Draft version June 12, 2025
Typeset using LaTeX **default** style in AASTeX7.0.1

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 [3,1,2]

[1] *Department of Physics and Astronomy*
The University of Western Ontario
London, Canada
[2] *Institute for Earth and Space Exploration (IESX)*
The University of Western Ontario
London, Canada
[3] *Centre for Science*
Athabasca University
Athabasca, Alberta, Canada

Submitted to AAS journals 12 June 2025

ABSTRACT

On 2032 December 22 the 60m 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. Depending on the actual impact location on the Moon as much as 10% of this material may accrete to the Earth on timescales of a few days. The lunar ejecta-associated particle fluence at 0.1 - 10 mm sizes could produce upwards of years to of order a decade 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 cis-lunar space and not confined solely to near-Earth space.

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 on 2032 December 22. Here we report on the amount of lunar material potentially injected into cis-lunar 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 (A. V. Moorhead et al. 2020) delivered directly to Low Earth Orbit (LEO) on relatively short (days to a few months) time scales, and that could pose a hazard to spacecraft.

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 December 2032. We emphasize that there exist order of magnitude uncertainties in the following analysis. This is particularly true in regard to ejecta size-frequency distributions at small sizes and the mass fraction of ejecta able to exceed lunar escape speed.

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

1. The size of the crater produced in the impact
2. The amount of material ejected in the impact which has speeds above lunar escape
3. The size frequency distribution 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.

Corresponding author: Paul Wiegert

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); K. R. Housen & K. A. Holsapple (2011).

Adopting the JWST determined diameter of 60 m for 2024 YR_4 (A. S. Rivkin et al. 2025), assuming a bulk density for 2024 YR_4 of 3000 kg m^{-3} and an impact speed of 13 km/s (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 μ_{crater}=0.22 and k_{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. 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 $\sim$ 5000 years. This emphasizes how unusual/rare a potential lunar impact is for an object as large as 2024 YR_4.

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 ($\sim$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 μm to mm-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 μ=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 size frequency distribution (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 one meter 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. Adopting 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 to 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 mm) $\sim 10^{5-9}$, N(> 1 mm) $\sim 10^{11-13}$, N(> 100 μm) $\sim 10^{14-16}$.

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 between 5 seconds and 14.4 minutes (0.01 days) depending on the context. 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 time scales. The orbital solution for 2024 YR_4 was obtained from the Center for Near-Earth Object Studies (CNEOS) Small-Body Database (SBDB) API [4] on 2025 June 5. This solution incorporates James Webb Space Telescope (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

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

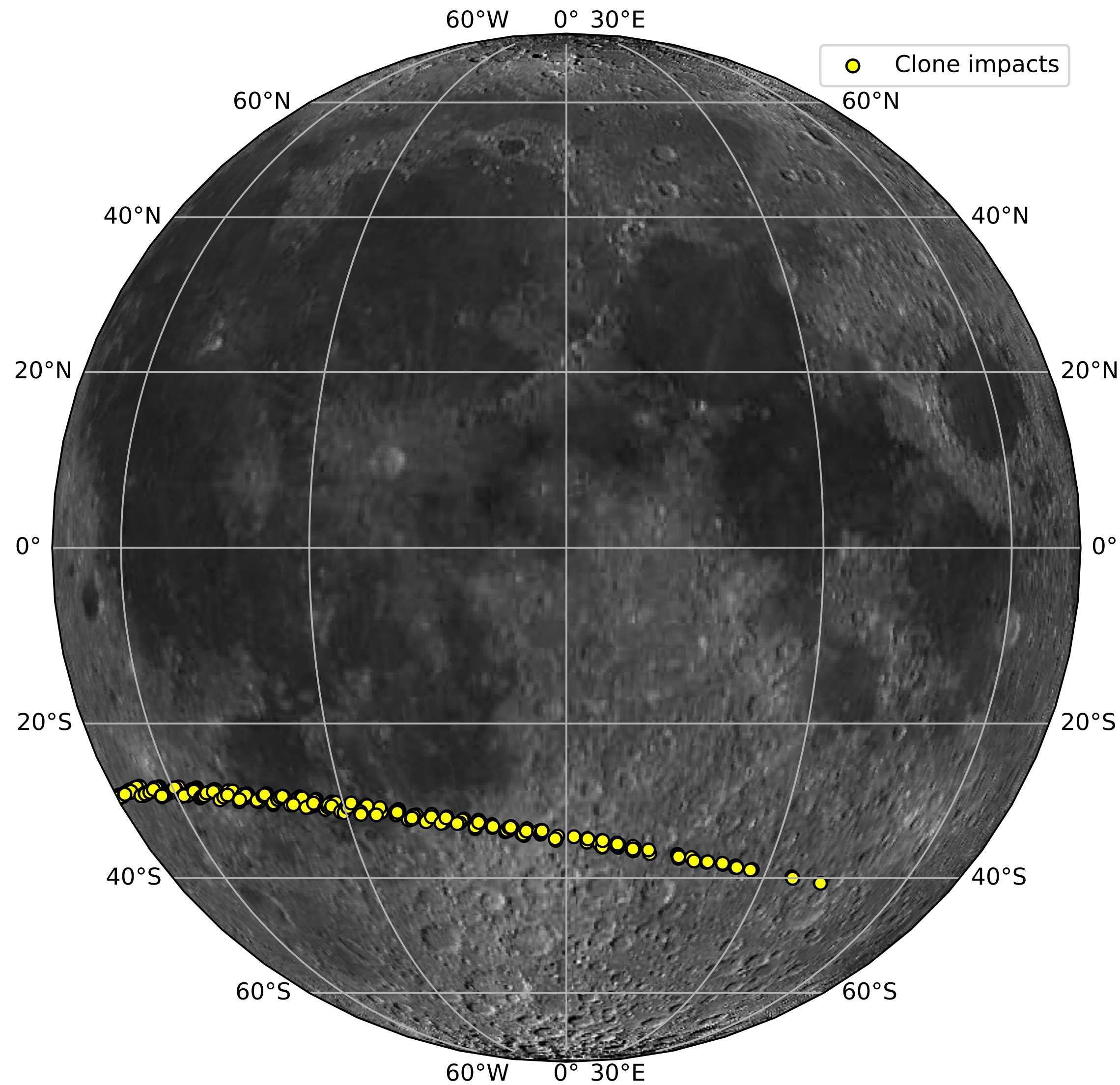

Figure 1. The current impact corridor for 2024 YR_4 (yellow) projected on a map of the Moon's near side from Lunar Reconnaissance Orbiter (E. J. Speyerer et al. 2011).

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 above-mentioned 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

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

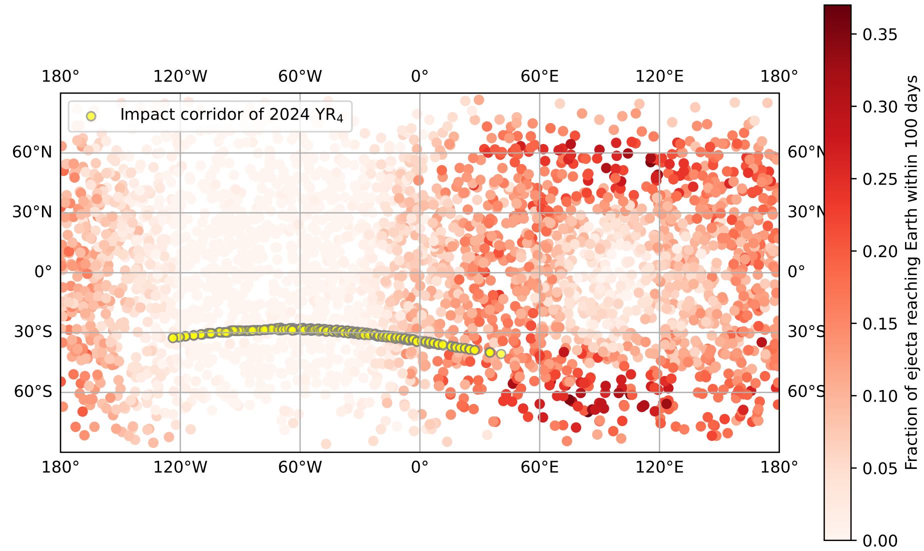

Figure 2. A map of the Moon showing randomly selected impact locations colored by the fraction of escaping ejecta delivered to Earth within 100 days. The current impact corridor for 2024 YR_4 is shown in yellow. See the main text for more details.

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, 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 time scales, 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 mini-moons (R. Jedicke et al. 2025), near-Earth objects and/or Earth co-orbital 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).

Ejecta trajectories are computed with the same code as was used for computing the trajectory of 2024 YR_4 (Section 3). The 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 (JDE) 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 1.6°. 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^o to the local normal (H. J. Melosh 1989). Specifically, each impact is taken to eject material at 2.6 km/s (just above the Moon's escape speed of 2.38 km/s) on a cone with an opening angle ranging from 45 ± 5^o to the local normal of the geoid (H. J. Melosh 1989). Though 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.

Ejecta particles are numerically integrated with a time step of 0.01 days (= 14.4 minutes) until they hit the Moon, 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 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 overplotted on Figure 2 reveals there is a substantial chance of 2024 YR_4 striking the Moon in a region of high delivery efficiency.

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 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 Mon 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 (LOLA) Global Digital Elevation Model (DEM) in a simple cylindrical projection at 118 m per pixel resolution (USGS Astrogeology Science Center 2014). This dataset 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 forwards 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 three days, while material from clone A would start arriving after five 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.

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 mm) $\sim 10^{5-9}$, N(> 1 mm) $\sim 10^{11-13}$, N(> 100 μm) $\sim 10^{14-16}$ 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} to 10^{-6} per square meter of cm sized particles, 10^{-4} to 10^{-2} per square meter of mm-sized particles and 0.1 to 10 per square meter of 100 μm sized particles.

5. EARTH IMPACT EFFECTS: SATELLITE AND LUNAR EJECTA IMPACT

For comparison to our results, 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 ~ 1 meteoroids D > 100 μm, $\sim 10^{-3}$ meteoroids D > 1 mm and $\sim 10^{-7}$ meteoroids D > 1 cm. For comparison our predicted flux therefore represents the equivalent exposure to the background impacting population (to the same mass limit) of 0.1-10, 0.1-10,

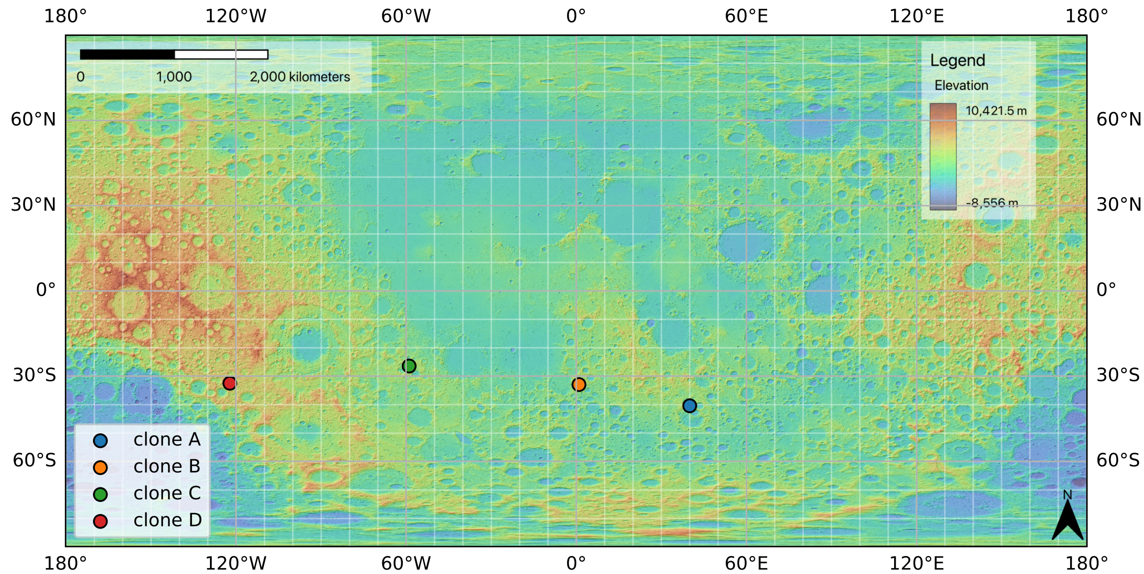

Figure 3. An elevation map of the Moon showing the locations of clones A through D selected for a more detailed study of their delivery efficiencies. See the main text for more details.

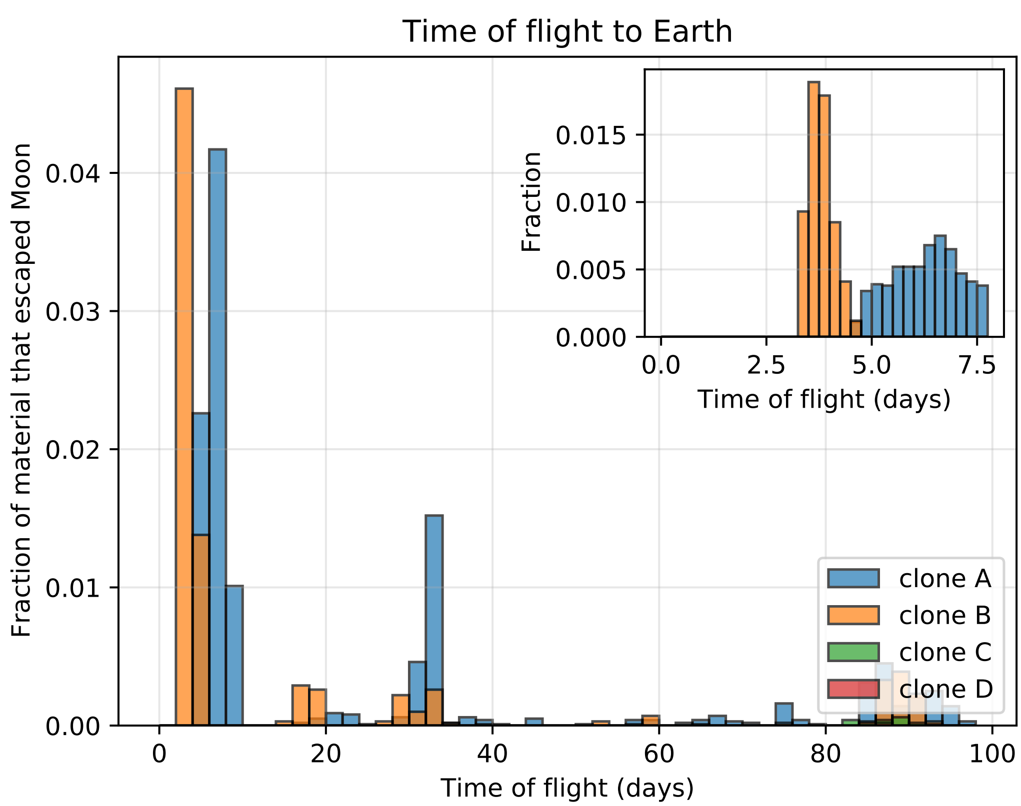

Figure 4. Time of flight from ejecta launch from the Moon until reaching the Earth for clones A through D. The inset panel shows a zoomed in view to show that first arrivals occur roughly three days after the impact for clone B and five days for clone A. The first material from clones C and D does not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

0.001-10 years respectively for satellites in Earth orbit over just a few days. The instantaneous flux could reach 10 to 1000 times the background sporadic meteor flux at sizes which pose a hazard to astronauts and spacecraft.

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 (E. Grün et al. 1985) while from Section 4 our expected delivery velocity will be near Earth escape. Thus the relative velocity at impact on an orbiting spacecraft should vary from 4 - 18 km/s 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 scale, it is worth noting that the current satellite cross-sectional area (active and inactive/debris) in LEO is expected to increase by a factor of 3-4 between now and 2032[6]. The total cross-sectional area of all satellites in LEO and Geosynchronous Earth Orbit (GEO) in 2032 will be of order 10^5 m^2, based on the nominal 10 m^2 (C. Johnson et al. 2021) typical area of Starlink satellites, which together with similar planned megaconstellation satellites will form the bulk of the active population. Given the very large total exposed area for satellites by 2032 it becomes possible that hundreds to thousands of impacts from mm-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.

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 a 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 James Webb Space Telescope (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 cm-sized ejecta, which can be very damaging, is most the 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 cm-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-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 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 somewhat muted by the low entry speed of ejecta.

6. CONCLUSIONS

If 2024 YR_4 strikes the Moon in 2032, it will (statistically speaking) be the largest impact in approximately 5000 years. 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 does allow for delivery efficiencies of up to 10%. This would result in particle fluxes at Earth of 10 to 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

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

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 returns to visibility in 2028. Material persisting in Earth orbit 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. Impacts on the Moon may generate particles which can interfere with Low Earth orbiting satellites.

ACKNOWLEDGMENTS

This study was supported in part by the NASA Meteoroid Environment Office under Cooperative Agreement No. 80NSSC24M0060 and by the Natural Sciences and Engineering Research Council of Canada (NSERC) Discovery Grant program (grants No. RGPIN-2018-05659 and RGPIN-2024-05200)

Software: SPICE, Cartopy, DE440, QGIS, geopandas

REFERENCES

Acton, C. H., Bachman, N. J., Semenov, B. G., & Wright, E. D. 2018, Planetary and Space Science, 150, 9, doi: 10.1016/j.pss.2017.02.013

Annex, A. M. 2020, Journal of Open Source Software, 5, 2050, doi: 10.21105/joss.02050

Bart, G. D., & Melosh, H. J. 2010, Icarus, 209, 337–357, doi: 10.1016/j.icarus.2010.05.023

Carrillo-Sanchez, J. D., Janches, D., Plane, J., et al. 2022, Planetary Science Journal, 3, 239, doi: 10.3847/PSJ/ac8540

Castro-Cisneros, J. D., Malhotra, R., & Rosengren, A. J. 2025, Icarus, 438, 116606, doi: 10.1016/j.icarus.2025.116606

Drolshagen, G., & Moorhead, A. 2019, The Meteoroid Impact Hazard for Spacecraft, ed. D. J. Asher, G. O. Ryabova, & M. D. Campbell-Brown, Cambridge Planetary Science (Cambridge: Cambridge University Press), 255–274, doi: 10.1017/9781108606462.019

Everhart, E. 1985, in Dynamics of Comets: Their Origin and Evolution, ed. A. Carusi & G. B. Valsecchi (Dordrecht: Kluwer), 185–202

Gardner, J. P., Mather, J. C., Abbott, R., et al. 2023, PASP, 135, 068001, doi: 10.1088/1538-3873/acd1b5

Gladman, B. J., Burns, J. A., Duncan, M. J., & Levison, H. F. 1995, Icarus, 118, 302, doi: 10.1006/icar.1995.1193

Grün, E., Zook, H., Fechtig, H., & Giese, R. 1985, Icarus, 62, 244–272

Holsapple, K. A. 1993, Annual Review of Earth and Planetary Sciences, 21, 333–373, doi: 10.1146/annurev.ea.21.050193.002001

Holsapple, K. A., & Schmidt, R. M. 1982, Journal of Geophysical Research: Solid Earth, 87, 1849–1870, doi: 10.1029/JB087iB03p01849

Holsapple, K. A., & Schmidt, R. M. 1987, Journal of Geophysical Research: Solid Earth, 92, 6350–6376, doi: 10.1029/JB092iB07p06350

Housen, K. R., & Holsapple, K. A. 2011, Icarus, 211, 856–875, doi: 10.1016/j.icarus.2010.09.017

Housen, K. R., Schmidt, R. M., & Holsapple, K. A. 1983, Journal of Geophysical Research: Solid Earth, 88, 2485–2499, doi: 10.1029/JB088iB03p02485

Jedicke, R., Alessi, E. M., Wiedner, N., et al. 2025, Icarus, 438, 116587, doi: 10.1016/j.icarus.2025.116587

Jedicke, R., Alessi, E. M., Wiedner, N., et al. 2025, Icarus, 438, 116587, doi: 10.1016/j.icarus.2025.116587

Jiao, Y., Cheng, B., Huang, Y., et al. 2024, Nature Astronomy, 8, 819, doi: 10.1038/s41550-024-02258-z

Johnson, C., Scott, L., & Thorsteinson, S. 2021, in AMOS Conference

Kreslavsky, M. A., & Asphaug, E. 2014, in 45th Annual Lunar and Planetary Science Conference, Lunar and Planetary Science Conference, 2455

Melosh, H. J. 1985, Geology, 13, 144–148, doi: 10.1130/0091-7613(1985)13⟨144:EORFFP⟩2.0.CO;2

Melosh, H. J. 1989, Impact cratering : a geologic process

Moorhead, A., Egal, A., Brown, P. G., Moser, D. E., & Cooke, W. 2019, Journal of Spacecraft and Rockets, 56, 1531–1545, doi: 10.2514/1.A34416

Moorhead, A. V., Kingery, A., & Ehlert, S. 2020, Journal of Spacecraft and Rockets, 57, 160–176, doi: 10.2514/1.A34561

Neukum, G., Ivanov, B., & Hartmann, W. K. 2001, Space Science Reviews, 96, 55–86, doi: 10.1023/A:1011989004263

Park, R. S., Folkner, W. M., Williams, J. G., & Boggs, D. H. 2021, AJ, 161, 105, doi: 10.3847/1538-3881/abd414

QGIS Development Team. 2025, QGIS Geographic Information System, QGIS Association. https://www.qgis.org

Rivkin, A. S., Mueller, T., MacLennan, E., et al. 2025, Research Notes of the AAS, 9, 70, doi: 10.3847/2515-5172/adc6f0

Singer, K. N., Jolliff, B. L., & McKinnon, W. B. 2020, Journal of Geophysical Research: Planets, 125, e2019JE006313, doi: 10.1029/2019JE006313

Speyerer, E. J., Robinson, M. S., Denevi, B. W., & LROC Science Team. 2011, in 42nd Annual Lunar and Planetary Science Conference, Lunar and Planetary Science Conference, 2387

USGS Astrogeology Science Center. 2014, LRO LOLA 118m Global Lunar DEM, https://astrogeology.usgs.gov/search/map/moon_lro_lola_dem_118m

Vickery, A. M. 1987, Geophys. Res. Lett., 14, 726, doi: 10.1029/GL014i007p00726

Watkins, R. N., Jolliff, B. L., Mistick, K., et al. 2019, Journal of Geophysical Research: Planets, 124, 2754, doi: 10.1029/2019JE005963