structured as follows: In Section 2, we address items 1–3. Items 4–5 are addressed in Sections 3 and 4. Finally, we estimate the fluence of lunar particles with $D > 0.1$ mm from a 2024 YR_4 impact and compare to the background meteoroid flux/hazard in Section 5.

2. Crater Production and Ejecta Properties

In what follows, we adopt the scaling relations for transient crater size, ejected mass, and velocity distribution summarized and described in K. A. Holsapple & R. M. Schmidt (1982), K. R. Housen et al. (1983), K. A. Holsapple & R. M. Schmidt (1987), K. A. Holsapple (1993), and K. R. Housen & K. A. Holsapple (2011).

Adopting the James Webb Telescope (JWST)–determined diameter of 60 m for 2024 YR_4 (A. S. Rivkin et al. 2025) and assuming a bulk density for 2024 YR_4 of 3000 kg m^{-3} and an impact speed of 13 km s^{-1} (appropriate for all locations along the potential lunar impact corridor; see Section 3), we may estimate a crater size. Using Π-scaling summarized in K. A. Holsapple (1993), appropriate for a target of hard rock in the gravity-dominated regime, we adopt cratering scaling exponents of $\mu_{\text{crater}} = 0.22$ and $k_{\text{crater}} = 1.0$ for a zeroth-order crater diameter estimate (K. R. Housen & K. A. Holsapple 2011). We choose hard rock as the fine regolith is expected to be no more than 10 m in depth (R. N. Watkins et al. 2019).

Under these assumptions, the impact will produce a transient crater of 1.4 km diameter. If instead we assume the impact is more appropriate to loose soil/fine regolith, we find a transient crater diameter of 0.7 km (K. A. Holsapple & R. M. Schmidt 1982, Table 1, case 5). Given the various uncertainties, we will assume that the impact of 2024 YR_4 into the Moon will produce a transient crater of order 1 km in diameter. For context, based on the lunar crater production flux of G. Neukum et al. (2001), a 1 km diameter crater forms every ∼5000 yr. This emphasizes how unusual/rare a potential lunar impact is for an object as large as 2024 YR_4, at least on human timescales if not on geological ones.

In general, impacts on the Moon produce ejecta, a portion of which may escape lunar gravity. H. J. Melosh (1985) showed that near-surface spallation during lunar impacts can loft a small portion (∼0.01%) of material above escape speeds. Subsequent work (K. R. Housen & K. A. Holsapple 2011) showed that most of the mass of high-velocity ejecta is in the form of micron- to millimeter-sized fragments.

For a 1 km diameter crater, we expect $\sim 10^{11}$ kg of mass to be displaced from the crater. Using the ejecta velocity formalism of K. R. Housen & K. A. Holsapple (2011) and an ejecta velocity exponent $\mu = 0.41$ appropriate for sandy material, we find that only 0.02%–0.2% of ejecta exceed lunar escape speed, implying release of $\sim 10^{7-8}$ kg during the impact.

The SFD of fines produced during lunar impacts is poorly constrained, with most work focusing on the large-end tail of the ejecta distribution (e.g., K. N. Singer et al. 2020). For simplicity, we follow the methodology of R. Jedicke et al. (2025) and assume that the largest ejecta fragments will be 1 m in diameter or smaller. We also adopt their assumption that a simple power law expresses the number of fragments between the smallest fines (assumed to be a micron in diameter) and this upper size limit. We adopt this SFD of the form

$$N(>D) = CD^{-u}, \tag{1}$$

where $N(>D)$ is the cumulative number of fragments with diameter larger than D, C is a normalizing constant, and u is the cumulative SFD power-law index. Typical values for u for large crater ejecta SFD are of the order 3–4 (G. D. Bart & H. J. Melosh 2010), a range we adopt. For an escaping ejecta mass of 10^{7-8} kg, we find $N(>10\text{ mm}) \sim 10^{5-9}$, $N(>1\text{ mm}) \sim 10^{11-13}$, and $N(>100\,\mu\text{m}) \sim 10^{14-16}$.

3. Impact Probability

To determine the lunar impact probability of 2024 YR_4, asteroid trajectories were calculated via the RADAU (E. Everhart 1985) 15th-order method using an external time step of 14.4 minutes (0.01 days) up to 2032 December 22 1200 UT (a few hours before the closest approach to the Moon) and a time step of 5 s from there through the encounter. The longer time step provides adequate coverage of the approach, sampling the asteroid's orbit thousands of times per heliocentric period. The shorter time step during the encounter—which occurs at a relative speed of 11 km s^{-1}— allows the resolution of impact locations to within roughly 50 km on the Moon's 3476 km diameter disk. The simulations included the effects of the Sun, Moon, and all the planets with their initial positions derived from the DE440 ephemeris (R. S. Park et al. 2021). Radiation forces were ignored as their effects are small on particles of these sizes on these timescales. The orbital solution for 2024 YR_4 was obtained from the Center for Near-Earth Object Studies Small-Body Database Application Programming Interface (API)[4] on 2025 June 5. This solution incorporates JWST observations taken on 2025 May 11, probably the last observations that can be taken before 2028, and which increased the chance of 2024 YR_4 striking the Moon slightly from 3.8% to 4.3%.[5] Ten thousand clones were created from the covariance matrix and numerically integrated forward to their impacts, which occur within a few minutes of 2032 December 22 1520 UT, depending on the exact impacting clone. Our simulations yield an impact probability of $4.1\% \pm 0.2\%$, consistent with the abovementioned value. The impact corridor as seen from the Earth is presented in Figure 1, that is, the 410 clones that strike the Moon are plotted. The plane of the orbit of 2024 YR_4 is well known, so there is little spread across the track; the length of the track results from uncertainty in its precise location along its orbit. If an impact occurs, it will be in the southern hemisphere, roughly between latitudes 30S and 40S, and largely on the Moon's leading side but with a 14% chance of impacting on the trailing side.

4. Ejecta Delivery Efficiency for 2024 YR_4 Impact

If an asteroid impact produced ejecta traveling in directions isotropic with respect to the Moon, then we might expect the Earth to intercept a fraction of that ejecta comparable to the fraction of the all-sky solid angle it subtends as seen from the Moon, or about 10^{-4}. However, material ejected from a single impact on the Moon will not be ejected isotropically. The fraction that will reach the Earth directly is highly sensitive to the location of the impact.

This sensitivity can be understood qualitatively. Because the Moon is orbiting the Earth at approximately 1 km s^{-1}, for ejected material to reach Earth quickly, the impacting object needs to hit the trailing edge of the Moon in such a way that the ejected material's velocity, after rising out of the Moon's gravitational well, largely cancels out the Moon's orbital velocity. This leaves an ejected particle almost stationary with respect to Earth, allowing it to fall straight down toward our planet. Particles may also be ejected on hyperbolic orbits that head directly for Earth. Many of these details were worked out in the context of the delivery of lunar meteorites to Earth by B. J. Gladman et al. (1995), though these authors were little concerned with the direct delivery of material to Earth, as lunar meteorites more often follow longer, more dynamically complex paths. M. A. Kreslavsky & E. Asphaug (2014) also considered the direct delivery of material to the Earth on short timescales in the context of searching for signs of large lunar impacts in the geological record. Other studies of lunar ejecta have primarily focused on the larger (meter) sizes and on the longer-term evolution of it into minimoons (R. Jedicke et al. 2025), near-Earth objects (NEOs), and/or Earth coorbital asteroids (Y. Jiao et al. 2024; J. D. Castro-Cisneros et al. 2025).

We will show that there is a significant probability for 2024 YR_4 to hit on a portion of the Moon with a delivery efficiency to Earth of greater than 10% of the total material ejected and that this debris moves quickly to near-Earth space.

4.1. Generic Delivery Efficiency

Before addressing the delivery efficiencies of possible 2024 YR_4 impacts specifically, we first examine simulated hypothetical impacts at randomly selected locations across the Moon on 2032 December 22, with points colored by the fraction of material delivered to Earth within 100 days (Figure 2). The figure was created from 300,000 simulated particles (3000 locations, each producing 100 ejected particles, and simulation time step 0.01 days; more details below).

Ejecta trajectories are computed with the same code as was used for computing the trajectory of 2024 YR_4 (Section 3). The

[4] https://ssd-api.jpl.nasa.gov/doc/sbdb.html

[5] https://science.nasa.gov/blogs/planetary-defense/2025/06/05/nasas-webb-observations-update-asteroid-2024-yr4s-lunar-impact-odds/

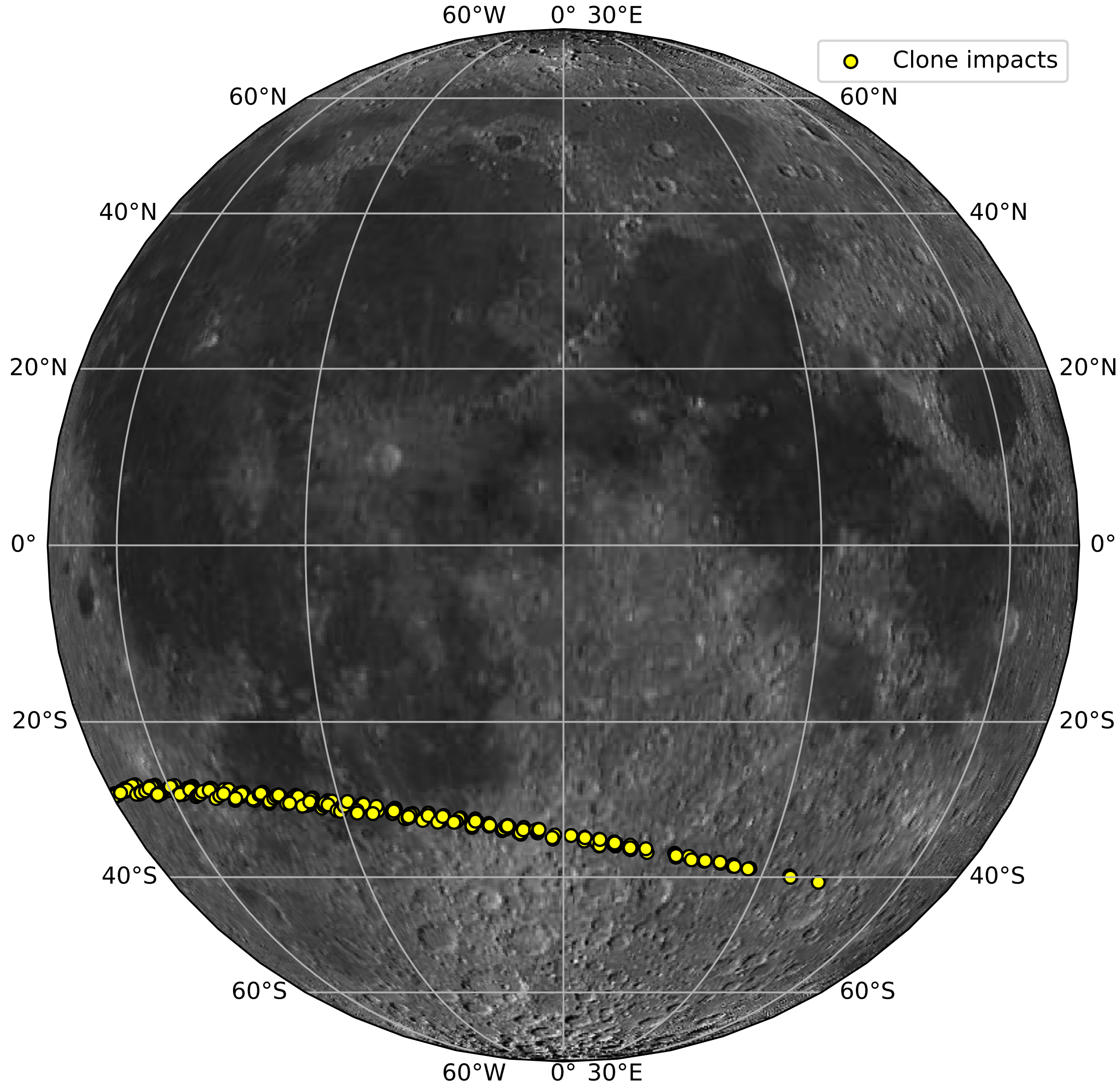

Figure 1. The current impact corridor for 2024 YR_4 (yellow) projected on a map of the Moon's near side from LRO (E. J. Speyerer et al. 2011).

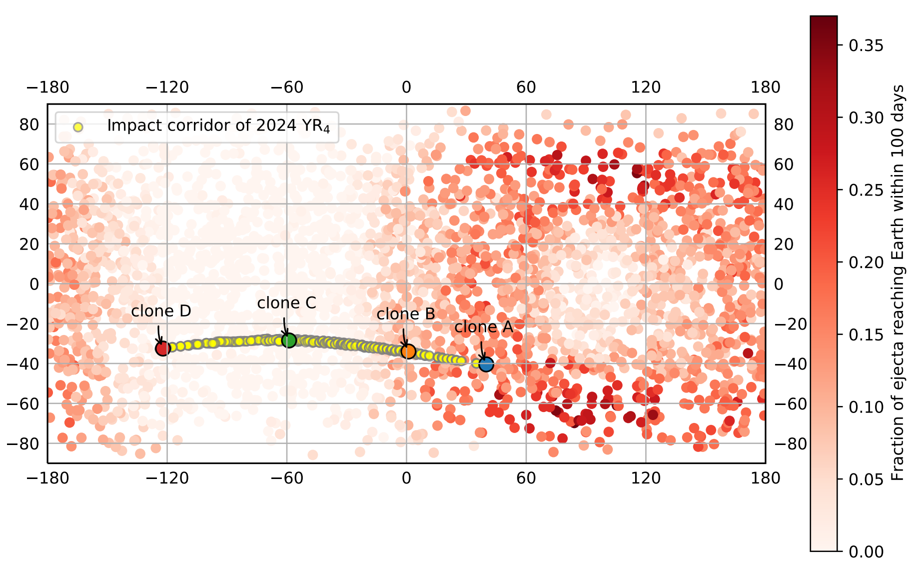

Figure 2. A map of the Moon showing randomly selected impact locations colored by the fraction of escaping ejecta delivered to Earth within 100 days. The current impact corridor for 2024 YR_4 is shown in yellow, with the specific impact locations examined more closely in Section 4.2 labeled as clones A-D. See Sections 4.1 and 4.2 of the main text for more details.

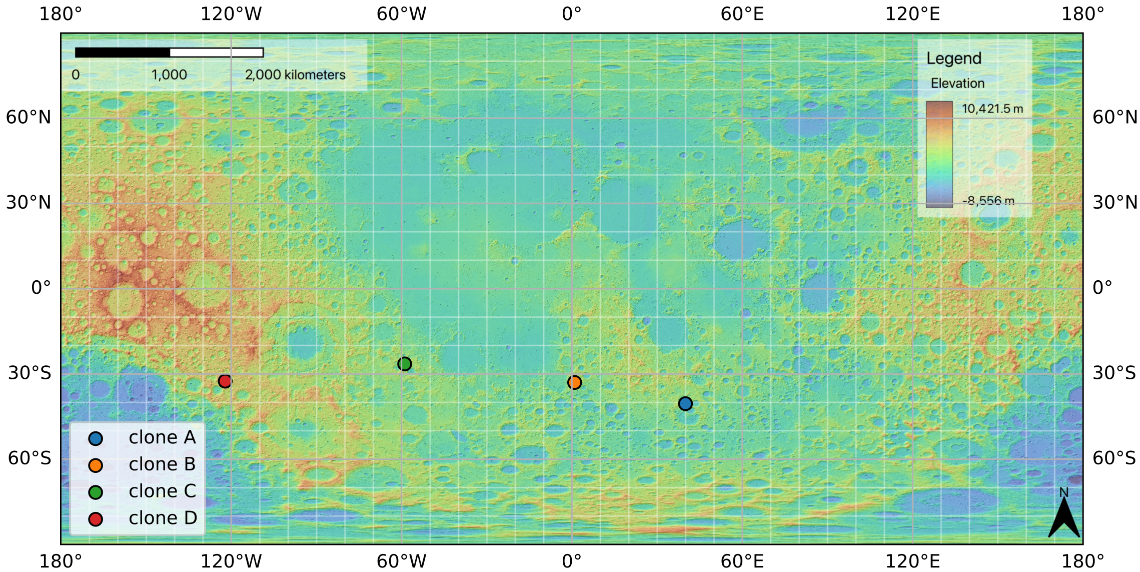

Figure 3. An elevation map of the Moon showing the locations of clones A through D selected for a more detailed study of their delivery efficiencies. See Section 4.2 of the main text for more details.

pole and orientation of the Moon at the time of impact were computed using the SpiceyPy Python wrapper (A. M. Annex 2020) for NASA's SPICE toolkit (C. H. Acton et al. 2018). Specifically, we retrieved the orientation of the Moon's north pole, the libration angle of the Moon (i.e., the angle between the Earth vector and the Moon's prime meridian), and the surface rotation speeds for Julian ephemeris date 2463589.139 corresponding to approximately 1520 UT on 2032 December 22. The Moon's north pole direction in the ecliptic J2000 frame is given by the unit vector $\vec{n} = [0.0127, \ -0.0245, \ 0.9996]$, indicating an obliquity relative to the ecliptic of $1\overset{\circ}{.}6$. The libration angle was found to be 0.696° east, meaning the sub-Earth point was slightly east of the Moon's prime meridian at the time. The rotational velocity of the lunar surface is found to be only a few meters per second, negligible compared to the ejection speeds being considered, and the rotational speed of the Moon's surface was ignored in the ejecta simulations.

The delivery efficiency to the Earth is sensitive to the precise direction and speed at which the material leaves the lunar surface. Here we adopt a single speed for ejected material, chosen just above the escape speed because this is what is expected of the bulk of the escaping material (A. M. Vickery 1987). We also adopt ejection on a cone at 45° to the local normal (H. J. Melosh 1989). Specifically, each impact is taken to eject material at 2.6 km s^{-1} (just above the Moon's escape speed of 2.38 km s^{-1}) on a cone with an opening angle ranging from $45° \pm 5°$ to the local normal of the geoid (H. J. Melosh 1989).

Ejecta particles are numerically integrated with a time step of 0.01 days (= 14.4 minutes) until they hit the Moon or Earth, depart the Earth's Hill sphere (that is, reach a distance larger than 0.01 au from Earth), or the 100 day time limit expires. From Figure 2, it can be seen that if the impact is on the leading side, very little or no material reaches Earth during the time frame in question; however, the delivery efficiencies can reach over 30% on the trailing side.

The delivery efficiency to Earth does depend on the ejection speed, and our choice of 2.6 km s^{-1} is near the optimum value for randomly distributed impacts. In Figure 2 (which assumes a 2.6 km s^{-1} ejection speed), 9.7% of impacts have delivery efficiencies greater than 10% to Earth. This drops to only 5% of impacts at ejection speeds of 2.55 or 2.65 km s^{-1} and to less than 1% at 2.52 and 2.81 km s^{-1}. However, with changing ejection speed, there is also a change in the pattern of high-efficiency impact locations. The pattern narrows and shifts away from 2024 YR$_4$'s impact corridor at lower ejection speeds (decreasing overall delivery efficiency), while it broadens and shifts toward the impact corridor at higher ones (which increases efficiency). Our choice of 2.6 km s^{-1} is likely optimistic, but although a more sophisticated approach could be taken, it is probably not justified until (and if) an impact of 2024 YR$_4$ on the Moon is better constrained.

The highest delivery rates would occur if 2024 YR$_4$ hit the trailing side of the Moon, though delivery efficiencies even along the midline of the Moon can be substantial. The impact corridor is overplotted on Figure 2: 81 of 410 clones that impact the Moon strike in regions with greater than 10% delivery efficiency to the Earth. Thus if 2024 YR$_4$ were to strike the Moon, then there is a 20% chance that the delivery efficiency will be 10% or higher. Together, there is a joint 0.8% chance of 2024 YR$_4$ (1) striking the Moon and (2) impacting in a region of high delivery efficiency. The odds of such a scenario well exceed the usual threshold of concern for asteroid Earth impact warning systems, which is one in a million (A. Milani et al. 2005; J. Roa et al. 2021), suggesting that though the risk is low, it is not completely negligible.

4.2. *Expected Delivery Efficiency from a 2024 YR$_4$ Lunar Impact*

To investigate the delivery efficiencies from different positions along the impact corridor, ejecta was modeled from four locations along it: clone A, which had the easternmost impact at longitude 40.7 East; clone B, which impacted closest to zero longitude (1.0 deg East); clone C, which impacts near 60 W longitude on the Moon's leading side; and clone D, which had the westernmost impact longitude, on the far side of the Moon at 123.7 West. The locations of the clone impacts are shown in Figure 3. The figure shows the Lunar Reconnaissance Orbiter (LRO) Lunar Orbiter Laser Altimeter Global Digital Elevation Model in a simple cylindrical projection at 118 m per

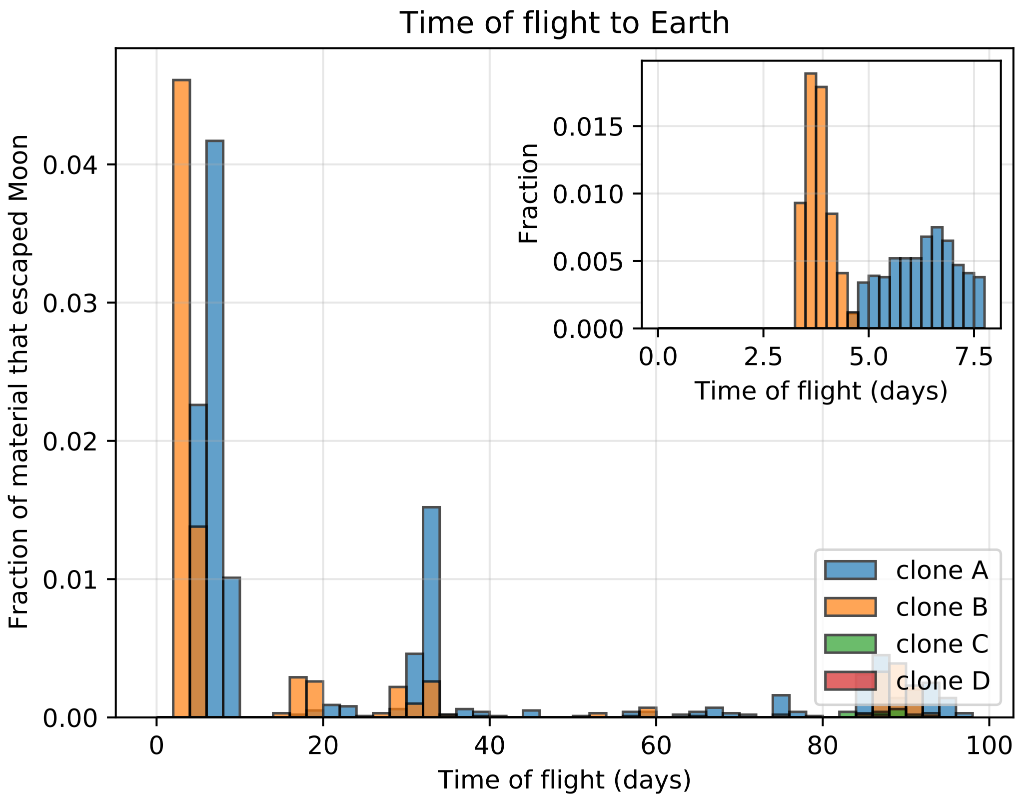

Figure 4. Time of flight from ejecta launch from the Moon until reaching the Earth for clones A through D. The inset panel shows a zoomed-in view to show that first arrivals occur roughly 3 days after the impact for clone B and 5 days for clone A. The first material from clones C and D does not arrive until over 80 days after impact.

pixel resolution (LOLA Science Team 2014). This data set was imported into QGIS, an open-source geographic information system maintained by the QGIS Development Team (2025), where we applied hillshading and overlaid other basic mapping features to produce a global elevation map of the lunar surface. However, the elevations are presented only for illustration purposes. The impact of clones of 2024 YR_4 are taken to occur and to produce ejecta when they intersect the lunar geoid.

Ten thousand particles were ejected from each site, and simulated forward with a 14.4 minute time step for 100 days. The fractions of ejected material delivered to Earth were 11.9%, 8.4%, 0.19%, and 0.04%, respectively and the time of flight of the material is shown in Figure 4.

Clones A and B produce material that arrives rapidly to Earth: in both of these cases, several percent of the total material ejected from the Moon strikes the Earth within roughly a week of its release. Material from clone B arrives more quickly, with first arrivals after only 3 days, while material from clone A would start arriving after 5 days. The material ejected from the Moon by impacts due to clones C and D only arrives at Earth after 80 days and is difficult to see in Figure 4; as expected, an impact on the leading side of the Moon does not deliver material quickly to Earth. Thus, the net delivery of material to Earth is quite sensitive to the impact location, with clone A- or B-like impacts generating high delivery rates, while C- or D-like events would produce negligible amounts.

If 2024 YR_4 were to impact near the the eastern edge of the impact corridor, roughly 10% of the 10^{7-8} kg of material ejected will reach the Earth quickly, the bulk arriving in just a few days. From our earlier computed particle numbers of $N(>10\text{ mm})$ $\sim 10^{5-9}$, $N(>1\text{ mm}) \sim 10^{11-13}$, and $N(>100\ \mu\text{m}) \sim 10^{14-16}$ and taking the Earth's area to be $\pi(6378\text{ km})^2 \sim 10^{14}\text{ m}^2$, then we can expect fluences of 10^{-10}–10^{-6} per square meter of centimeter-sized particles, 10^{-4}–10^{-2} per square meter of millimeter-sized particles, and 0.1 to 10 per square meter of 100 μm sized particles.

5. Earth Impact Effects: Satellite and Lunar Ejecta Impact

Given the results of the Section 4, the instantaneous meteoroid flux could—if the asteroid impacts the Moon in a favorable spot—reach 10 to 1000 times the background meteoroid flux at sizes that pose a hazard to astronauts and spacecraft. These sizes range from 100 μm (capable of cutting exposed wires or penetrating a spacesuit; C. D. Cwalina et al. 2015; W. Cooke et al. 2017; A. Moorhead et al. 2019) to 1 cm (capable of mission-ending damage).[6] The standard interplanetary meteoroid flux model (A. Moorhead et al. 2019) predicts a mean annual flux impacting a randomly tumbling flat plate of 1 m^2 area near Earth of $\sim$1 meteoroids $D > 100\ \mu$m, $\sim 10^{-3}$ meteoroids $D > 1$ mm, and $\sim 10^{-7}$ meteoroids $D > 1$ cm. Our predicted flux thus represents an equivalent exposure of up to 10 yr (0.1–10, 0.1–10, and 0.001–10 yr for each size range, respectively) over just a few days.

However, the above is a mass-limited comparison—the actual damage caused by an impact depends on several factors, most notably relative speed. The mass averaged meteoroid speed near Earth is 20 km s^{-1}(E. Grün et al. 1985), while from Section 4, our expected delivery velocity will be near-Earth

[6] https://www.esa.int/Space_Safety/Space_Debris/Hypervelocity_impacts_and_protecting_spacecraft

escape. Thus, the relative velocity at impact on an orbiting spacecraft should vary from 4 to 18 $km\,s^{-1}$, and so our mass limit may produce a factor of several less equivalent penetration damage than sporadic meteoroid impacts, but this is not significant for our order of magnitude comparison.

This added impact exposure will result in accelerated degradation of Earth-orbiting satellites. This would occur in low Earth orbit (LEO) in particular as the relative equivalent exposure of the background sporadic population will be potentially of order years to a decade. This will all occur during the few days of maximum ejecta delivery from a 2024 YR_4 impact.

For comparison to the impact risk from orbital debris, we note that the potential particle enhancement from a 2024 YR_4 impact will greatly exceed the total impact risk from both orbital debris and background meteoroids to spacecraft in very LEO (below 270 km altitude) and at higher altitudes (above a few thousand kilometers) (A. Moorhead & M. Matney 2021). At intermediate altitudes, the relative increase in impact risk from 2024 YR_4 debris compared to orbital debris will depend on the satellite orbital inclination and impact direction. For example, near 1000 km altitude, satellites in highly inclined orbits would see an impact enhancement in the ram-facing spacecraft comparable to the normal daily background orbital debris fluxes for sizes capable of penetrating 1 mm thickness of aluminum (A. Moorhead & M. Matney 2021).

For scale, it is worth noting that the current satellite cross-sectional area (active and inactive/debris) in LEO is expected to increase significantly between now and 2032.[7] We estimate the total cross-sectional area of all satellites in LEO and geosynchronous earth orbit in 2032 will be of order 10^7 m^2. This estimate is based on the nominal $\approx 100\,m^2$ area of the next generation of Starlink V2 minisatellites now being launched[8] together with the plan to orbit 30,000 by 2032.[9] Here we assume that this number of Starlink satellites will be matched by roughly twice as many total satellites from all other planned megaconstellations and that these will be similar in size to the next generation of Starlink satellites, forming the bulk of the active population. While we caution that this cross-sectional area calculation is at best an order of magnitude estimate, given the very large total exposed area for satellites by 2032, it becomes possible that thousands to tens of thousands of impacts from millimeter-sized debris ejected by a lunar impact from 2024 YR_4 will be experienced across the entire satellite fleet. Such impacts may damage satellites but are small enough to generally not end active missions or cause breakups.

If the orbital debris environment remains comparable in orbital distribution to today's, then we expect the relative risk to increase with increasing satellite number but that the risk will scale with altitude much as it does today.

The ejection of material from the Moon could be a serious hazard to Moon-orbiting spacecraft (e.g., Lunar Gateway) but would likely pose even greater dangers to any lunar surface operations, given that most ejecta mass will accumulate across a wide swath of the Moon. The precise timing and locales affected should be examined for the specific impact location should observations in 2028 result in a predicted lunar impact.

In addition to increased flux over a few days, there is also material delivered to long-lived (months to years) Earth orbits that could pose an ongoing concern to space-based assets. These could affect operations of meteoroid-sensitive space platforms over longer time frames, though we note that the JWST, which is expected to remain operational in 2032 (J. P. Gardner et al. 2023) is located at the Sun–Earth L_2 point, which is not included in this study.

We note that the production of centimeter-sized ejecta, which can be very damaging, is most uncertain as it is greatly affected by the choice of the ejecta SFD power-law exponent. Given our fluence values, the probability of impact by centimeter-sized lunar ejecta on any satellite surface across the entire constellation would remain of order 10% or less. Quantifying better this upper range in the ejecta debris is important as such large impacts are generally considered to be mission-ending events and could also lead to satellite breakup in some scenarios (G. Drolshagen & A. Moorhead 2019).

Finally, the relatively low-velocity lunar ejecta that will impact the atmosphere may provide an opportunity for atmospheric sampling of debris. We do not expect significant numbers of larger (decimeter- to meter-sized) ejecta from the 2024 YR_4 impact, given the small crater size (e.g., R. Jedicke et al. 2025), so meteorites are unlikely (though not impossible). However, the mass input over a week timescale from the impact of 10^{3-4} tonnes (t) of lunar material would exceed the average daily mass input of meteoroids, which is of order 10–50 t (J. D. Carrillo-Sanchez et al. 2022) by several orders of magnitude. In this scenario, almost any debris collected in the atmosphere is likely to be of lunar origin during the sedimentation timescale of dust to the Earth's surface. The resulting meteor shower could last a few days and be spectacular, though the number of visible meteors would be somewhat muted by their low entry speed.

6. Conclusions

If 2024 YR_4 strikes the Moon in 2032, it will (statistically speaking) be the largest impact in approximately 5000 yr. The delivery of ejecta escaping the Moon to near-Earth space is highly sensitive to the precise impact location, but the impact corridor as understood at this writing suggests that there is an overall 1% chance that both (1) 2024 YR_4 will strike the Moon and (2) that the impact will have a delivery efficiency to Earth $\geqslant$10%. The 1:100 odds of this scenario exceed the usual threshold of concern for asteroid Earth impact warning systems, which is one in a million (A. Milani et al. 2005; J. Roa et al. 2021), indicating that this outcome is sufficiently likely to warrant further study.

If such an impact occurs, it would result in particle fluxes at Earth of 10–1000 times their background values and could produce effective exposures equivalent to years in space over just a few days. The resulting meteor shower at Earth could be eye-catching, with rates orders of magnitude above usual background rates, but meteor light production will be reduced by their relatively low in-atmosphere speeds. The travel time from lunar impact to Earth is typically several days but does depend on the precise location of the impact if it even occurs, which probably cannot be determined until the asteroid

[7] https://nova.space/press-release/seven-tons-of-satellites-to-be-launched-daily-on-average-over-the-next-decade-amid-value-chain-consolidation/

[8] https://spaceflightnow.com/2023/02/26/spacex-unveils-first-batch-of-larger-upgraded-starlink-satellites/

[9] https://www.reuters.com/legal/us-court-rejects-challenges-fcc-approval-spacex-satellites-2024-07-12/

returns to visibility in 2028. Material persisting in Earth orbits for longer times could also present a hazard.

Our analysis highlights that issues of planetary defense extend beyond just the effects of impacts on Earth's surface. The NASA Planetary Defense Strategy and Action Plan (2023)[10] states on page 11 that "planetary defense encompasses all the capabilities needed to detect and warn of potential asteroid or comet impacts *with Earth* and then to either prevent or mitigate their possible effects" (emphasis added). The Moon itself is not explicitly mentioned in that 42 page document except to note that space situational awareness systems acting in support of missions to the Moon could also be used for NEO detection and tracking. Though this is admittedly only one of many documents addressing the topic of planetary defense, current thinking has as a rule considered it to pertain only to the mitigation of asteroid impacts with the Earth itself.

At the same time, the Moon does already effectively figure in basic planetary defense considerations, as (for example) impact probabilities with the Moon for NEOs like 2024 YR_4 are routinely calculated and published. However, the parameters for lunar defense are different for the Earth. The size range of interest is also different for the Moon because of its airless surface. Objects too small to survive entry into Earth's atmosphere could strike the Moon's surface at hypervelocity, dispersing material at high speed over a wide area and even ejecting material into space. And should historically important sites be part of the equation? 2024 YR_4 is unlikely to strike near any landed lunar missions, with the possible exception of Surveyor 7 (P. Stooke 2025, private communication), but what if the impact corridor passed near the Apollo 11 site? These are all issues that require additional thought. We suggest that the global space community consider extending the formal definition and scope of planetary defense beyond the confines of planet Earth itself to the wider domain of near-Earth and lunar space, where hardware assets and spacefaring humans could suffer adverse affects from NEO impacts under situations not addressed by traditional Earth impact scenarios.

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Software: SpiceyPy (A. M. Annex 2020), SPICE (C. H. Acton et al. 2018), DE440 (R. S. Park et al. 2021), QGIS (QGIS Development Team 2025).

ORCID iDs

Paul Wiegert https://orcid.org/0000-0002-1914-5352
Peter Brown https://orcid.org/0000-0001-6130-7039
Jack Lopes https://orcid.org/0009-0000-7999-3241
Martin Connors https://orcid.org/0000-0003-0634-9599

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