Hazard Assessment of Meteoroid Impact for the Design of Lunar Habitats

C. Beck[1], H.Montoya[1], D. Gomez[1], S. Dyke[1,2], A. Bobet[1], J. Melosh[3], and J. Ramirez[1]
[1]Lyles School of Civil Engineering, Purdue University, [2]School of Mechanical Engineering, Purdue University, and
[3]Department of Earth, Atmospheric, and Planetary Sciences, Purdue University

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Introduction

- Meteoroids pose a risk to lunar structures due to their high frequency of occurrence and hypervelocity impact. Continuous meteoroid impacts can harm structural elements and vital equipment compromising the well-being of lunar inhabitants.

Figure 1. *Meteoroid Impact (Boston Globe).*

Hazard Identification

- Meteoroid impacts is the dominant surface process on the Moon due to high velocities, high frequency, and secondary effects involved with impact [1].

Primary Effect:

Direct Damage/Impact

Figure 2. *Meteoroid Impact and Damage (Science ABC and ESA).*

Secondary Effects:

Ejected Particles

Figure 3. *Ejected particle due to impact (123RF).*

Seismic Activity

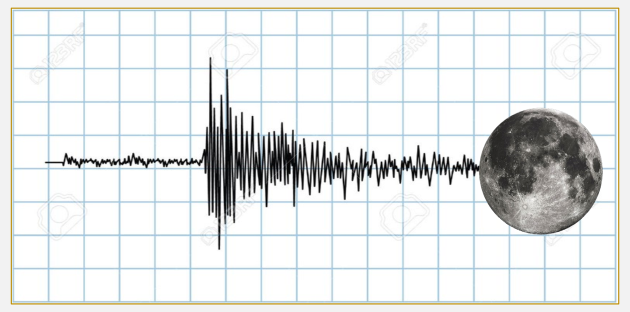


Figure 4. *Seismic illustration (SpaceFacts).*

Hazard Characterization

- The properties of an impacting object and its struck surface is crucial for predicting the associated damage.

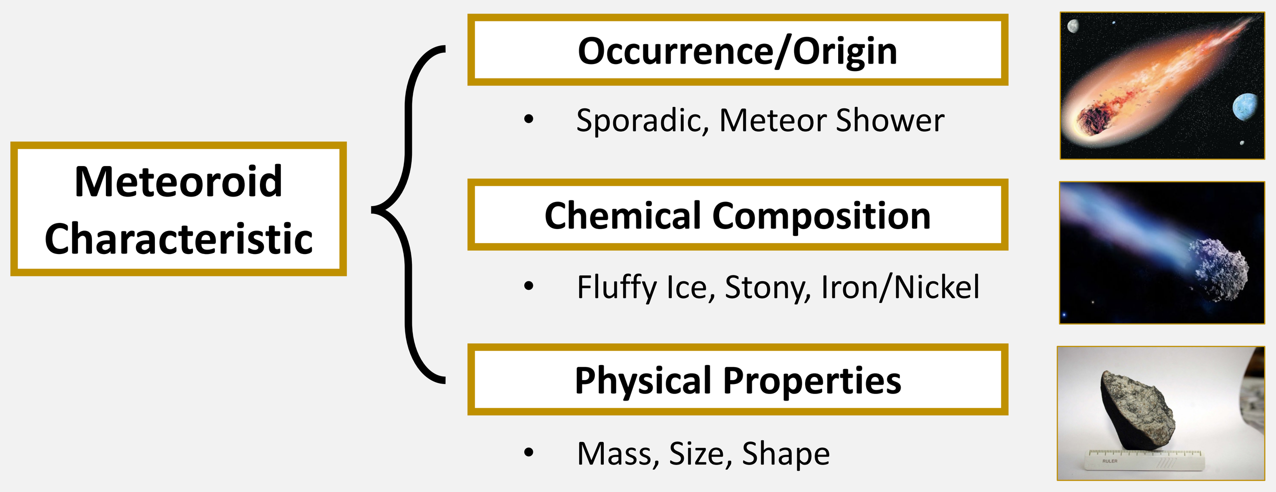


Figure 5. *Meteoroid Characteristic Diagram.*

Hazard Quantification Methodology

- The analysis for hazard quantification is performed to understand meteoroid characteristics and estimate the potentially damaging energy. Lunar impact flash data from the NASA's Lunar Monitoring Program [2] is used to perform the following analyses.

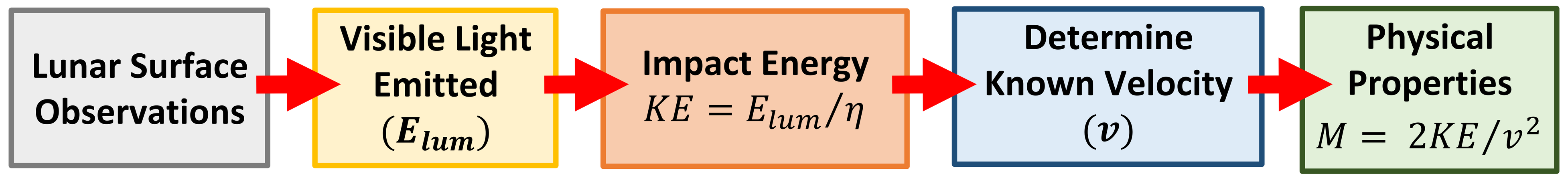


Figure 6. *Characteristic Calculation Diagram (E_{lum} is the luminous energy, η is the luminous efficiency).*

Preliminary Statistical and Frequency Analysis:

- The probability density function (PDF) for the estimates on kinetic energy, mass, and diameter (assuming spherical shape) along with the exponential distribution PDF for these estimates were calculated. Five different frequency analysis techniques were performed to estimate the frequency of these kinetic energy magnitudes.

Secondary Statistical and Frequency Analysis:

- Secondary statistical analysis used Monte Carlo Simulation of independent variables, mass and velocity, to determine range for kinetic energy associated with impacts. Mass range defined from data (1 to 145 g) and velocity determined from physics (11 to 72 km/s)
- Focused on eliminating epistemic uncertainty by removing velocity assumption for meteoroid impacts not associated with meteor shower
- Validity of possible distributions to characterize data confirmed with probability plots, such as in Figure 7

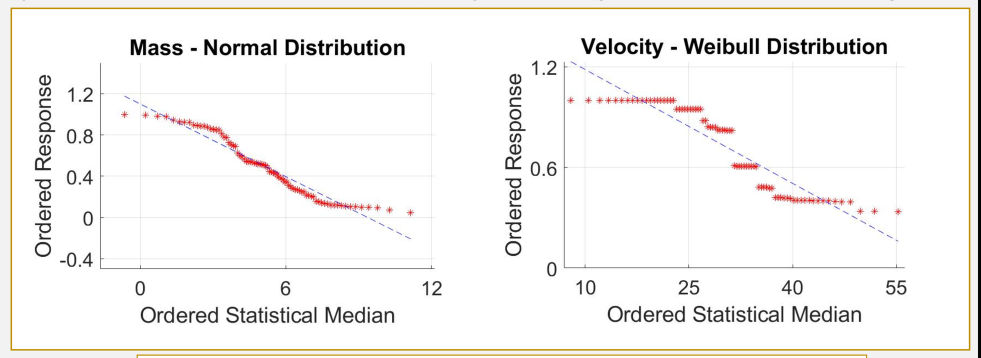


Figure 7. *Example probability plots for velocity and mass*

Results

Primary Statistical and Frequency Analysis Results:

- The exponential distribution is believed to be a good fit to the data. It yields values for the probability of extreme values that were not apparent during the time of observation.
- The numerical formula was chosen to give the best estimates seeing that it yielded the most conservative values which is ideal for design purposes. In Figure 8, the return periods are plotted along with the magnitude of impact energy. This plot provides a performance criteria spectrum of return periods and the amount of damage associated to impact energy.

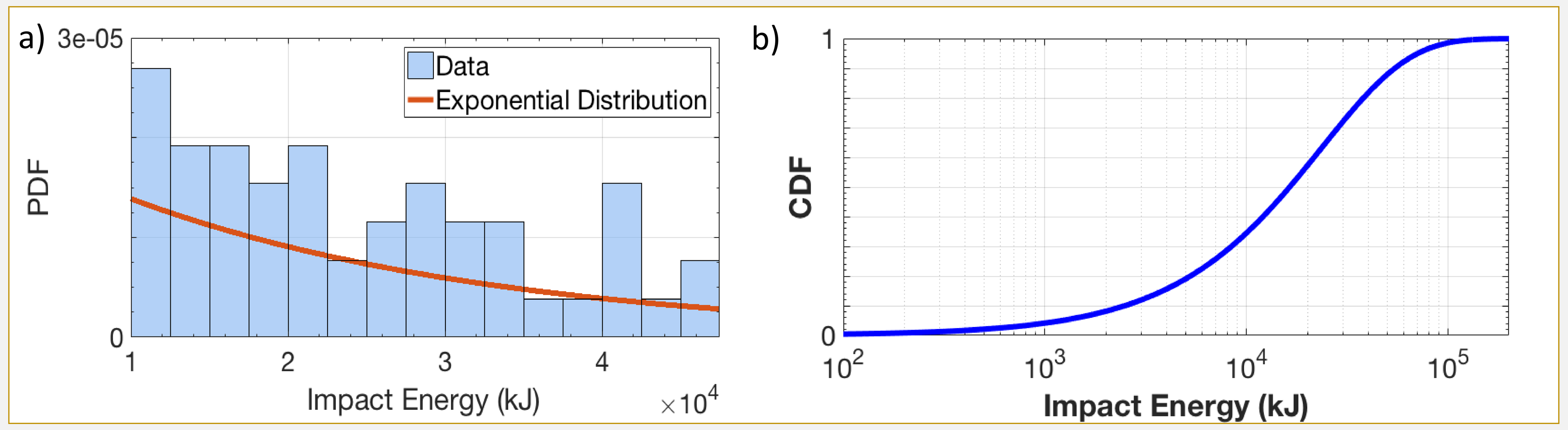


Figure 8. *Lunar Impact Data Analysis: a) Probabilistic density function with exponential distribution; b) Cumulative distribution function.*

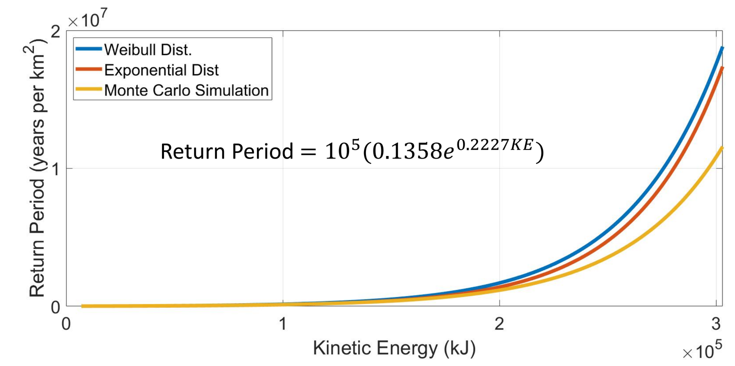
Secondary Statistical and Frequency Analysis Results:

- Characteristic Monte Carlo simulation is developed using the best-fit distributions for velocity and mass, Weibull and normal, respectively

Characteristics	Velocity (km/s)	Mass (g)	KE ($J*10^7$)
Max	67.72	200.48	48.04
Min	11.06	0.00	0.00
Average	31.11	34.22	3.65
St. Dev	9.95	27.85	4.13

ABOVE: Table 1. *Simulation characteristics for data comparison*

RIGHT: Figure 9. *Estimated return periods*



- Figure 9 shows possible fluctuation of return periods for a meteoroid hazard
- All three have similar return periods until 1.4*10^5 kJ when exponential nature of deterministic distributions controls
- Mass and velocity flux plotted against project data, MEM, and Steinberg validate distribution trends and provide insight into frequency of impacts with given characteristics

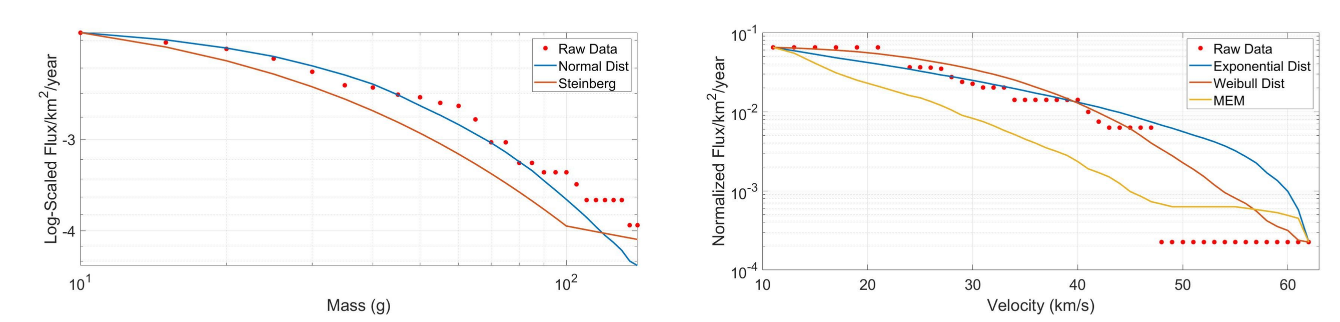


Figure 10. *Normalize flux of mass and velocity for various simulations, data sets, and distributions*

Conclusions and Future Work

- It is possible to identify which characteristics of a meteoroid determine the magnitude of damage associated with it.
- The amount of observations are limited and result in large uncertainties. A sufficient number of impact flashes is needed to calculate precise characteristics of meteoroid impacts.
- The probabilities of impact by meteoroids are fairly known and meteoroid characteristics can be estimated, but the consequences of damage on the different materials will help estimate the risk of an object exposed to the lunar environment.
- Effect of secondary impacts (ejecta) should be characterized

References

[1] Heiken, G., Vaniman, D., and French, B. (1991). "Lunar Surface Processes: Impact Processes." *Lunar Sourcebook: A User's Guide to the Moon*, Cambridge University Press, 61-85.

[2] Suggs, R.M., Moser, D., Cooke, W., and Suggs, R.J. (2014). "The flux of kilogram-sized meteoroids from lunar impact monitoring." *Icarus*, 238, 23-26.