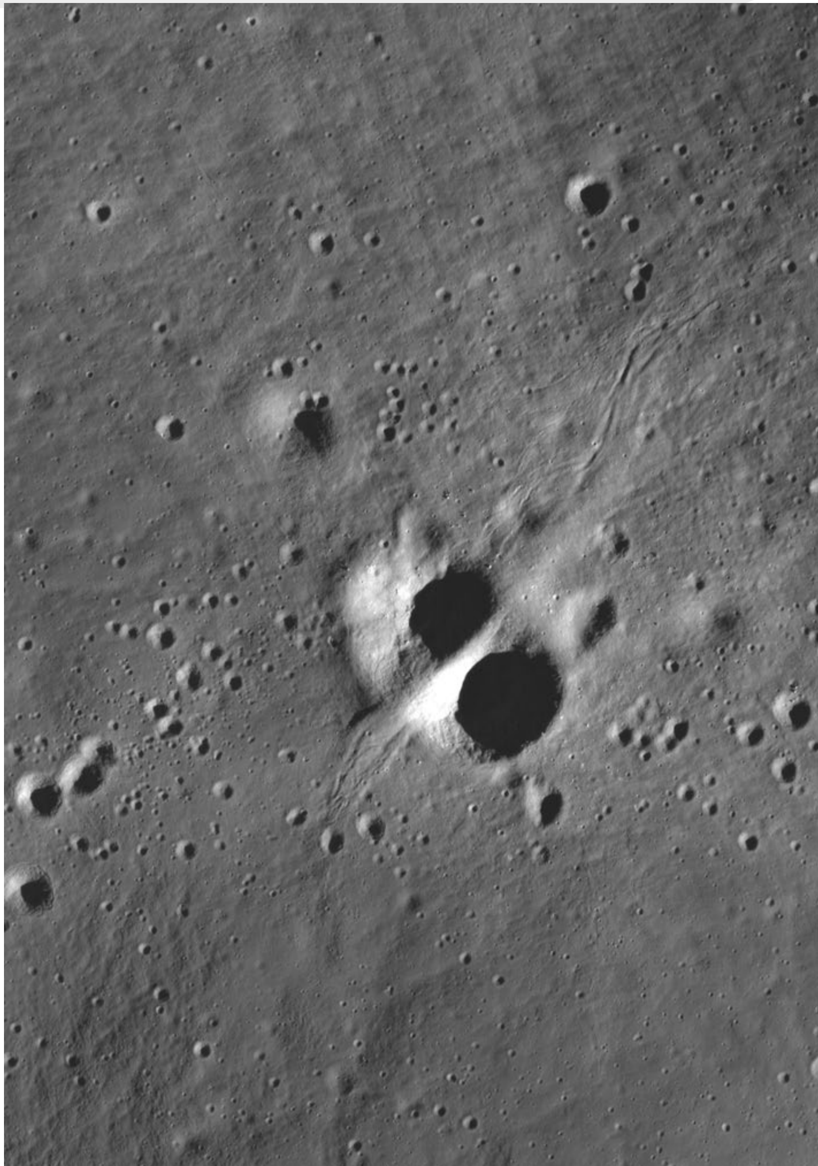
Some Unexpected Results from Lunar Ejecta

Mark Matney, Ph.D.
Orbital Debris Program Office
NASA Johnson Space Center

Space Impacts

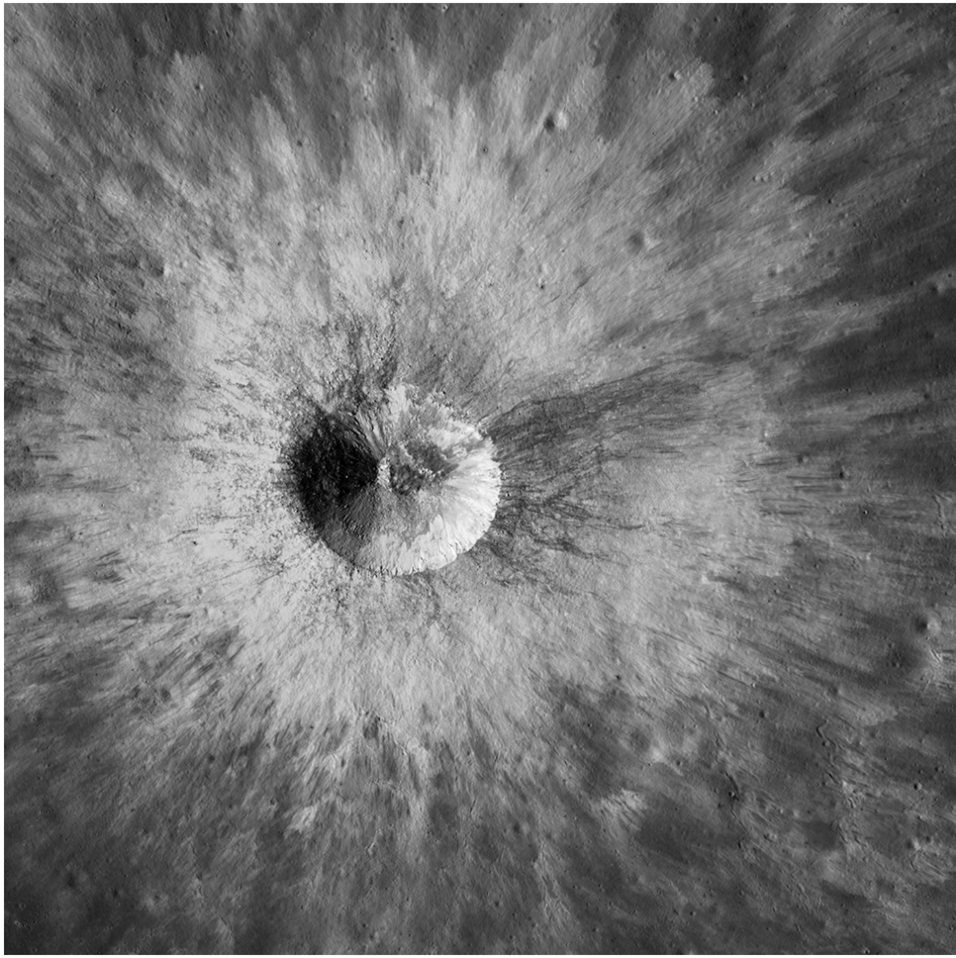
- **Since the beginning of the Space Age, scientists have known that space activities expose spacecraft and astronauts to dangerous high-velocity impacts**
  - **Meteoroids**
  - **Asteroids**
  - **Anthropogenic Orbital Debris**

- **The Moon and other airless bodies have a long history of crater-producing impacts by meteoroids and asteroids**



Ejecta

- A high-velocity impact on a planetary surfaces can excavate a crater with volume many times larger than the original impactor
- The excavated material can be ejected at high velocities from the crater
- On an airless body (like the Moon) this ejecta can travel hundreds or thousands of kilometers from the impact site
- This ejecta can create an additional hazard to human operations (in addition to the meteoroid/asteroid direct impact risk)



Apollo

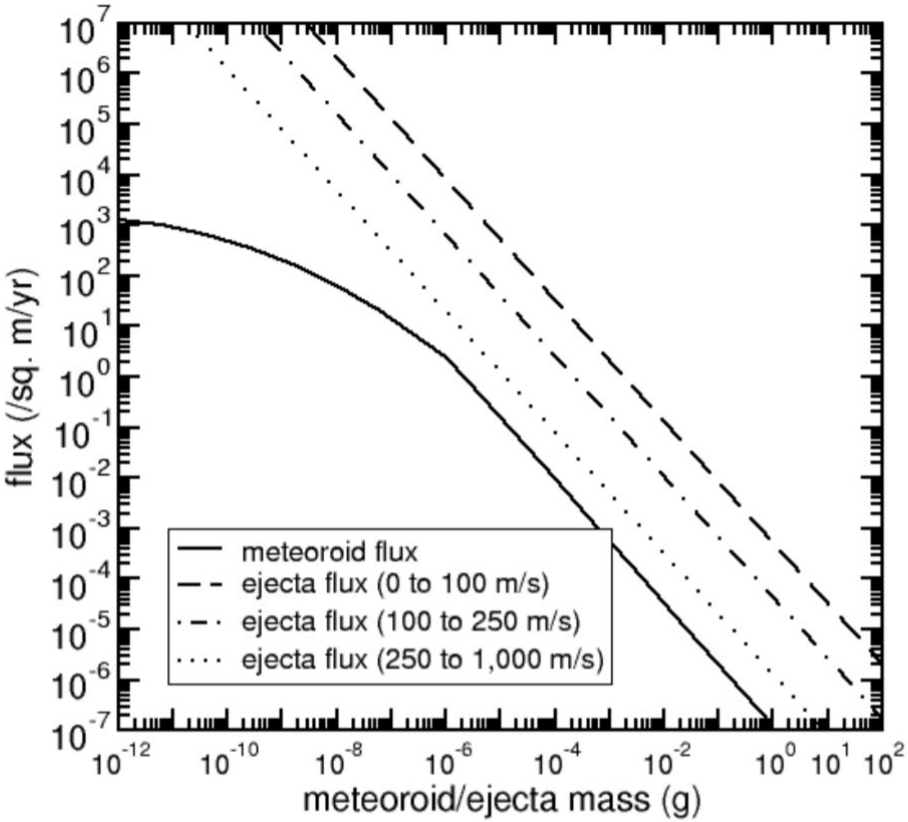


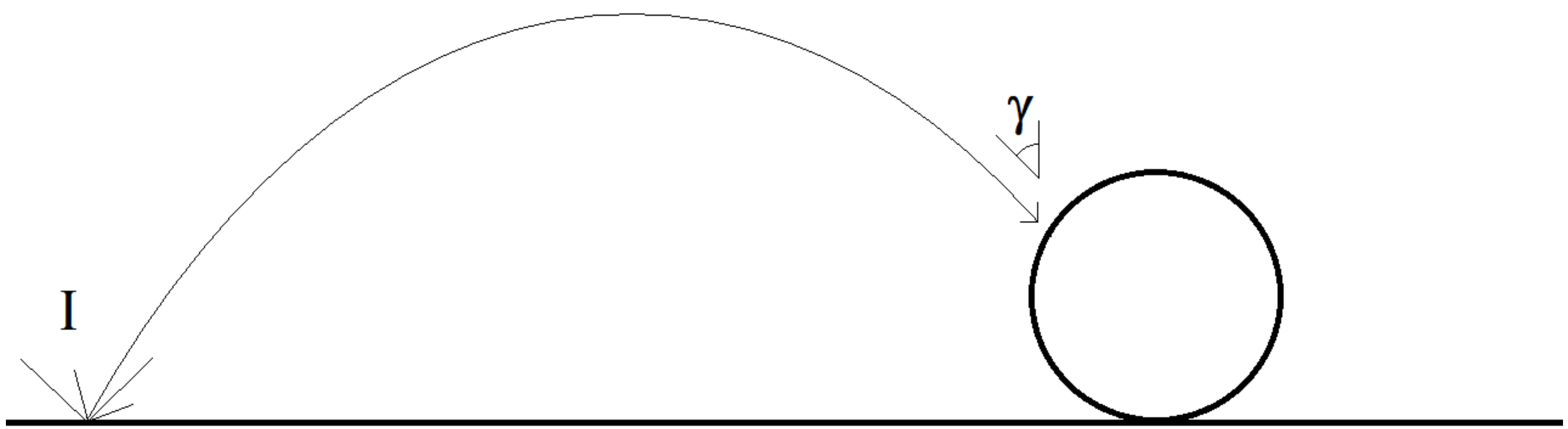
Fig. 2 NASA SP-8013 cumulative ejecta flux environment.

- **This ejecta environment was recognized by the Apollo program, and the Lunar Module was designed to survive it.**
- **However since the Apollo missions, further research has indicated the Apollo ejecta environment may be over-conservative.**
- **With renewed interest in Lunar exploration, NASA is revisiting the ejecta model**
- **Anthony DeStefano at MSFC has designed an updated lunar ejecta model for the Design Specification for Natural Environments (DSNE), which has been recently reviewed by the NASA Engineering Safety Center (NESC)**

Unexpected Results

- **The NESC review revealed some interesting aspects about lunar ejecta (and ejecta on other airless bodies) that affect human and robotic operations on or near the surface**

- **"Traditional" interpretation of the ejecta environment considers ejecta that is thrown up by the impact, passes through apoapis, then impacts the asset descending "from above" (Case I, zenith angle γ < 90°)**



Unexpected Results

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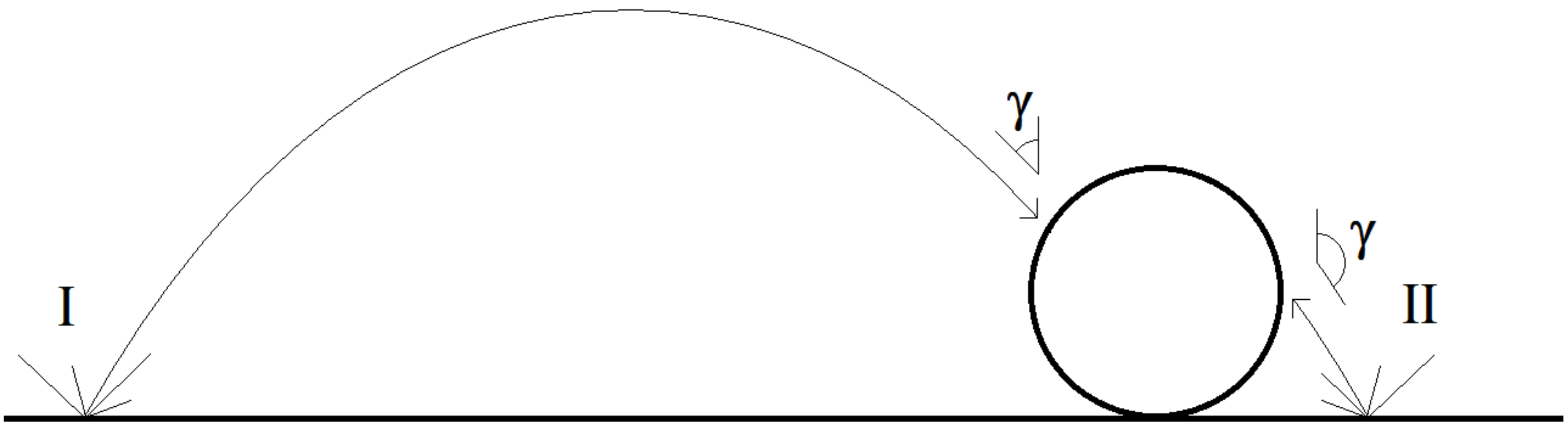
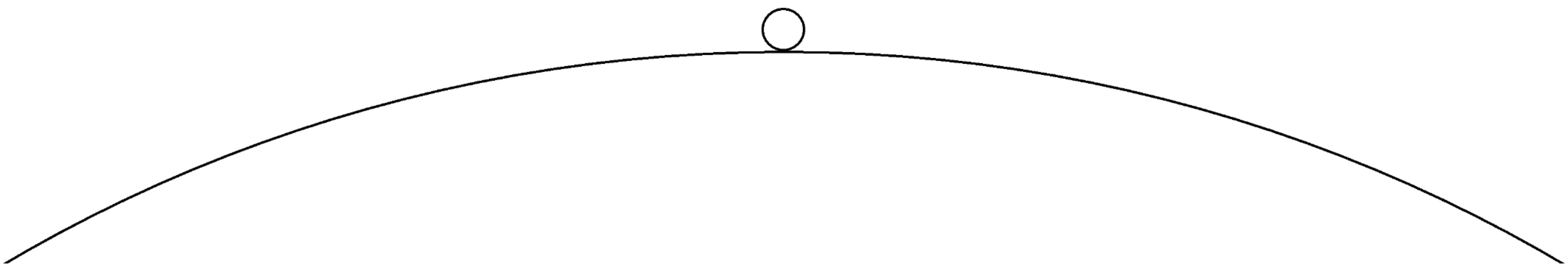
- **“Traditional” interpretation of the ejecta environment considers ejecta that is thrown up by the impact, passes through apoapis, then impacts the asset descending “from above” (Case I, zenith angle γ < 90°)**

- **However, primary impacts near the target also creates ejecta that can strike the asset ascending “from below” (Case II, zenith angle γ > 90°)**



Monte Carlo

- **In order to study this effect, a Monte Carlo model was used to simulate the ejecta environment**



- **Monte Carlo procedure**
    1. **A target sphere with radius 500 m is placed on the surface of a spherical Moon**
    2. **A primary impact site is randomly chosen on the lunar surface**
    3. **A single ejecta particle is created, with randomized azimuth, zenith angle, and speed based on the distribution to be tested**
    4. **The Kepler orbit (with no perturbations) for that ejecta particle is computed, and it is determined whether the particle orbit intersects the target sphere before it re-encounters the Moon's surface**
    5. **The conditions of that impacting ejecta particle are recorded to a file**
    6. **The process is repeated from step 2 until a sufficient number of Monte Carlo runs have been completed**

Distributions

- **For this study, the speed (v) distribution used by DeStefano was adopted**

$$D(v)dv \propto \left(\frac{v}{v_{min}}\right)^{-2.2} dv$$

  - **The minimum velocity chosen was set to 100 m/s like that of DeStefano**

- **Ejecta azimuth was assumed to be isotropic**
- **A simple zenith angle distribution was assumed**

$$D(\gamma) \propto \sin\gamma \cos\gamma$$

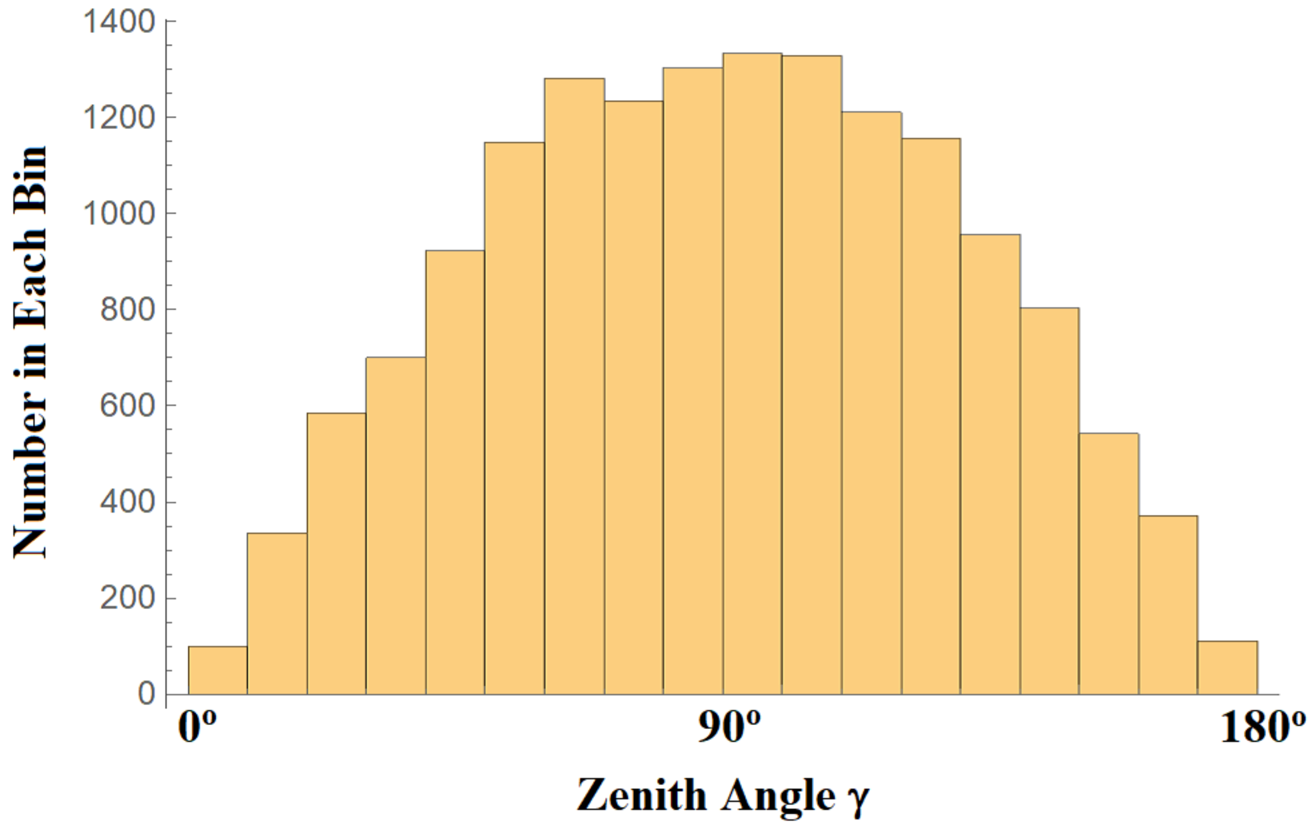
- **This is similar to an isotropic distribution, but with an extra term that reduces ejecta parallel to the lunar surface**

- **The target asset is a sphere so that the directional flux can easily be computed by dividing the number of particles penetrating the sphere per unit time by the cross-sectional (πr^2) area of the sphere**

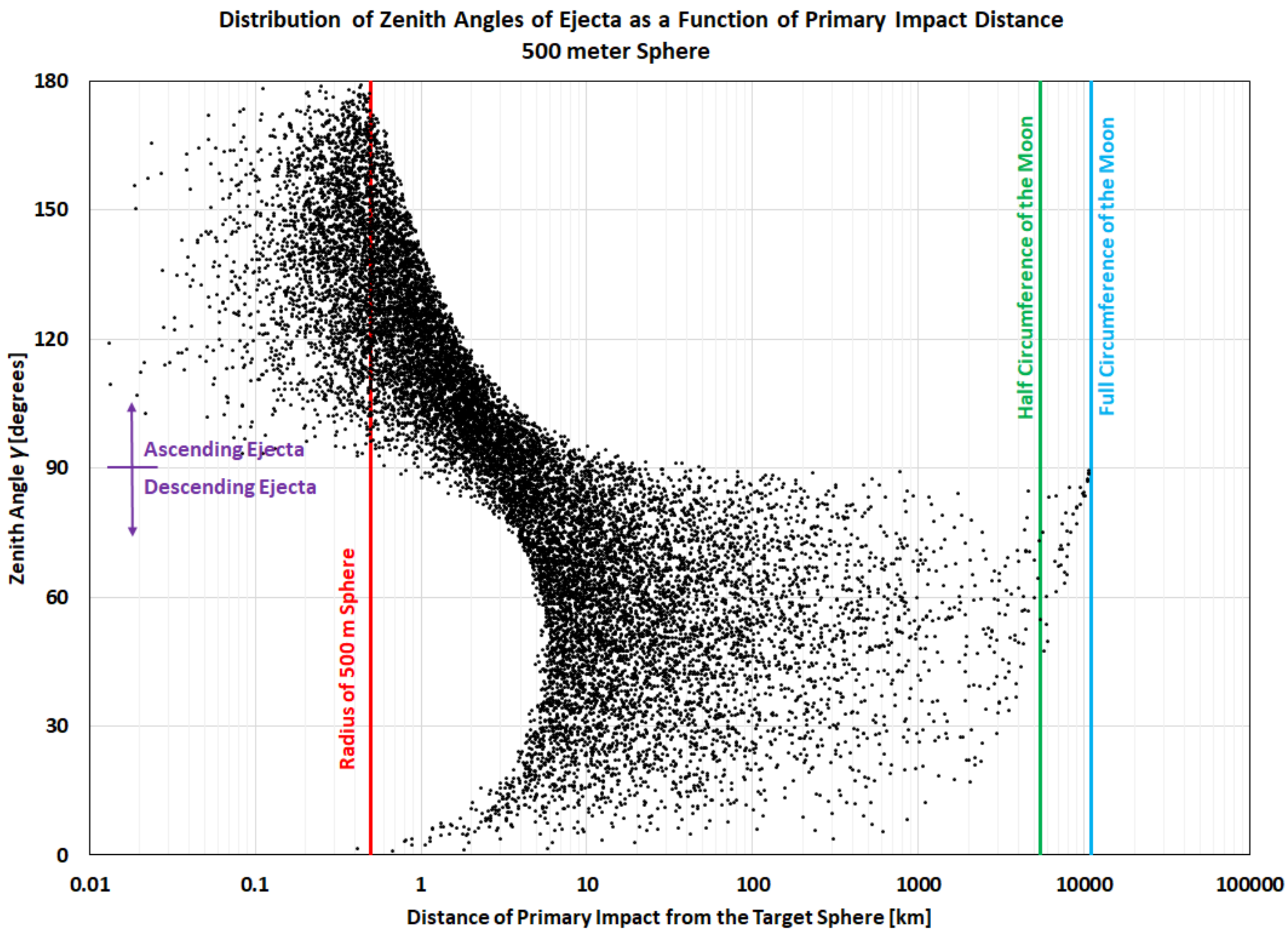
Distribution of Impactors on the Spherical Asset

- The histogram of the impacts on the target sphere shows a nearly-symmetric distribution in zenith angle
  - Roughly half the flux is from the ascending "from below" population

- The distribution is very similar to an isotropic one



Ejecta Distribution as a Function of Range and Zenith Angle

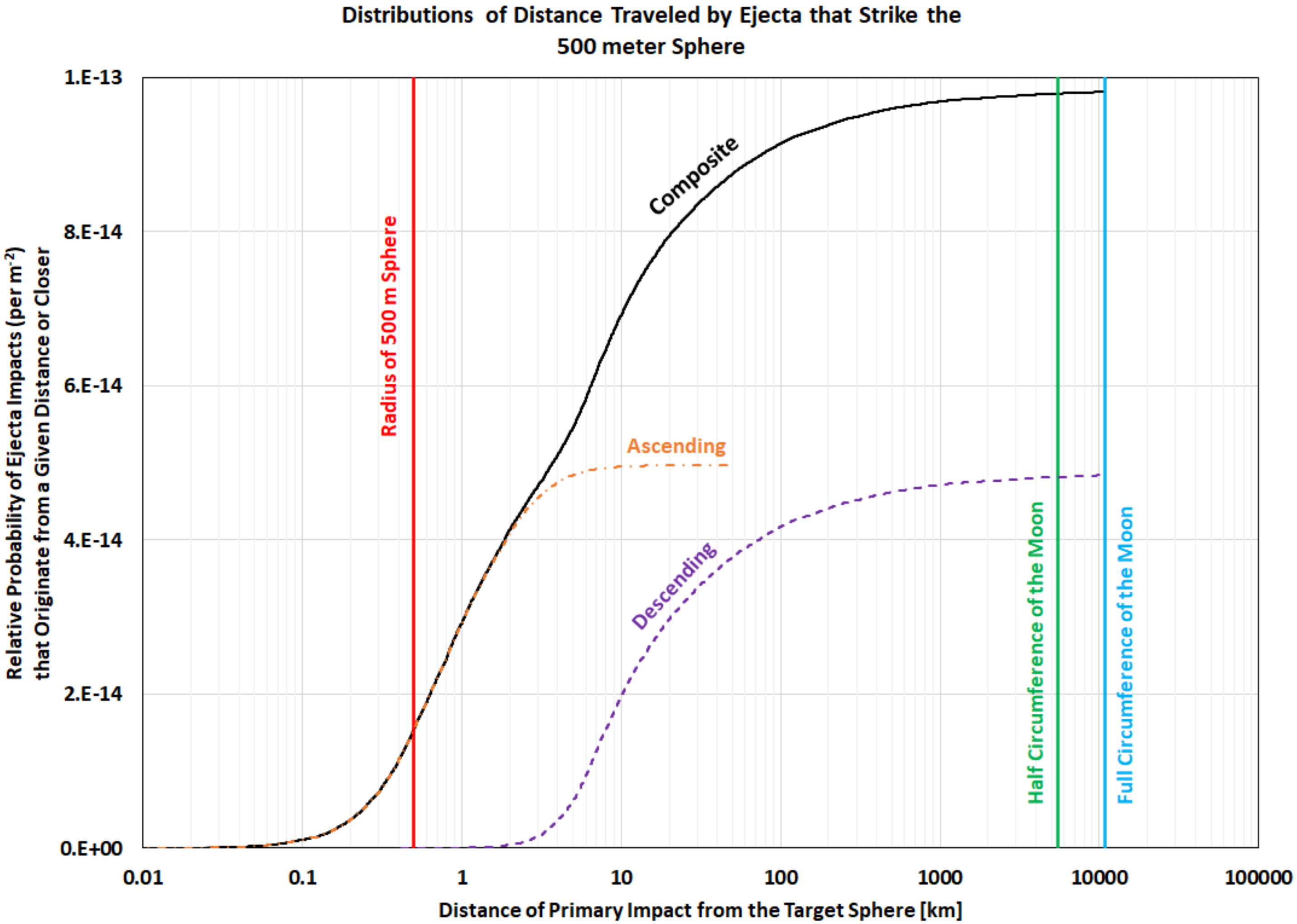


Observations

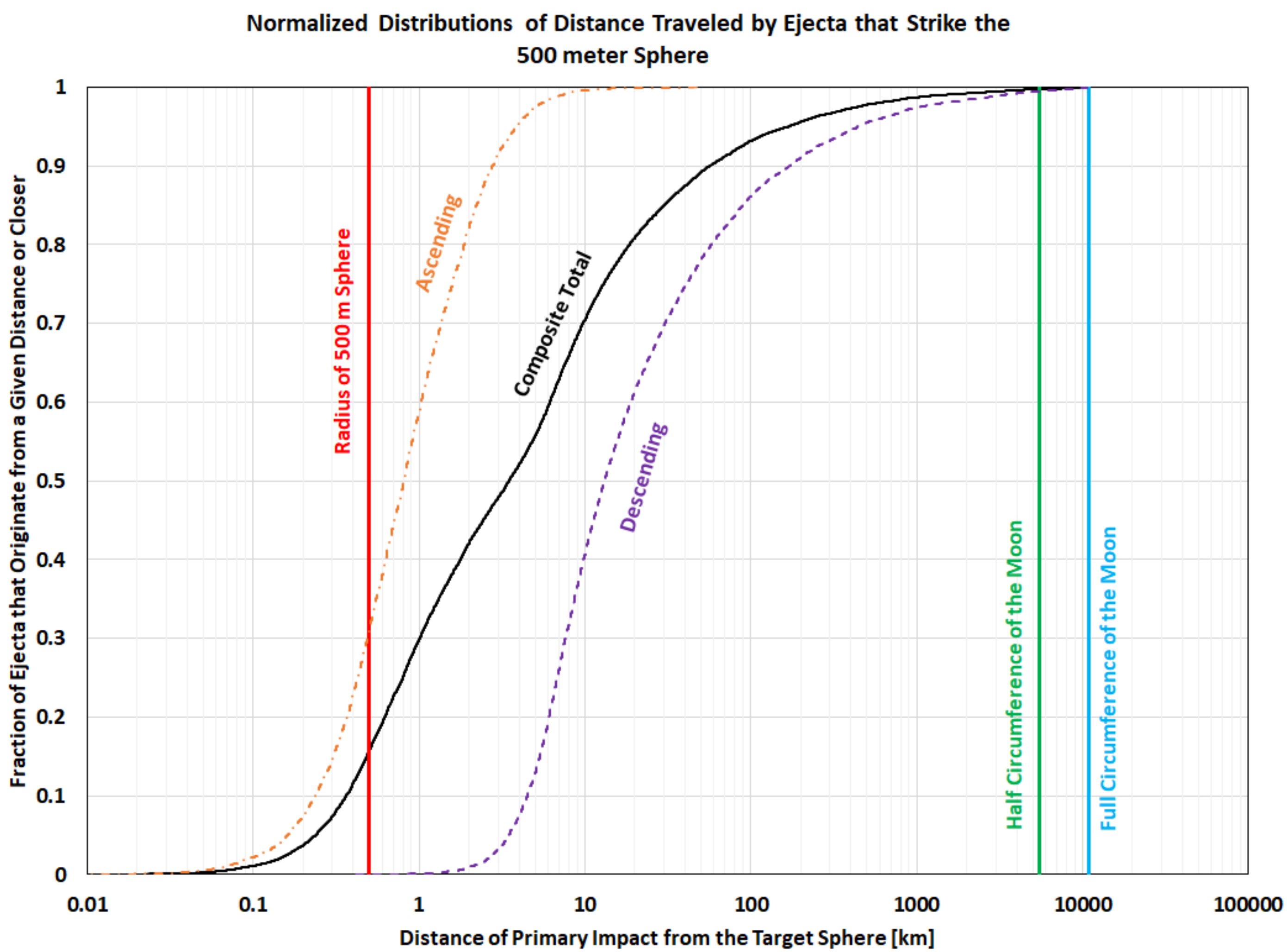
- The ascending ejecta comes from primary impacts near the target sphere
- Many of the primary impacts that produce ascending impactors take place "beneath" the target sphere
  - Shadowing by the primary not considered
- A majority of the descending impactors take place from primary impacts not far (tens to hundreds of km) from the target sphere
- There are ejecta impacts from distant primary impacts, but not many
  - Some travel more than halfway around the Moon
- There is no obvious enhanced flux from primary impacts at the antipode
  - The expected increase in flux is offset by the low probability of such an impact location
- The detailed geometry of the near-field ejecta flux is dependent on the size and shape of the target

National Aeronautics and Space Administration

Cumulative Distributions as a Function of Distance to Primary Impact Locations



Normalized Cumulative Distributions as a Function of Distance to Primary Impact Locations

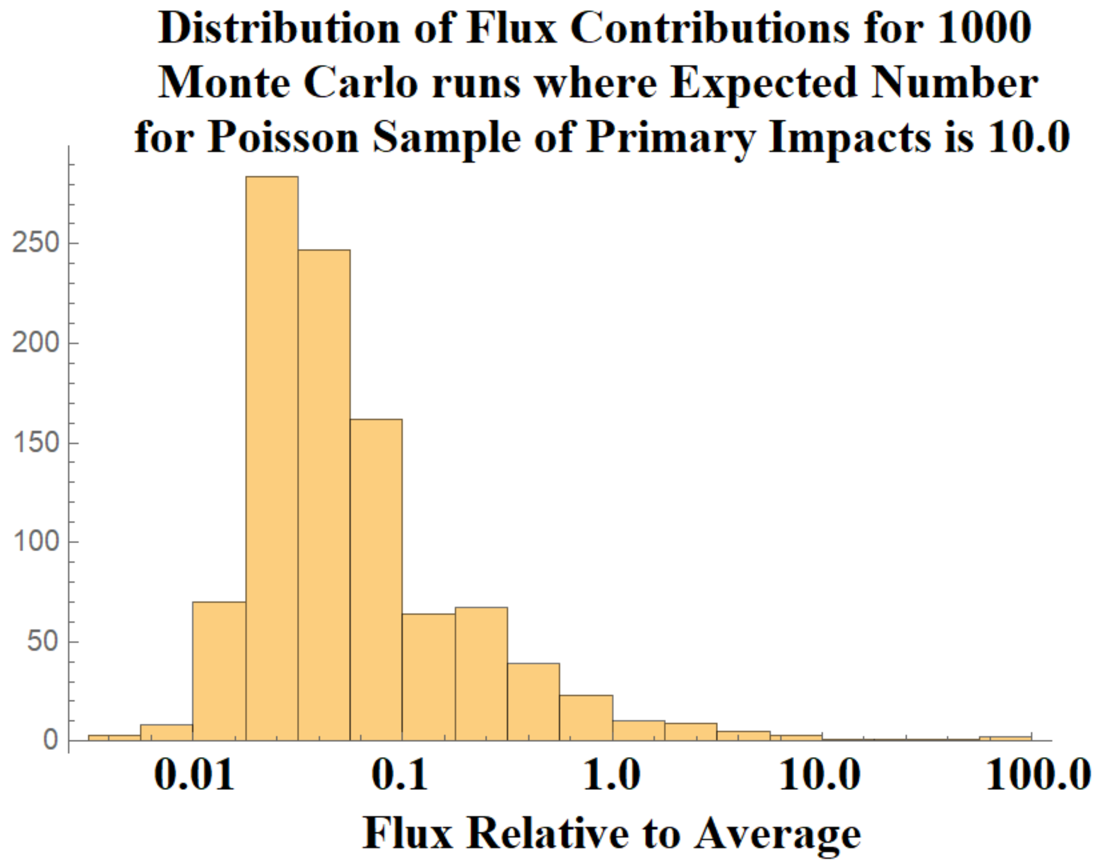


Stochastic Behavior of Primaries

- **Because most of the ejecta flux is from impacts near the asset, the flux can show stochastic behavior**

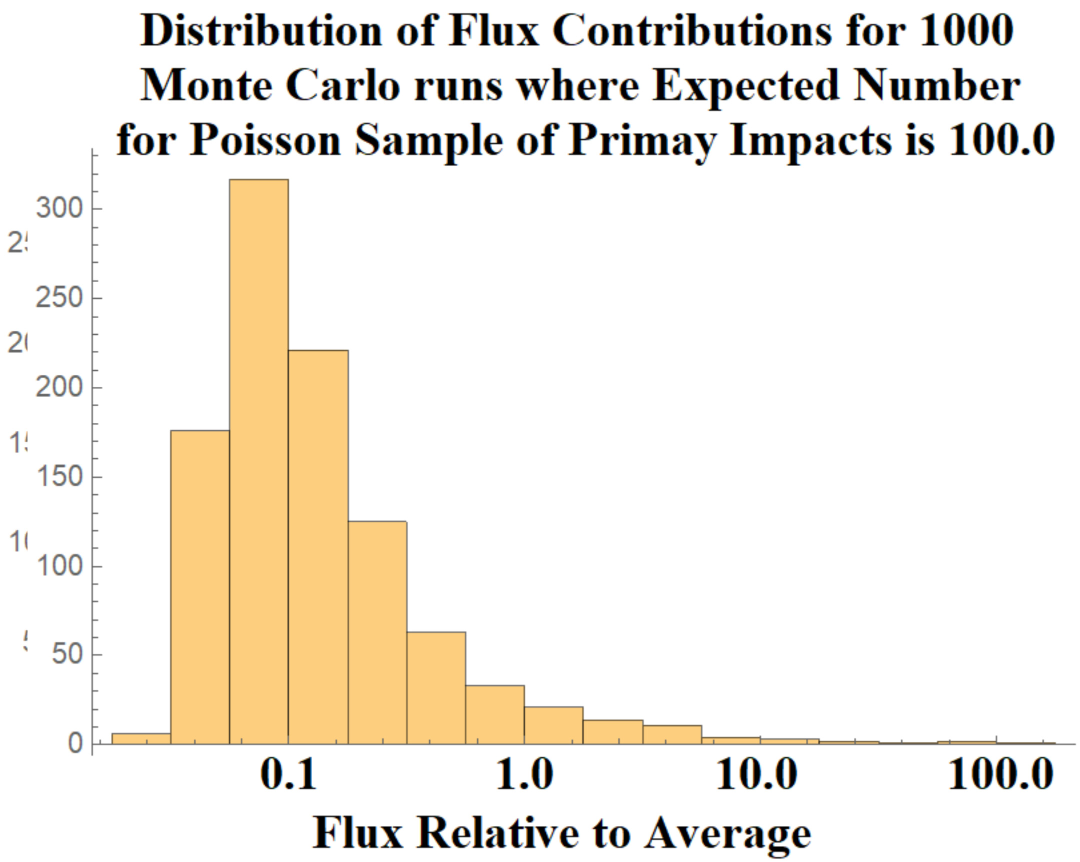
- **In order to examine this phenomenon, a Monte Carlo procedure was used to simulate this variability**
  1. **An integer number of primary impacts is randomly generated from Poisson sample of the expectation value (10.0, 100.0, 1000.0)**
     - **Simulates exposure for a finite length of time**
  2. **For each primary impact, the probability of an ejecta impact on the sphere is computed**
     - **Analyzed only the descending population**
  3. **The probability is summed and compared to the average value**
  4. **The procedure is repeated for 1000 Monte Carlo runs**

Stochastic Behavior of Primaries



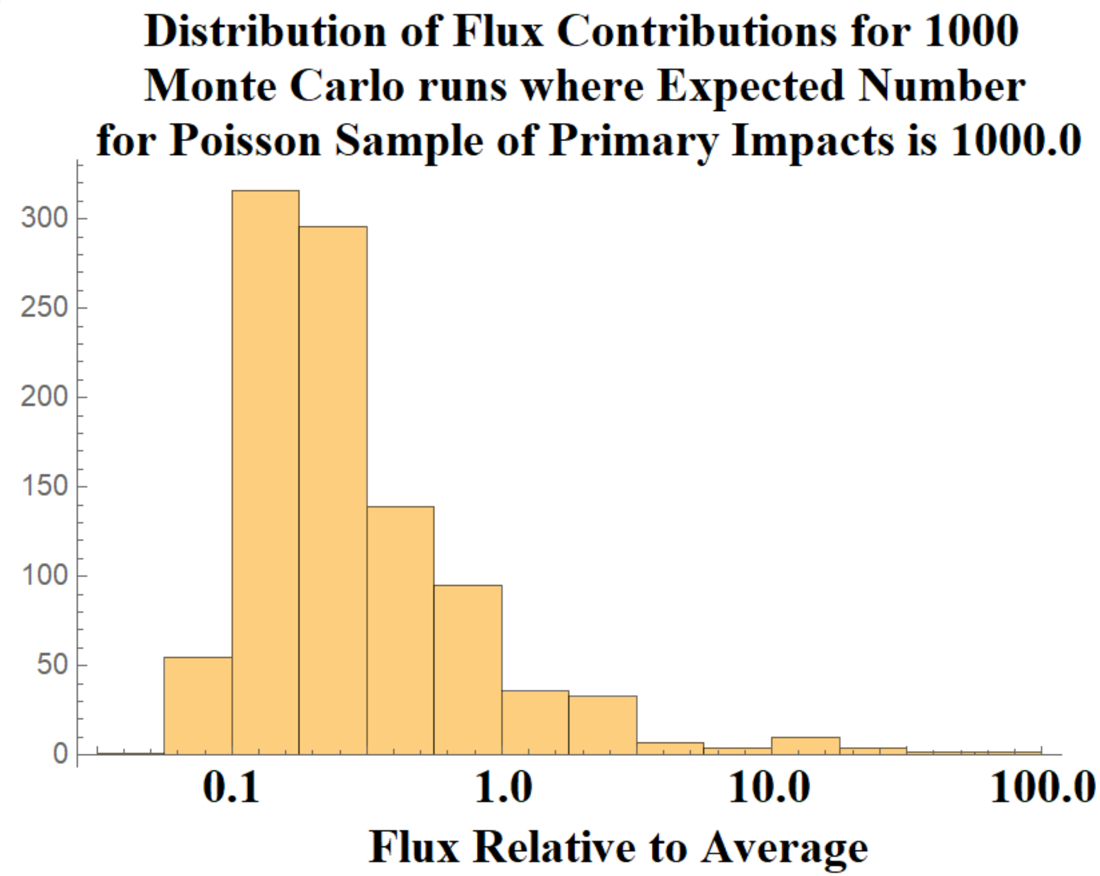
- **3% of cases exceed the mean value**

Stochastic Behavior of Primaries



- **6% of cases exceed the mean value**

Stochastic Behavior of Primaries



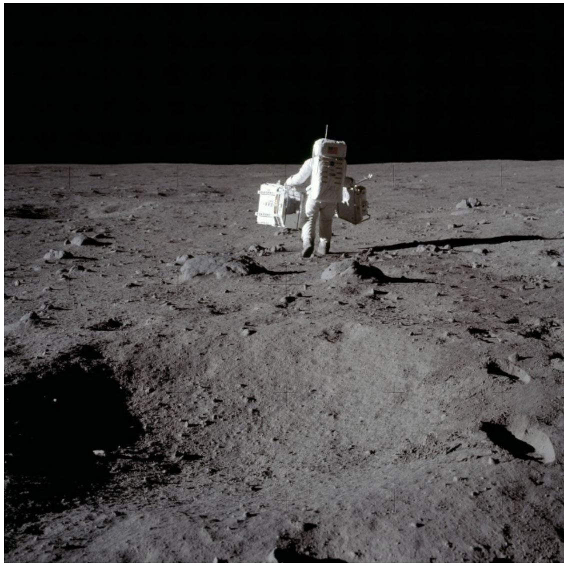
- **10% of cases exceed the mean value**

Observations

- The flux is usually significantly lower than the mean value
- On rare occasions, the flux can exceed the mean flux by orders of magnitude
- Variability much greater than simple Poisson sampling error
- If we include the ascending population, this effect would be even more pronounced
- This effect has implications for how risks for missions are computed
  - Probabilistic Risk Assessments?

Conclusions

- **Ejecta risk is not just from descending ejecta, but from ascending ejecta due to near-field impacts as well**
  - **Risk from ascending ejecta similar in magnitude to the descending risk**
  - **Ascending ejecta includes particles exceeding the escape speed (which are not an issue with descending ejecta), so the risk may actually be higher**
  - **Risk from ascending ejecta dependent on the shape and size of the asset**



- **The flux from a primary impact is very much dependent on the location relative to the asset, which results in stochastic behavior of impact risk**
  - **Implications for how mission risk computed**
- **The ejecta environment is not limited to the surface of the airless body, but creates a kind of “halo” of particles around the body that can affect orbiting assets as well**