The Lunar Meteoroid Ejecta Environment

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NASA MSFC Natural Environments

Meteor Workshop 8/28/2024

Huntsville, Alabama

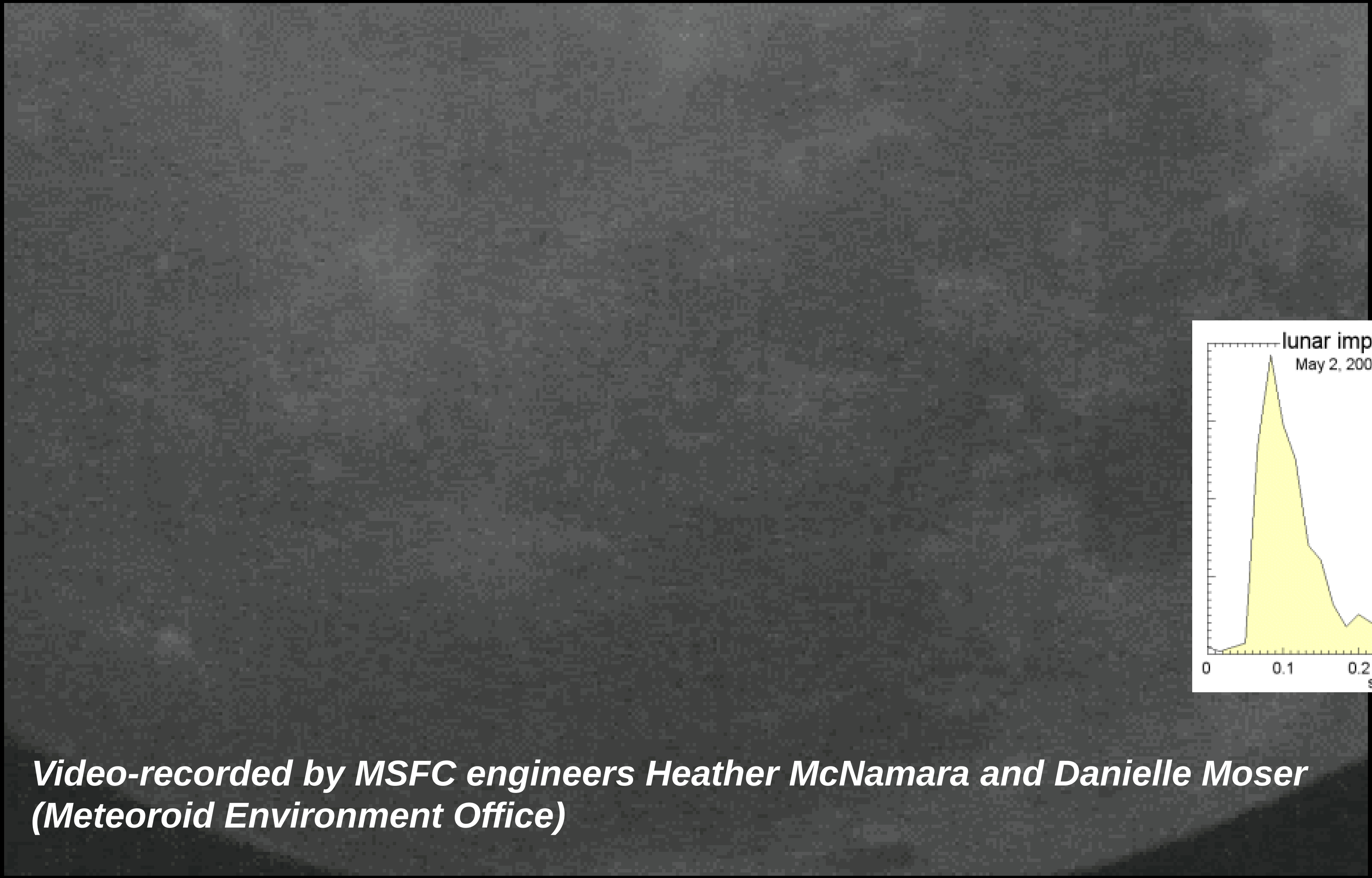
Automated Lunar and Meteor Observatory (ALaMO)

- Telescopes
  - Two 14” (0.35m), south dome and tower

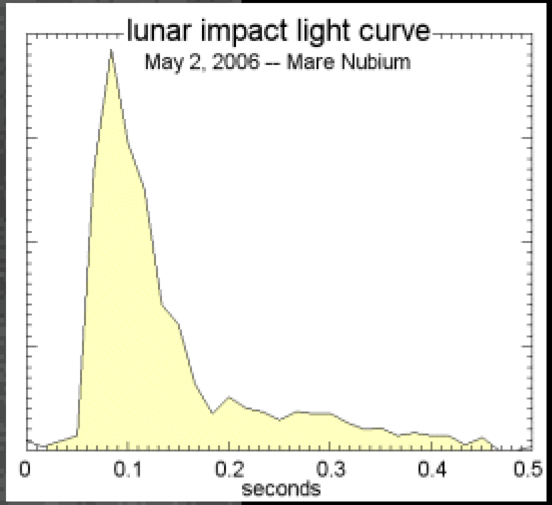
MSFC, Huntsville, Alabama

Meteor Showers:
Watching an impact from Earth… May 2, 2006

A piece of debris from Comet Encke struck the plains of Mare Nubium, making a crater about 3 meters wide.

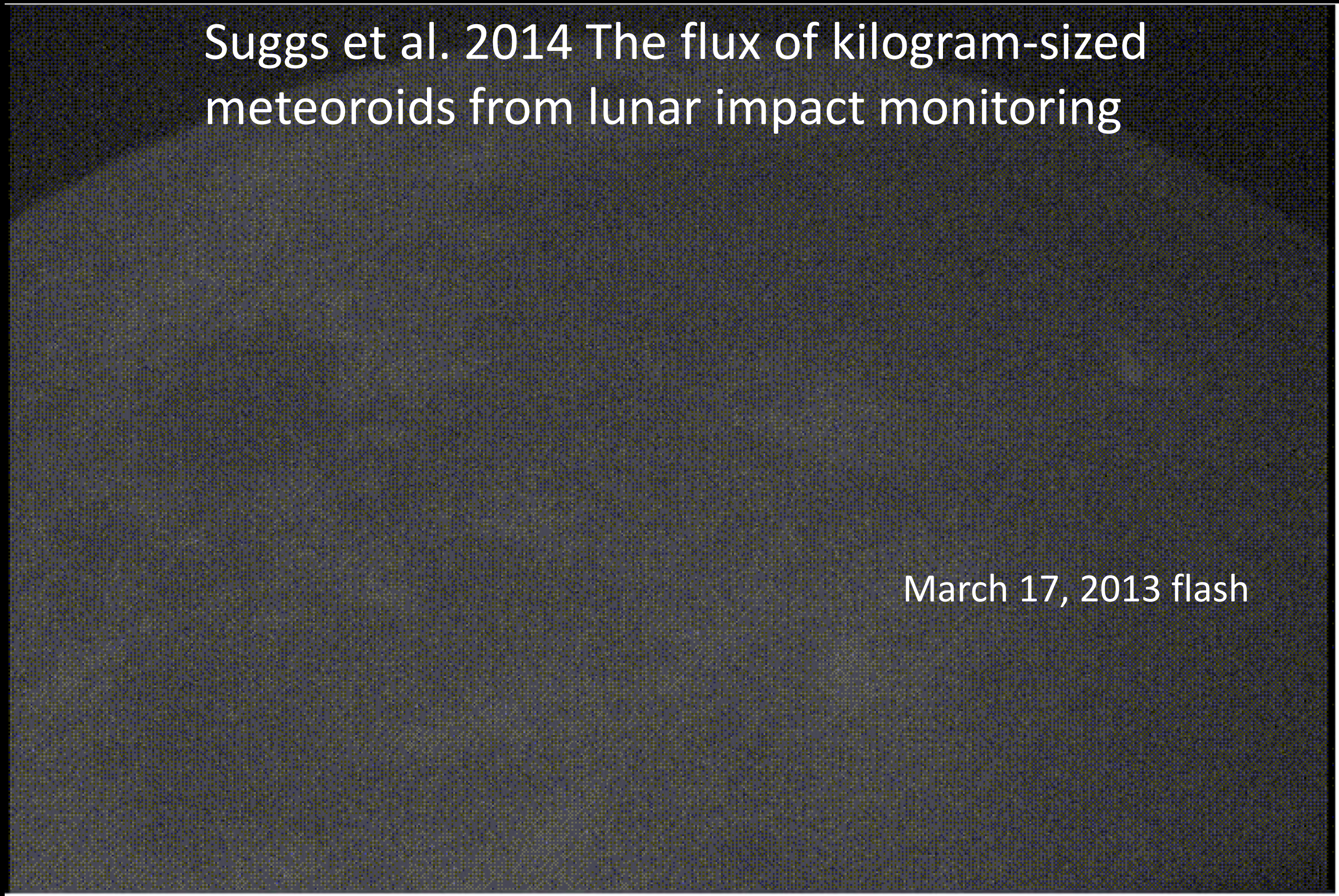


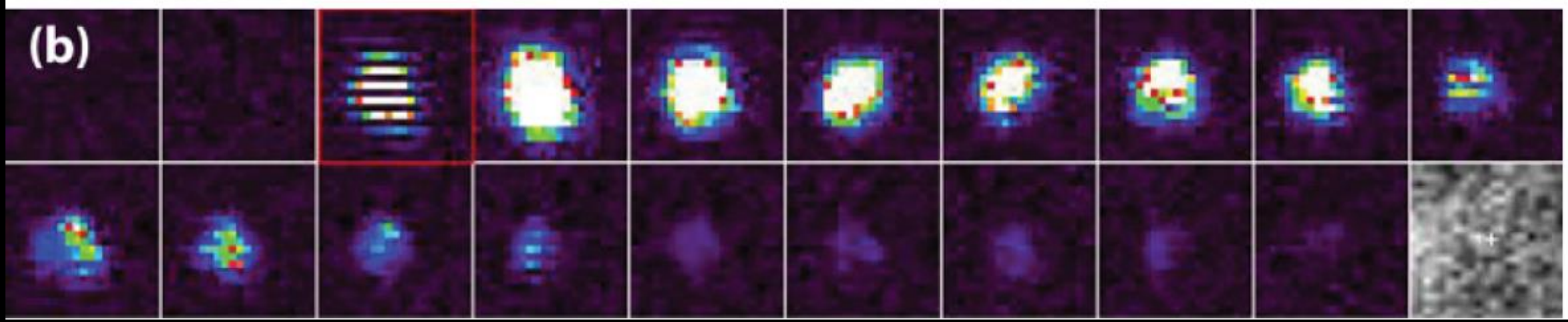
Video-recorded by MSFC engineers Heather McNamara and Danielle Moser (Meteoroid Environment Office)

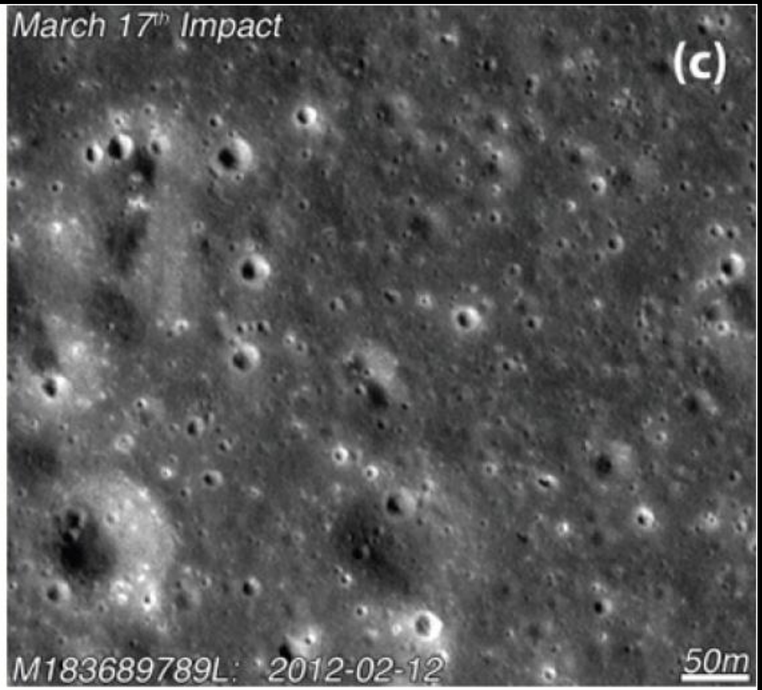


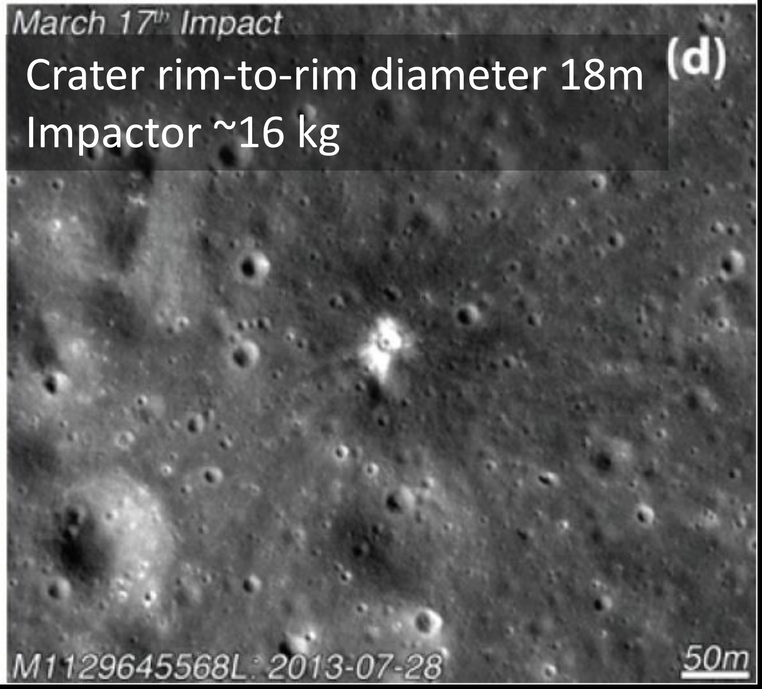
https://www.nasa.gov/vision/universe/solarsystem/13jun_lunarsporadic.html

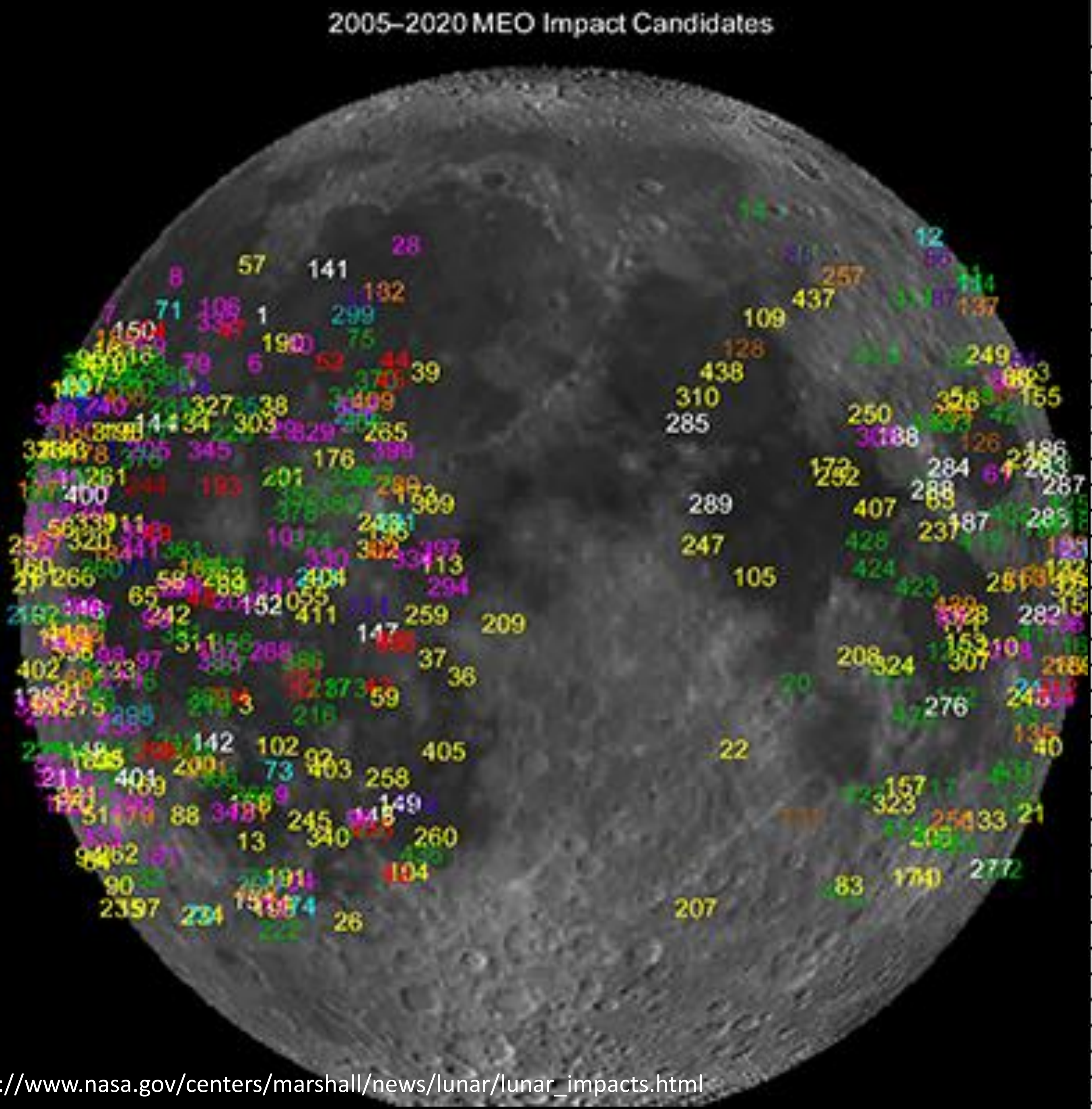
Suggs et al. 2014 The flux of kilogram-sized meteoroids from lunar impact monitoring











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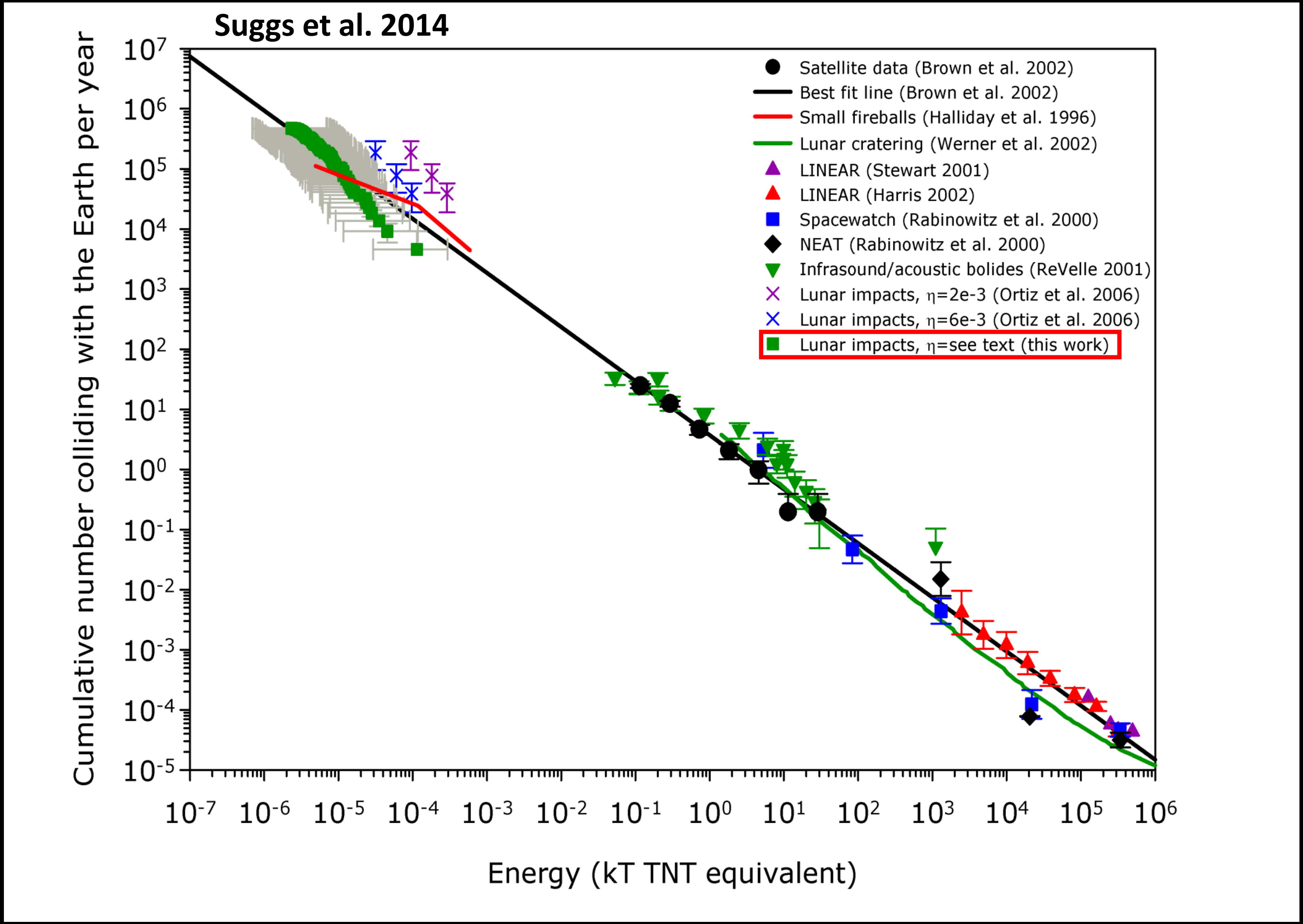
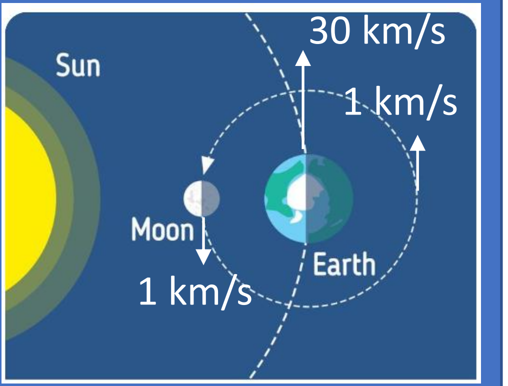
403	02 Apr 2017	01:14:11	1	Unk	two 14”
404	02 Apr 2017	03:19:40	1	Unk	two 14”
405	30 Apr 2017	02:05:49	2	Unk	two 14”
406	29 Jul 2017	03:01:34	1	Unk	two 14”
407	13 Oct 2017	08:41:39	2	Unk	two 14”
408	23 Oct 2017	23:44:51	1	Unk	two 14”
409	24 Oct 2017	00:25:49	1	Unk	two 14”
410	27 Oct 2017	01:15:38	2	Unk	two 14”
411	27 Oct 2017	02:23:05	1	Unk	two 14”
412	13 Dec 2017	11:46:55	1	Geminid	two 14”
413	13 Dec 2017	11:49:39	1	Geminid	two 14”
414	13 Dec 2017	11:59:58	1	Geminid	two 14”
415	14 Dec 2017	10:30:25	1	Geminid	two 14”
416	14 Dec 2017	10:46:31	1	Geminid	two 14”
417	14 Dec 2017	10:50:21	1	Geminid	two 14”
418	14 Dec 2017	10:52:04	1	Geminid	two 14”
419	14 Dec 2017	11:02:15	1	Geminid	two 14”
420	14 Dec 2017	11:13:19	1	Geminid	two 14”
421	14 Dec 2017	11:14:14	1	Geminid	two 14”
422	14 Dec 2017	11:16:38	1	Geminid	two 14”
423	14 Dec 2017	11:18:03	1	Geminid	two 14”
424	14 Dec 2017	11:26:51	1	Geminid	two 14”
425	14 Dec 2017	11:34:42	1	Geminid	two 14”
426	14 Dec 2017	11:40:00	1	Geminid	two 14”
427	14 Dec 2017	11:43:13	1	Geminid	two 14”
428	14 Dec 2017	11:45:25	1	Geminid	two 14”
429	14 Dec 2017	11:45:52	1	Geminid	two 14”
430	14 Dec 2017	11:46:37	1	Geminid	two 14”
431	14 Dec 2017	12:00:19	1	Geminid	two 14”
432	14 Dec 2017	12:01:25	1	Geminid	two 14”
433	14 Dec 2017	12:04:47	1	Geminid	two 14”
434	14 Dec 2017	12:06:16	1	Geminid	two 14”
435	20 Apr 2018	04:07:51	1	Lyrid	14”, 20”
436	11 Dec 2018	23:50:50	2	Geminid	14”, 20”
437	26 Jul 2019	09:28:40	1	Unk	14”, 20”
438	24 Oct 2019	08:33:35	1	Unk	14”, 20”
439	24 Oct 2019	11:02:46	2	Orionid	14”, 20”
440	03 Nov 2019	01:33:28	1	Unk	14”, 20”
441	21 Oct 2020	00:23:42	1	Orionid	14”, 20”
442	22 Oct 2020	02:11:49	1	Orionid	14”, 20”
443	21 Nov 2020	00:18:21	1	Unk	14”, 20”

https://www.nasa.gov/centers/marshall/news/lunar/lunar_impacts.html

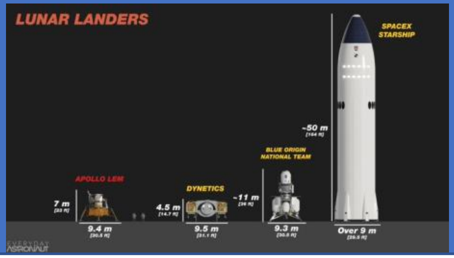

Suggs et al. 2014
Cumulative number colliding with the Earth per year
Energy (kT TNT equivalent)
Satellite data (Brown et al. 2002)
Best fit line (Brown et al. 2002)
Small fireballs (Halliday et al. 1996)
Lunar cratering (Werner et al. 2002)
LINEAR (Stewart 2001)
LINEAR (Harris 2002)
Spacewatch (Rabinowitz et al. 2000)
NEAT (Rabinowitz et al. 2000)
Infrasound/acoustic bolides (ReVelle 2001)
Lunar impacts, η=2e-3 (Ortiz et al. 2006)
Lunar impacts, η=6e-3 (Ortiz et al. 2006)
Lunar impacts, η=see text (this work)

Input
Lunar Surface Properties

Meteoroids & Near-Earth Objects

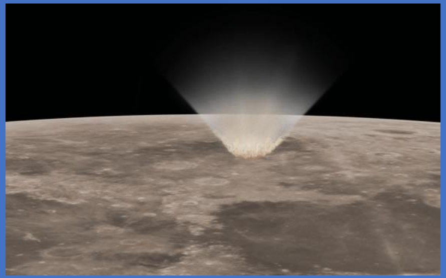


Asset Definition

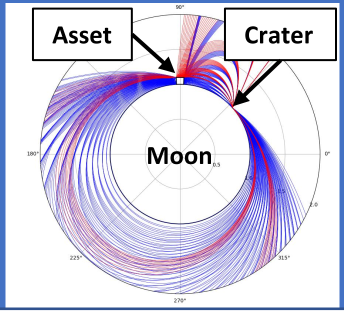


Function
(Monte Carlo-based)

Crater Generation & Ejecta Distribution



Ejecta Trajectory Mapping & Asset Collision Detection



Output
Ejecta Particle Fluxes at Asset

Post-Processing
DSNE Formatting

```
# LMEEM Version bf9c144, Lunar Meteoroid Engineering Model
# Density: 3.1 g/cc
# Velocity: 0.175604    0.463691    1.138011    3.000000    4.200000
# Number Flux [#/m2/yr]
#
 Meteoroid Ejecta Mass >=   10^-6 g
  Speed Bin [m/s]     100 - 300   300 - 1000    1000-2400    2400-3600    3600-4800
  Elevation [deg] Speed Average [km/s]
 PHI1 PHI2 PHIavg      0.185022     0.575222     1.543550     2.819775     4.079963
  -90  -80 -82.93 1.118478e-06 9.689981e-08 3.099713e-09 1.278601e-10 5.887860e-12
  -80  -70 -74.21 2.305703e-05 1.986938e-06 8.008821e-08 2.861581e-09 3.802145e-10
  -70  -60 -64.54 4.469324e-05 4.104602e-06 1.614122e-07 1.596535e-08 1.876424e-09
  -60  -50 -54.69 1.604738e-04 1.294188e-05 6.955087e-07 3.155076e-08 7.814674e-09
  -50  -40 -44.78 3.017431e-04 2.757815e-05 1.378249e-06 7.615529e-08 9.672176e-09
  -40  -30 -34.85 8.897097e-04 7.624669e-05 3.352179e-06 2.246467e-07 4.209925e-08
  -30  -20 -24.90 9.917985e-04 9.487280e-05 4.948891e-06 2.559265e-07 4.183342e-08
  -20  -10 -14.94 5.708549e-03 5.494105e-04 2.741152e-05 1.564420e-06 3.926226e-07
  -10    0  -4.98 2.522558e-01 2.456056e-01 1.992385e-01 1.568557e-02 3.257384e-03
    0   10   4.98 1.574728e+00 2.025544e+00 1.195886e+00 0.000000e+00 0.000000e+00
   10   20  14.94 5.285327e-01 4.022264e-01 1.657976e-01 0.000000e+00 0.000000e+00
   20   30  24.90 2.850326e-01 2.166956e-01 8.651605e-02 0.000000e+00 0.000000e+00
   30   40  34.85 1.637222e-01 1.307294e-01 5.133827e-02 0.000000e+00 0.000000e+00
   40   50  44.78 9.972082e-02 7.999164e-02 3.073328e-02 0.000000e+00 0.000000e+00
   50   60  54.69 5.799623e-02 4.514529e-02 1.793725e-02 0.000000e+00 0.000000e+00
   60   70  64.54 2.998146e-02 2.241829e-02 9.277436e-03 0.000000e+00 0.000000e+00
   70   80  74.21 1.119988e-02 8.026073e-03 3.569999e-03 0.000000e+00 0.000000e+00
   80   90  82.93 1.654110e-03 1.214268e-03 5.283659e-04 0.000000e+00 0.000000e+00

 Meteoroid Ejecta Mass >=   10^-5.5 g
  Speed Bin [m/s]     100 - 300   300 - 1000    1000-2400    2400-3600    3600-4800
  Elevation [deg] Speed Average [km/s]
 PHI1 PHI2 PHIavg      0.185123     0.572095     1.531252     2.810075     4.077148
  -90  -80 -82.93 4.328479e-07 3.560021e-08 1.221797e-09 2.565777e-11 1.246277e-12
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  -70  -60 -64.54 1.829650e-05 1.532752e-06 6.553555e-08 3.445336e-09 8.876119e-10
  -60  -50 -54.69 6.139801e-05 5.161517e-06 2.425358e-07 1.127022e-08 2.316288e-09
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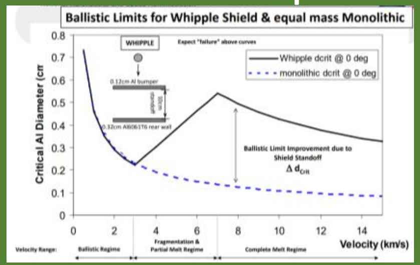
```

Legend:

- MSFC Natural Environments
- JSC HVIT
- SMA

Input
Ballistic Limit Equations



Ejecta Particle Fluxes

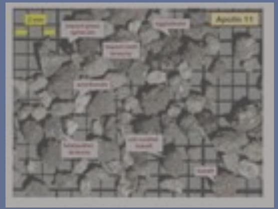
Function
Bumper

Output
Impact Fluxes & Probability-of-no-penetration

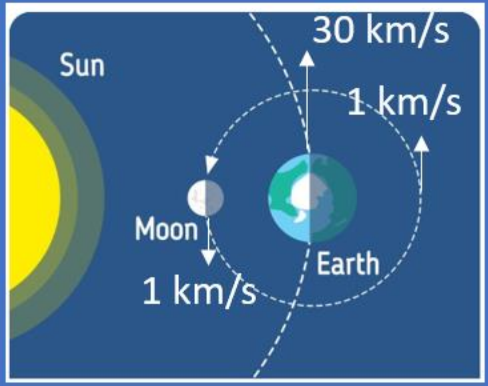
Risk Assessment

Input

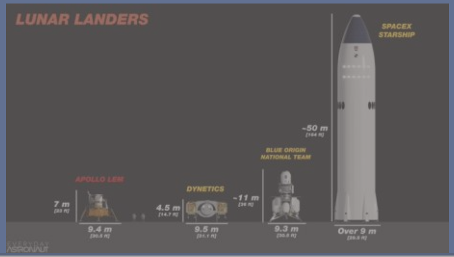
Lunar Surface Properties



Meteoroids & Near-Earth Objects



Asset Definition



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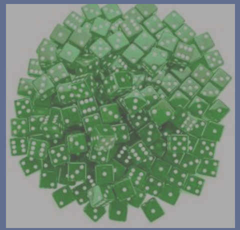

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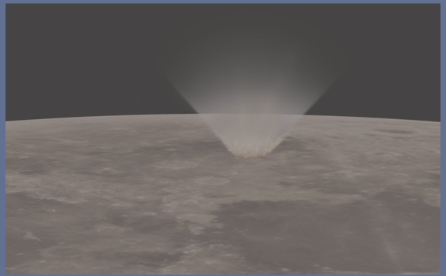

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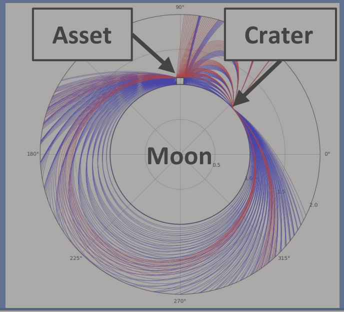
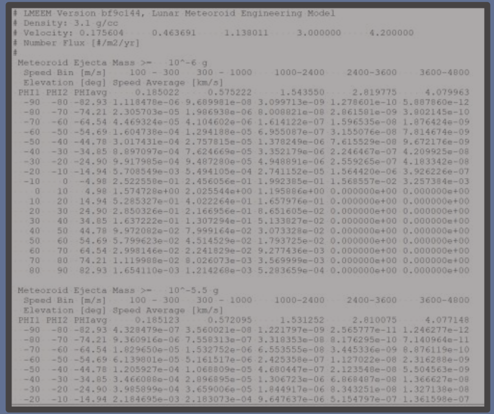


Output

Ejecta Particle Fluxes at Asset

Post-Processing

DSNE Formatting



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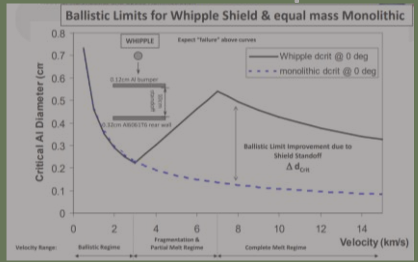
  -30  -20 -24.90 3.985899e-04 3.659006e-05 1.844917e-06 8.343251e-08 1.327138e-08
  -20  -10 -14.94 2.184695e-03 2.183073e-04 9.647637e-06 5.154797e-07 1.361598e-07
```

Legend:

- MSFC Natural Environments
- JSC HVIT
- SMA

Input

Ballistic Limit Equations



Ejecta Particle Fluxes

Function

Bumper

Output

Impact Fluxes & Probability-of-no-penetration

Risk Assessment

Two meteoroid populations, low and high density
Higher density impactors cause more ejecta and at faster speeds

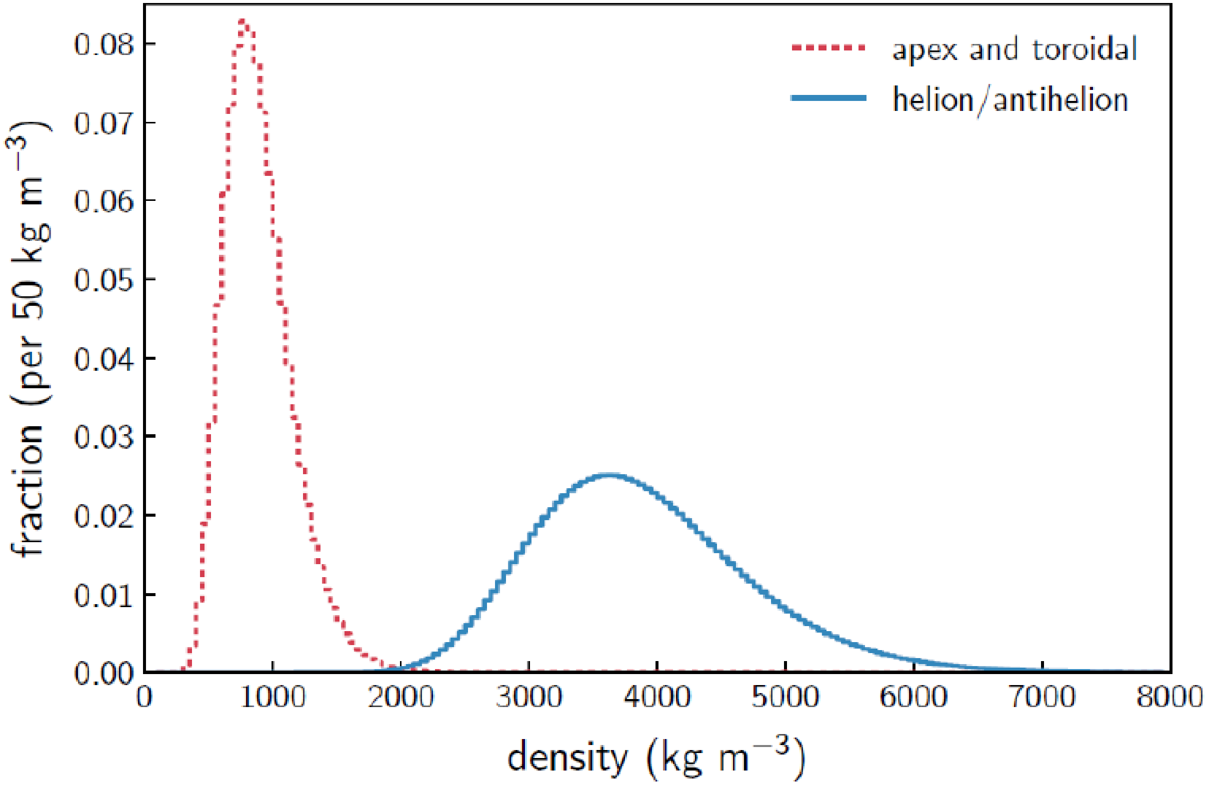


Figure 10: Meteoroid density distribution according to the MEM3 User Guide. The apex and toroidal meteoroid sources constitute the low-density population, while the helion/antihelion source constitutes the high-density population. Each set of densities follows a log-normal distribution [c.f. Figure 11, *Moorhead et al.*, 2019].

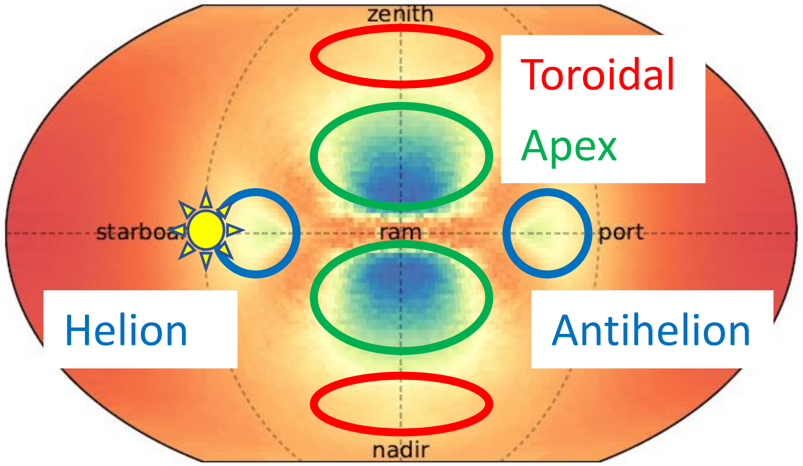
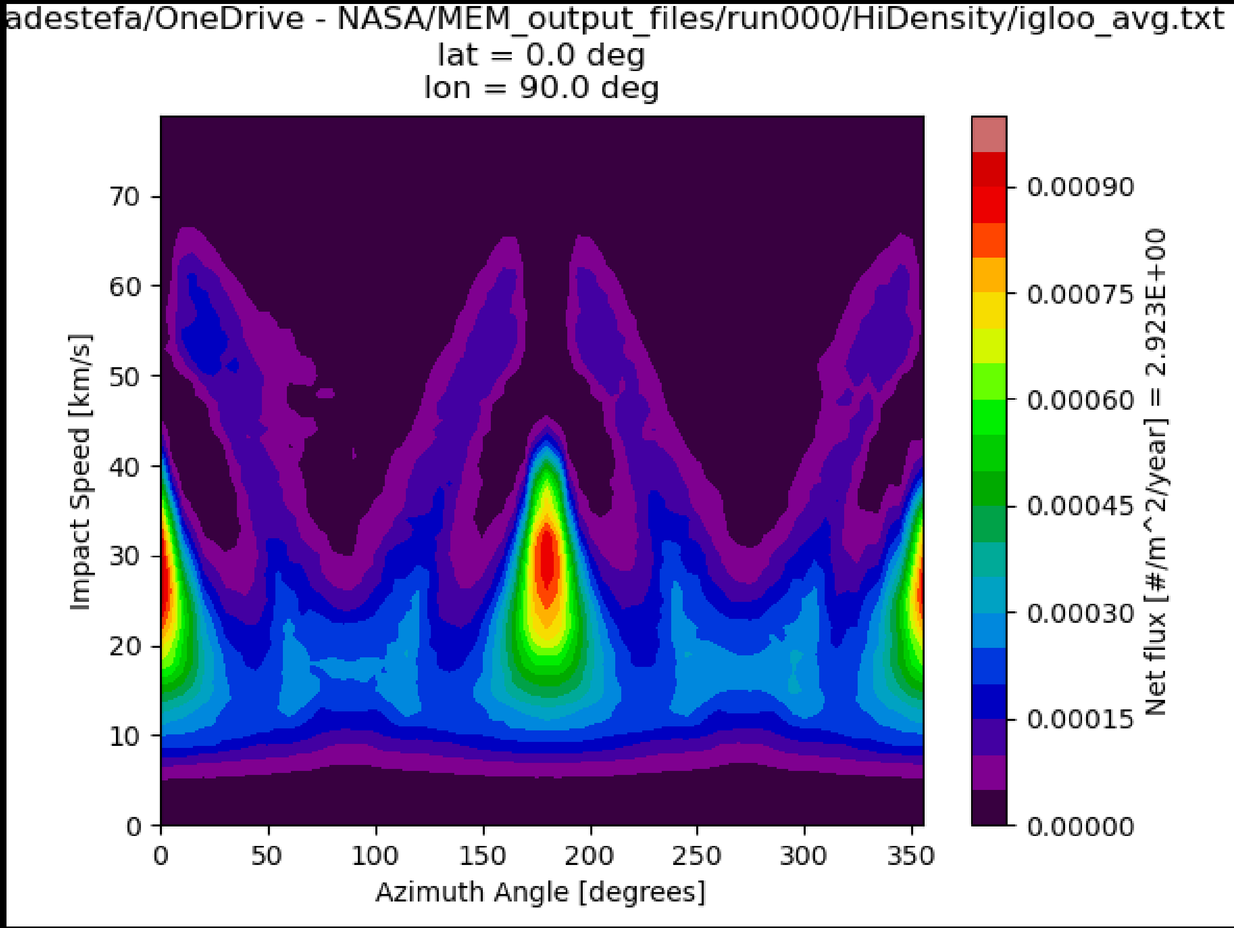


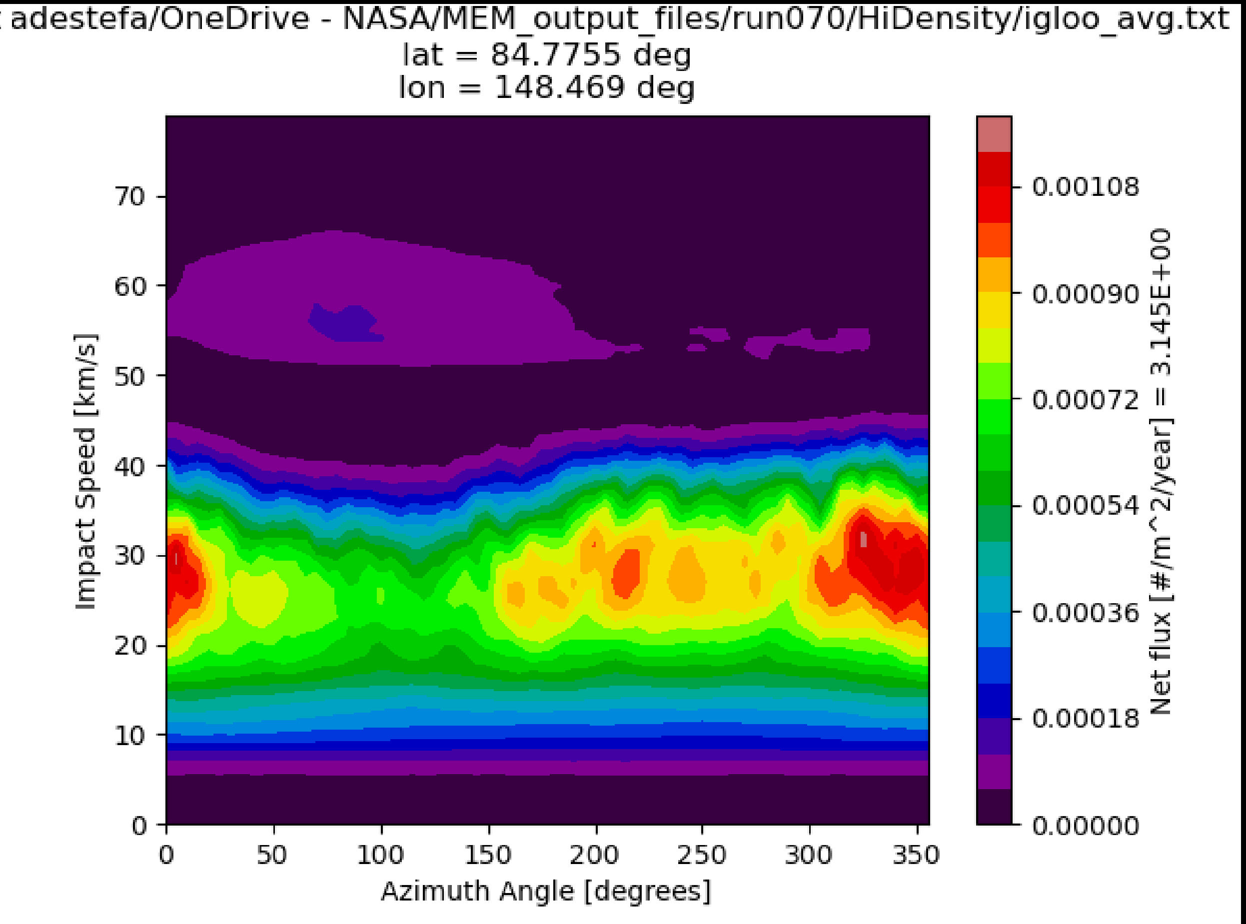
Figure 2.4: Average interplanetary meteoroid speed as calculated by MEM 3 for a spacecraft that is orbiting the Sun at 1 au but is not near the Earth. Color indicates the average speed of all meteoroids originating from a particular direction. The directionality is plotted in a body-fixed frame, in which the center (0° in azimuth and 0° in altitude) corresponds to the spacecraft's direction of motion.

Meteoroid flux at lunar surface is dependent on latitude and longitude location

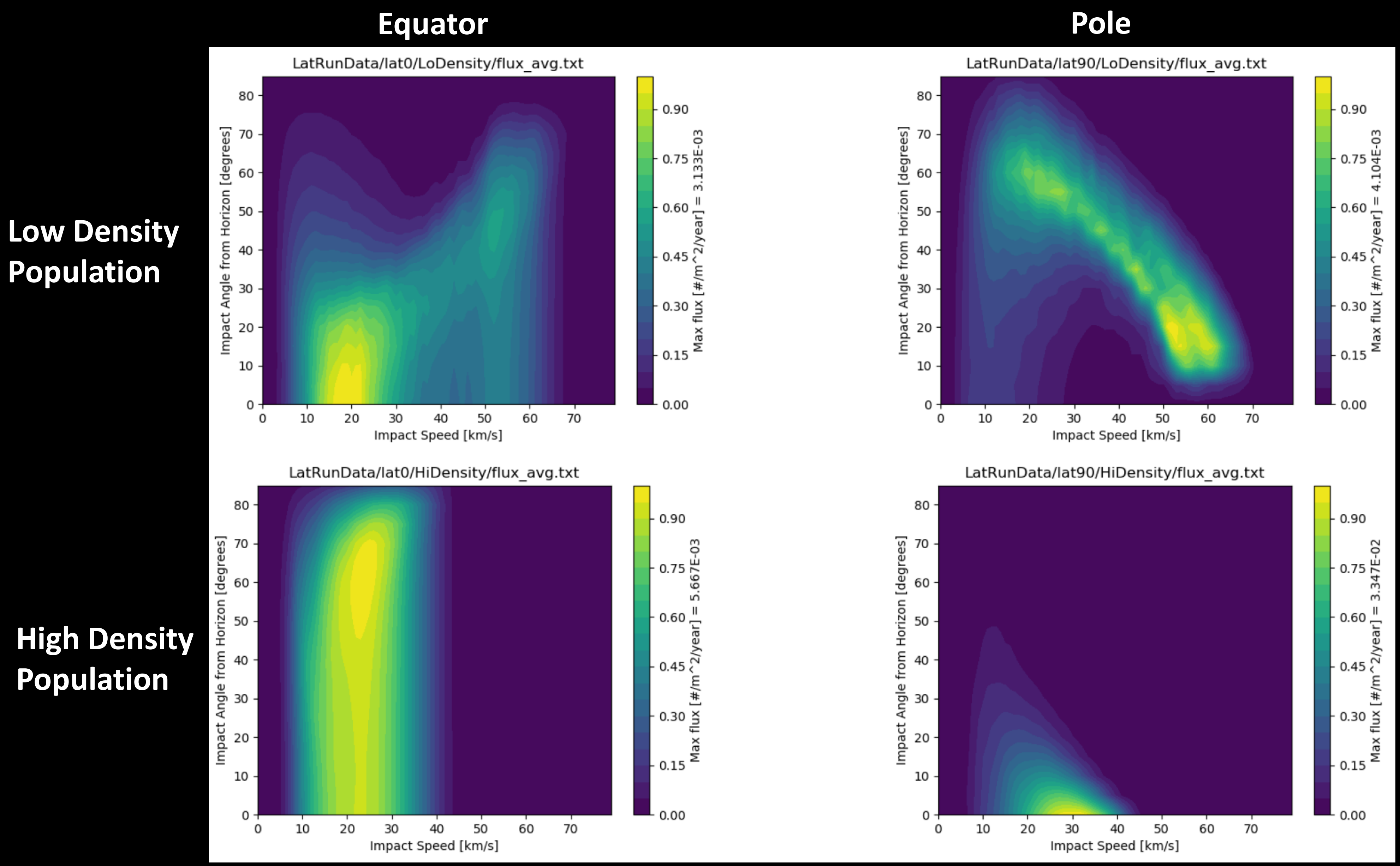
Equator at eastern limb



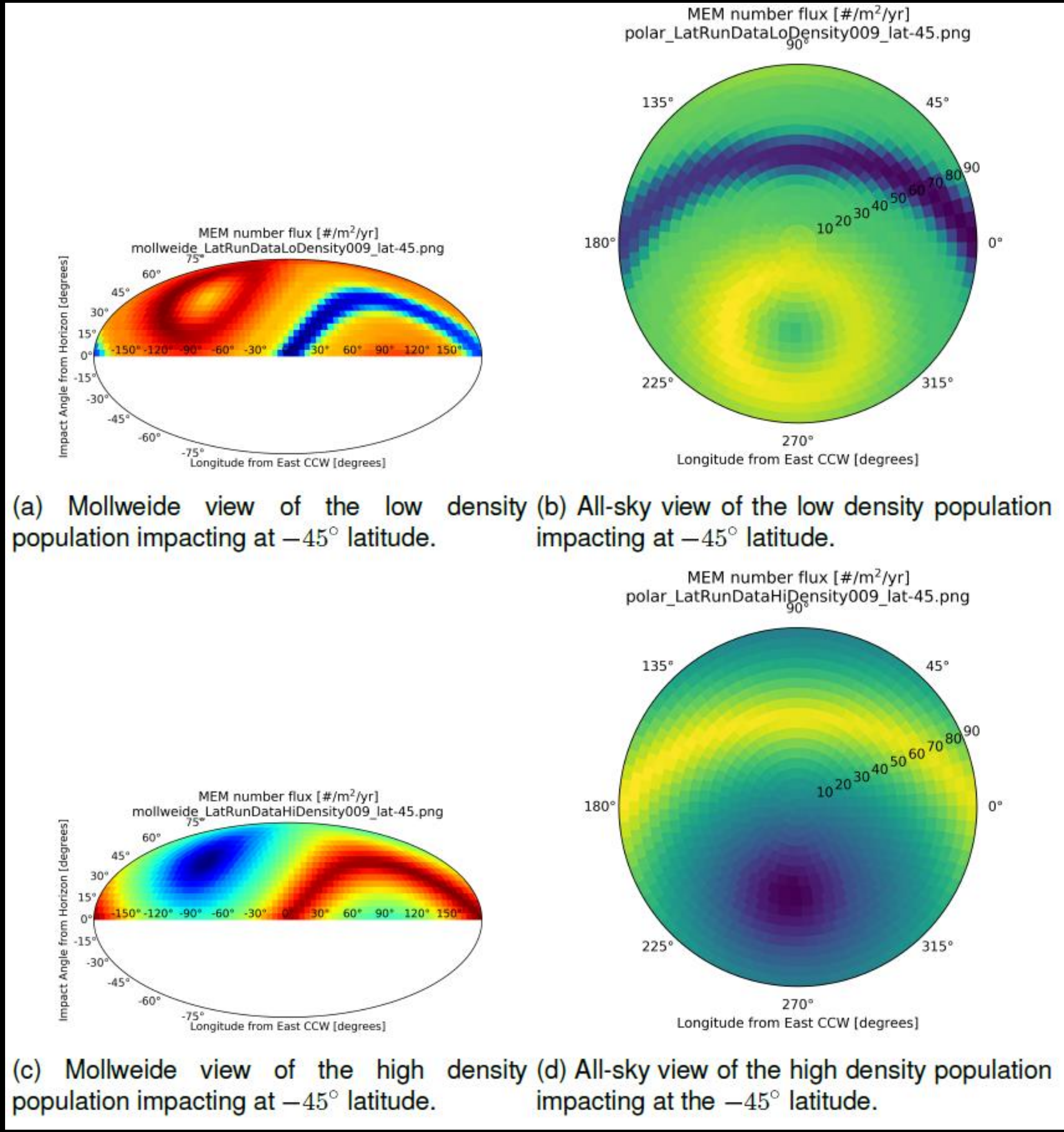
Near north pole at far side



Meteoroid flux at lunar surface is dependent on latitude and longitude location



Meteoroid flux at lunar surface is dependent on latitude and longitude location



(a) Mollweide view of the low density population impacting at -45° latitude.

(b) All-sky view of the low density population impacting at -45° latitude.

(c) Mollweide view of the high density population impacting at -45° latitude.

(d) All-sky view of the high density population impacting at the -45° latitude.

Mass Distribution of Near-Earth Objects (NEOs) used to scale NEO fluxes to different mass ranges

The largest impactor mass 10^8 g is equivalent to one impact on the Moon with a 1/760 chance in 19 years

The mass-limited flux at the lunar surface can be shown to be [see, *Moorhead*, 2020]

$$g_{\leftmoon}(m) = 2.89 \times 10^{-11}\mathrm{m}^{-2}\mathrm{yr}^{-1} \cdot m^{-0.9}, \qquad (3.4)$$

where m is the mass of the impactor in kg.

OSMA/MEO/Lunar-001

27 May 2020

This memo describes a brief analysis we have conducted to estimate the flux of small asteroids and comets (those between about 0.1 and 1000 meters in diameter) onto the lunar surface. We have based this analysis on the Brown et al. (2002) large impactor flux at the Earth and the impact velocity distribution of bolides reported by the Center for Near Earth Object Studies (CNEOS).[1] Both of these data sources are kinetic-energy-limited and correspond to the impact flux at the same location: the Earth's atmosphere.

Speed Distribution of NEOs based on observations

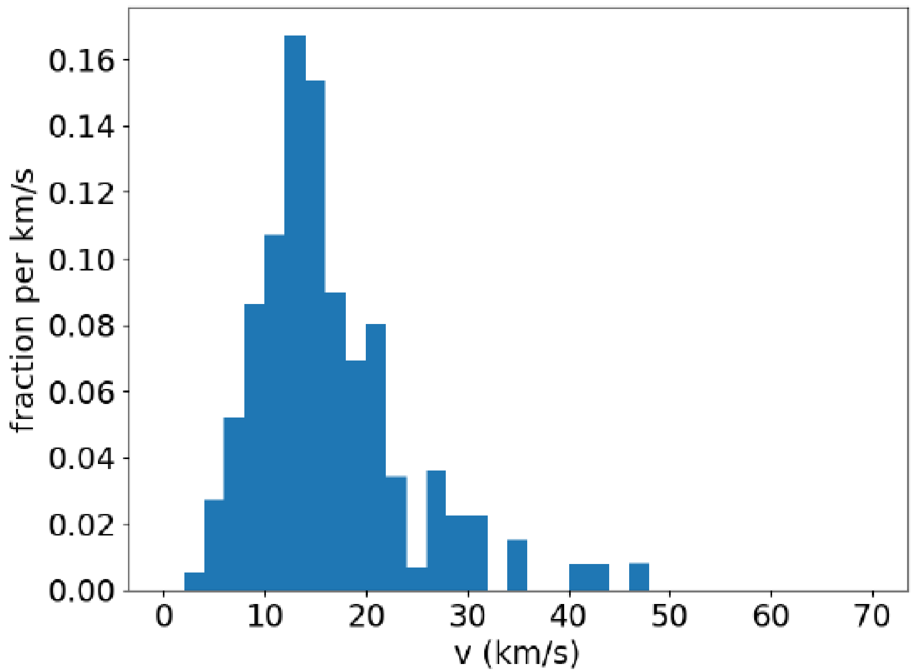


Figure 14: Mass-limited speed distribution at the lunar surface.

The speed distribution of NEO's is shown in Figure 14. The values (fraction of flux per bin) in each bin are midpoint values, where the bins have a size of 2 km s^{-1}. Note also that because the flux is a power law, this speed distribution is independent of limiting mass.

Sporadic meteoroids dominate over long-term
Meteoroid showers can dominate over short-term

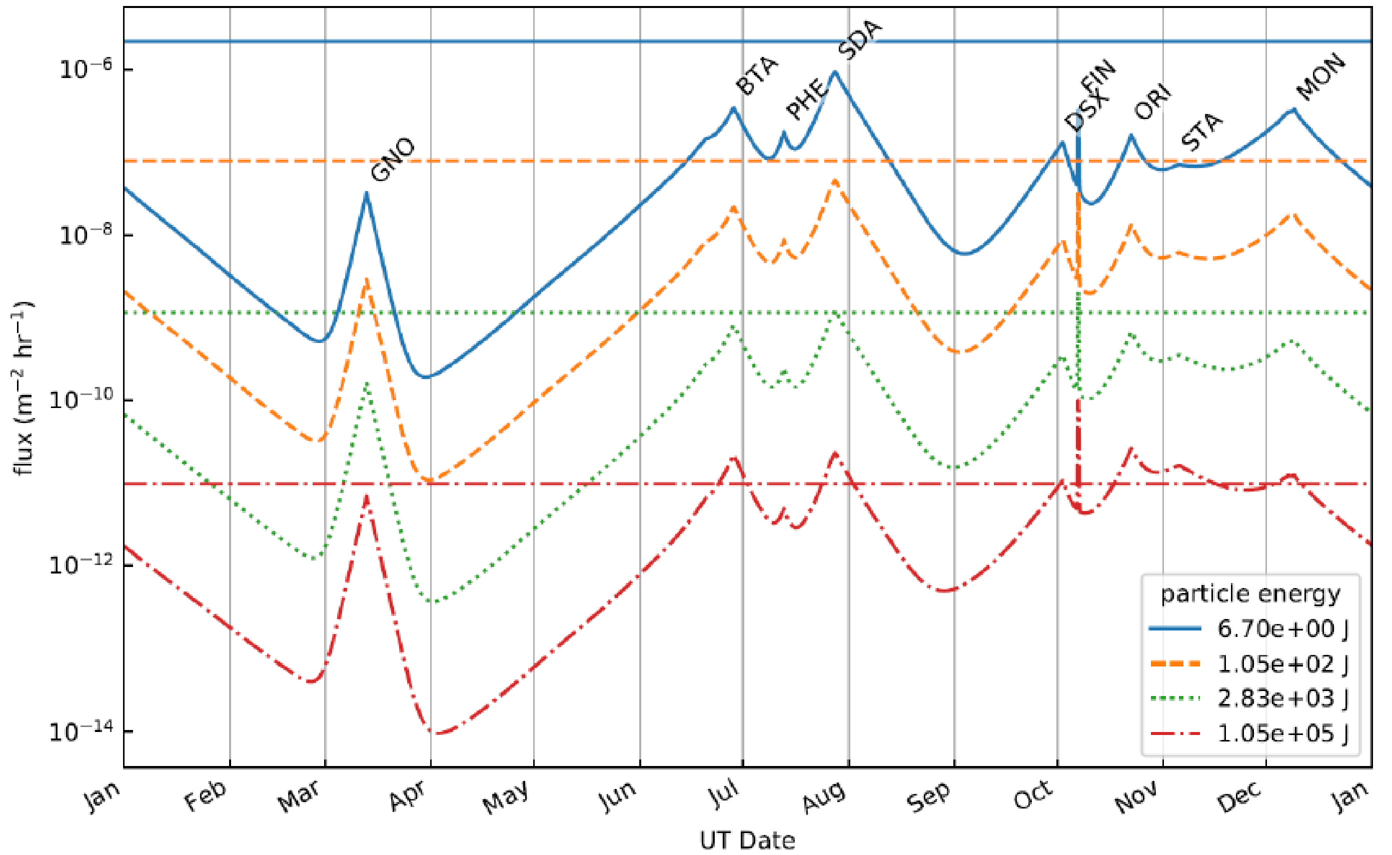
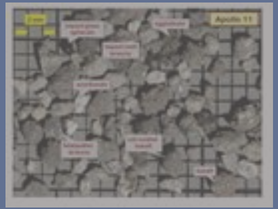


Figure 15: Meteor shower flux (variable lines) and sporadic meteoroid flux (horizontal lines) over the course of 2021. Fluxes are quoted to four limiting particle kinetic energies; these kinetic energies correspond to particles with diameters of 0.04 cm, 0.1 cm, 0.3 cm, and 1 cm, assuming a density of 1 g cm^{-3} and a speed of 20 km s^{-1}, [see Figure 1, *Moorhead et al.*, 2020].

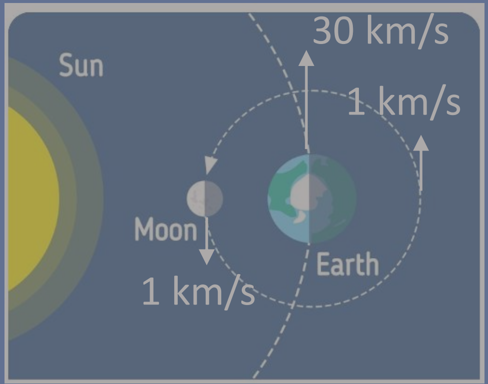
Small particles
|
|
Large particles

Input

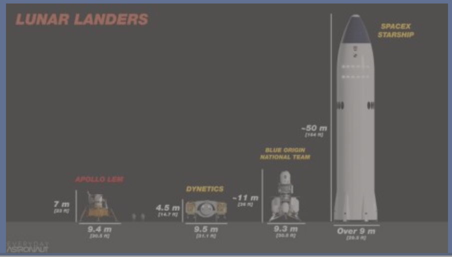
Lunar Surface Properties



Meteoroids & Near-Earth Objects

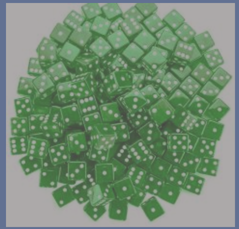


Asset Definition

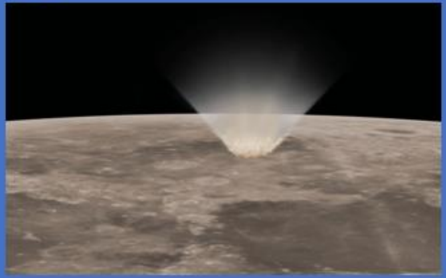


Function

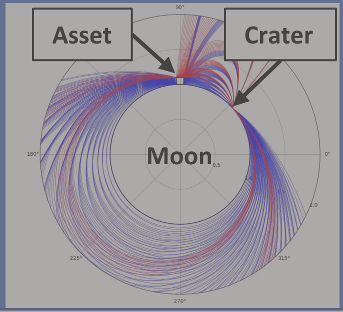
(Monte Carlo-based)



Crater Generation & Ejecta Distribution



Ejecta Trajectory Mapping & Asset Collision Detection

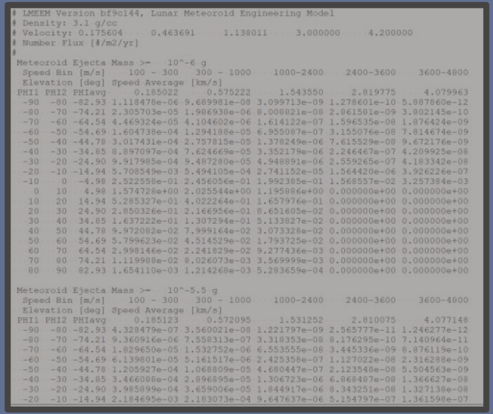


Output

Ejecta Particle Fluxes at Asset

Post-Processing

DSNE Formatting

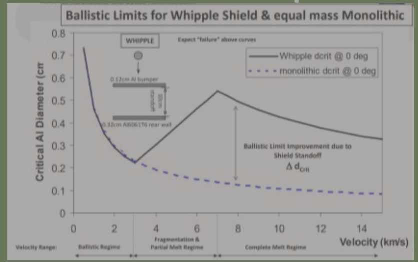


Legend:

- MSFC Natural Environments
- JSC HVIT
- SMA

Input

Ballistic Limit Equations



Ejecta Particle Fluxes

Function

Bumper

Output

Impact Fluxes & Probability-of-no-penetration

Risk Assessment

Theory: Crater Formation and Ejecta Transport

1. Contact & Compression, 2. Excavation, 3. Modification

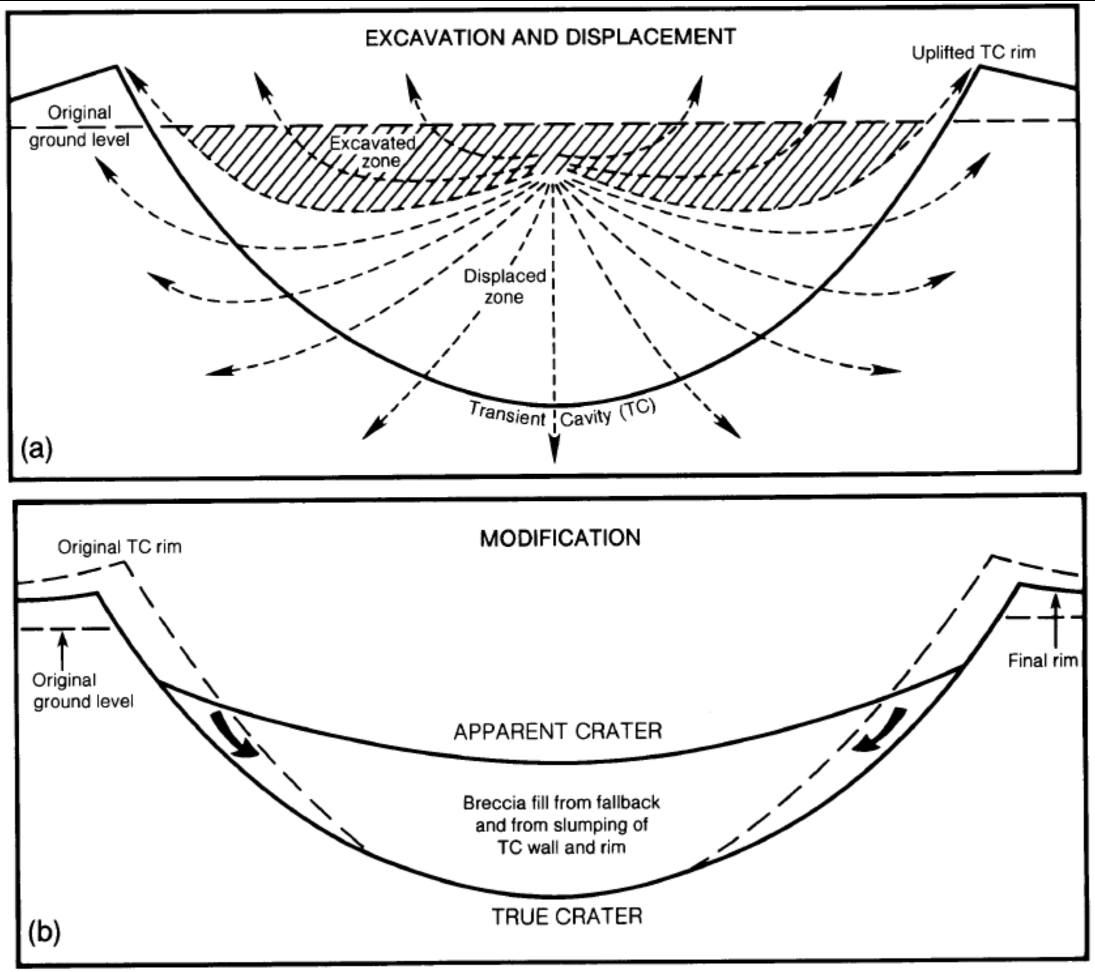


Fig. 4.3. Model of the formation of a simple crater. **(a)** Formation of the transient cavity by a combination of excavation and displacement induced by the cratering flow field, which in turn is established by the shock and rarefaction waves. **(b)** Inward collapse of the transient cavity walls and rim to form an interior breccia lens and the final apparent crater [see text (section 4.1.2) for further details].

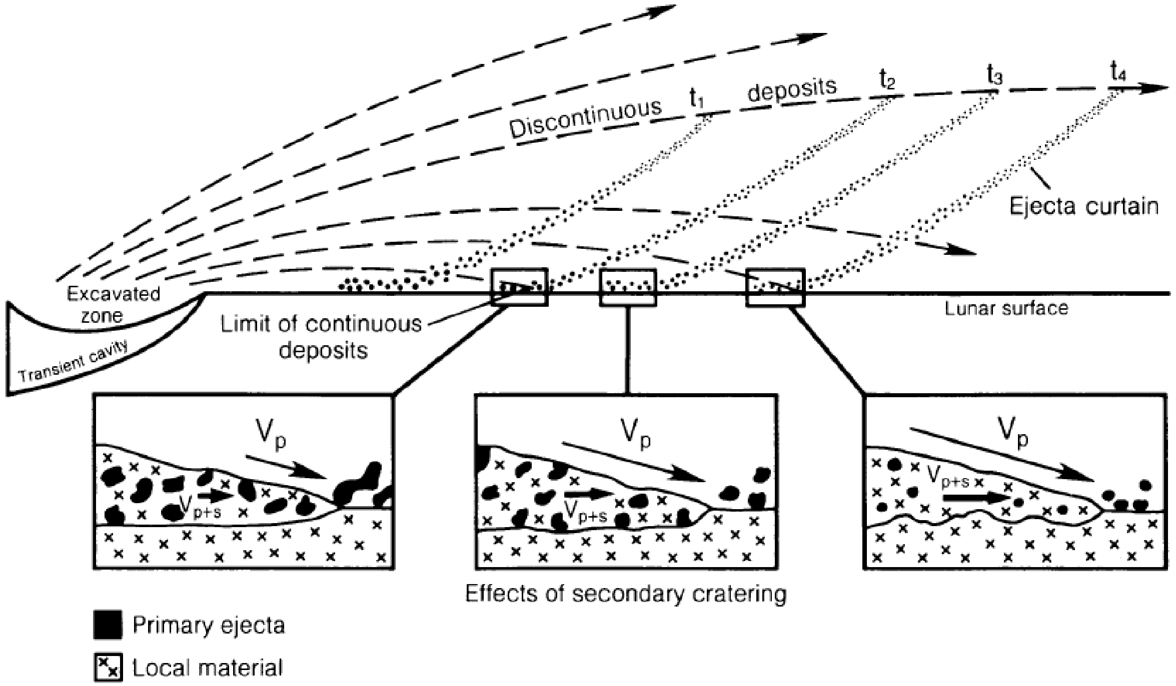
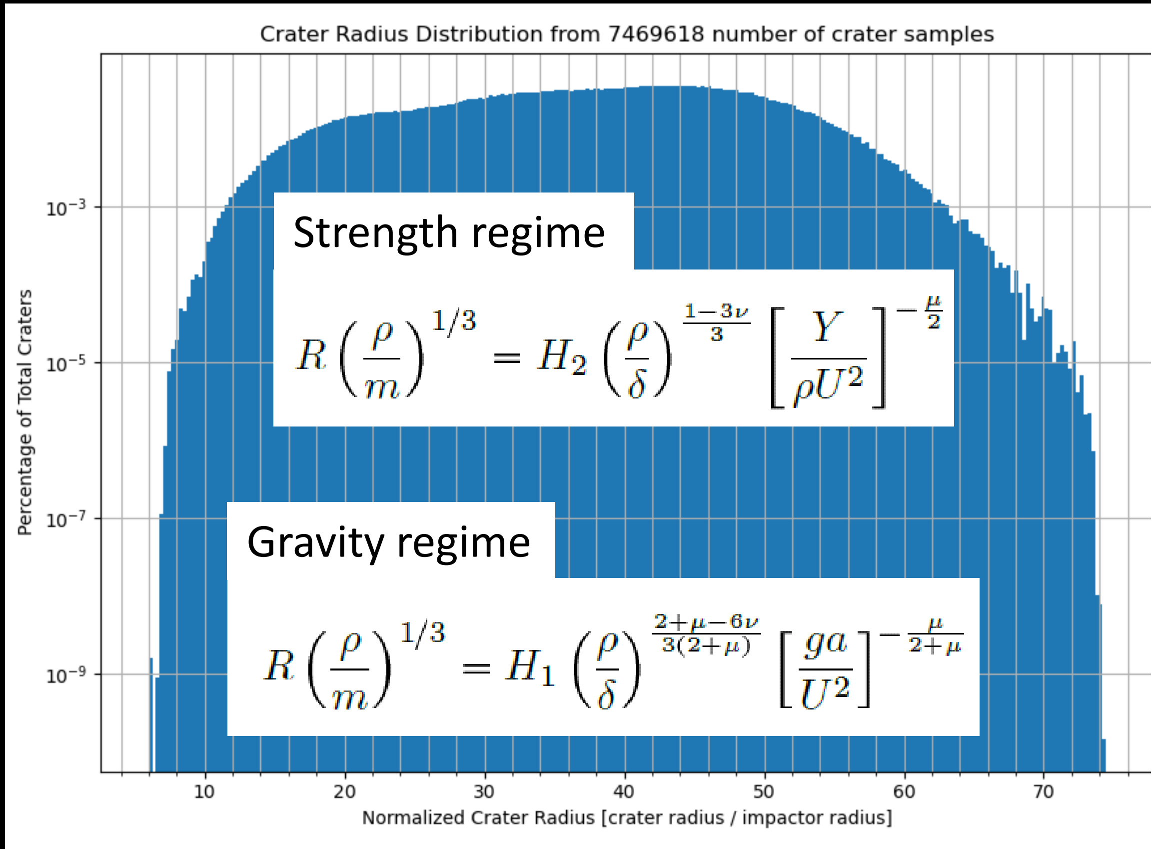


Fig. 4.6. Ejection processes and interaction of ejecta with the lunar surface. Ejecta leave the crater cavity along discrete, relatively shallow ballistic trajectories. At any given time (t) these trajectories define an outrunning ejecta curtain. Coarse-grained, low-velocity ejecta travel along low-angle trajectories and are concentrated at the base of the curtain. They impact close to the crater and excavate modest amounts of local substrate material (see insert; V_p = impact velocity of ejecta; V_{p+s} = radial flow velocity of the resultant debris surge combining "primary" and "secondary" ejecta). Finer-grained fragments reside higher in the ejecta curtain, having been ejected at increasingly higher V_p and steeper angles. As the curtain sweeps radially across the surrounding target, higher-velocity ejecta impact the surface causing local materials to be incorporated in the debris surge, resulting in increasingly higher flow velocities of the debris surge (after *Oberbeck*, 1975).

Lunar Sourcebook, Heiken et al. 1991

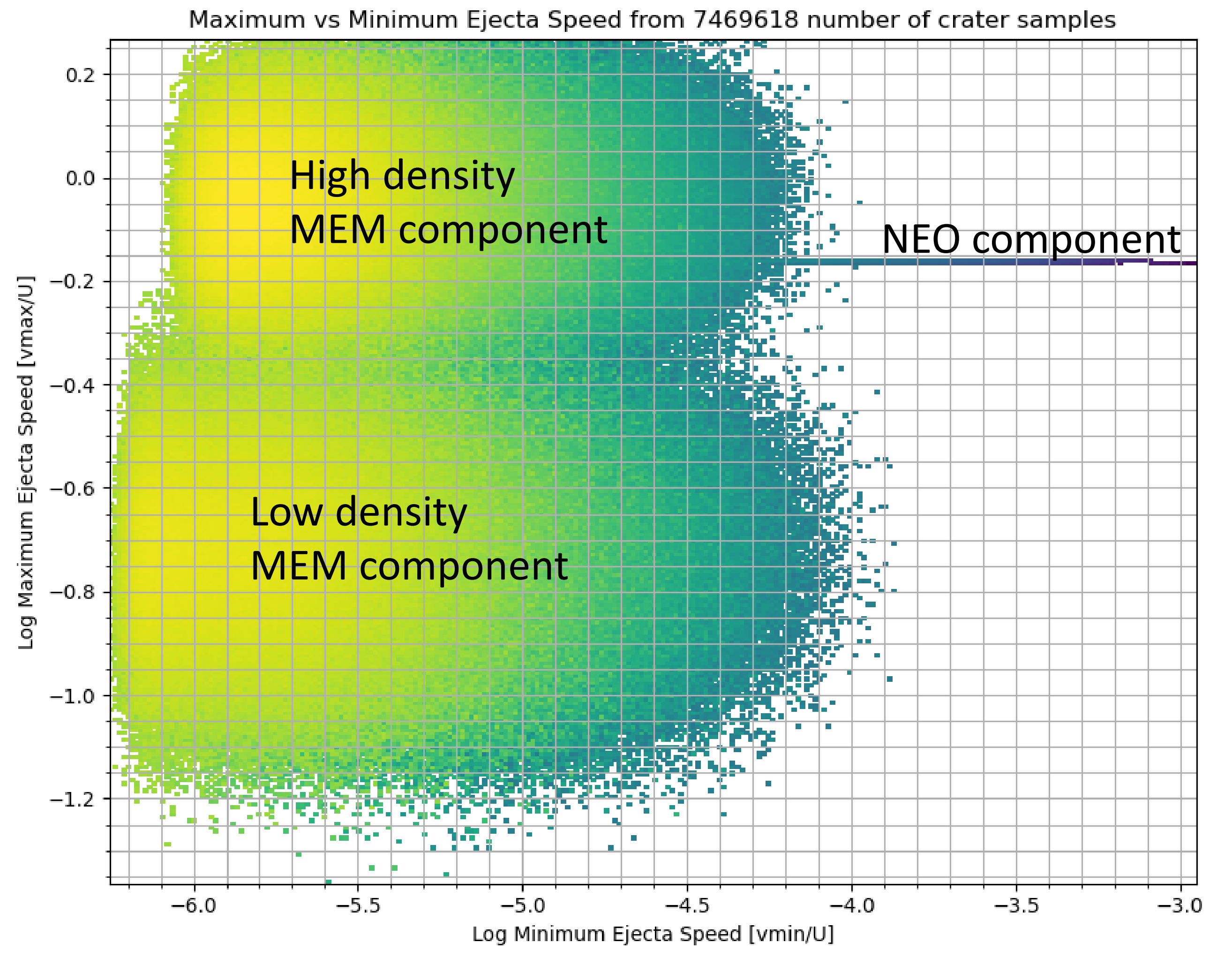
Crater Radius & Bounding Ejecta Speeds

Crater radius R depends on impactor mass m, bulk density δ, & speed U + lunar gravity g + regolith bulk density ρ, strength Y, & material type (H_1, H_2, μ, ν)

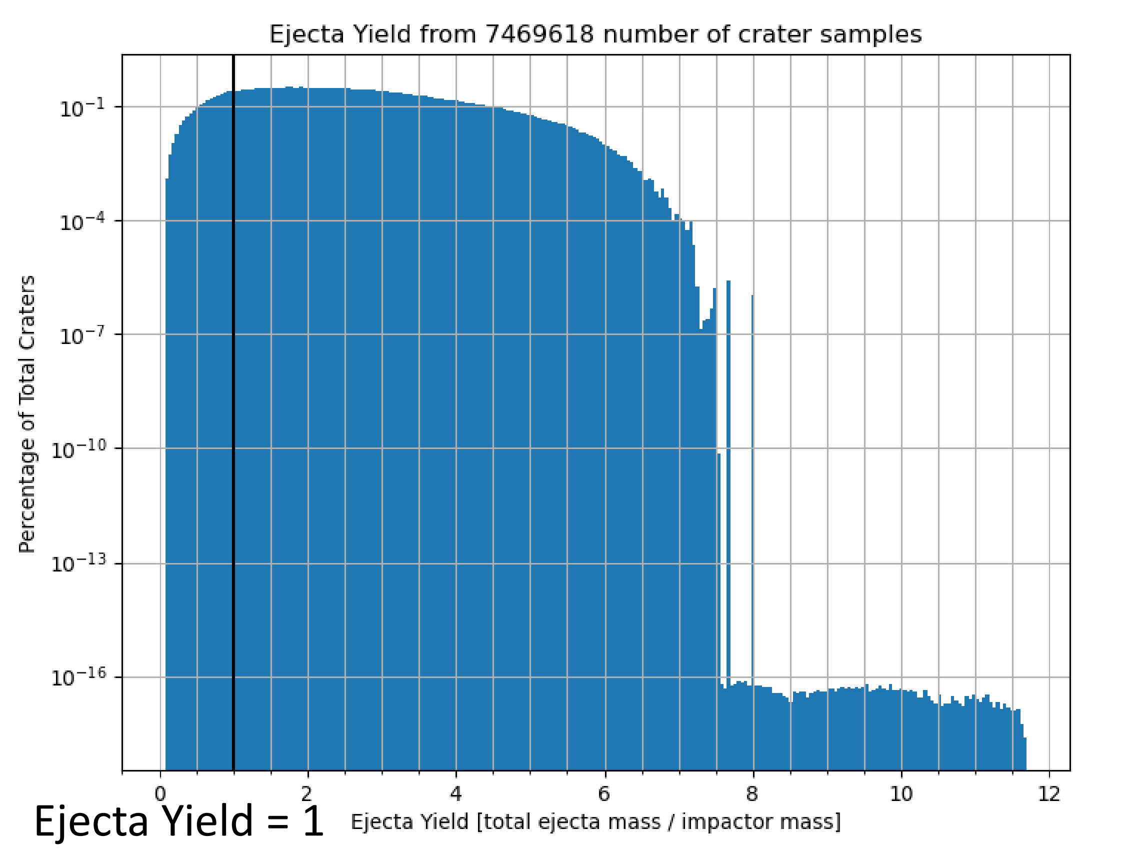


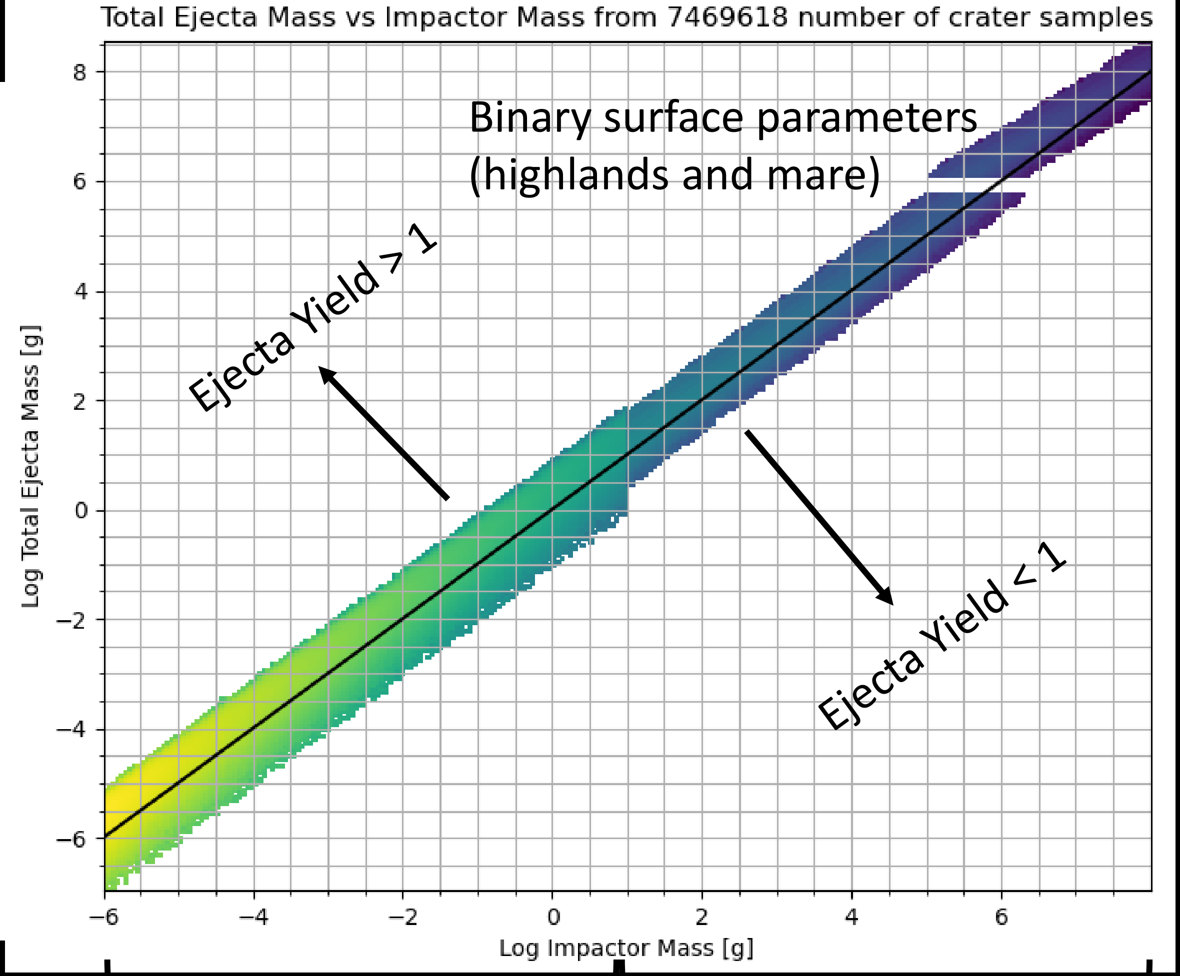
$$R\left(\frac{\rho}{m}\right)^{1/3} = H_2\left(\frac{\rho}{\delta}\right)^{\frac{1-3\nu}{3}}\left[\frac{Y}{\rho U^2}\right]^{-\frac{\mu}{2}}$$

$$R\left(\frac{\rho}{m}\right)^{1/3} = H_1\left(\frac{\rho}{\delta}\right)^{\frac{2+\mu-6\nu}{3(2+\mu)}}\left[\frac{ga}{U^2}\right]^{-\frac{\mu}{2+\mu}}$$



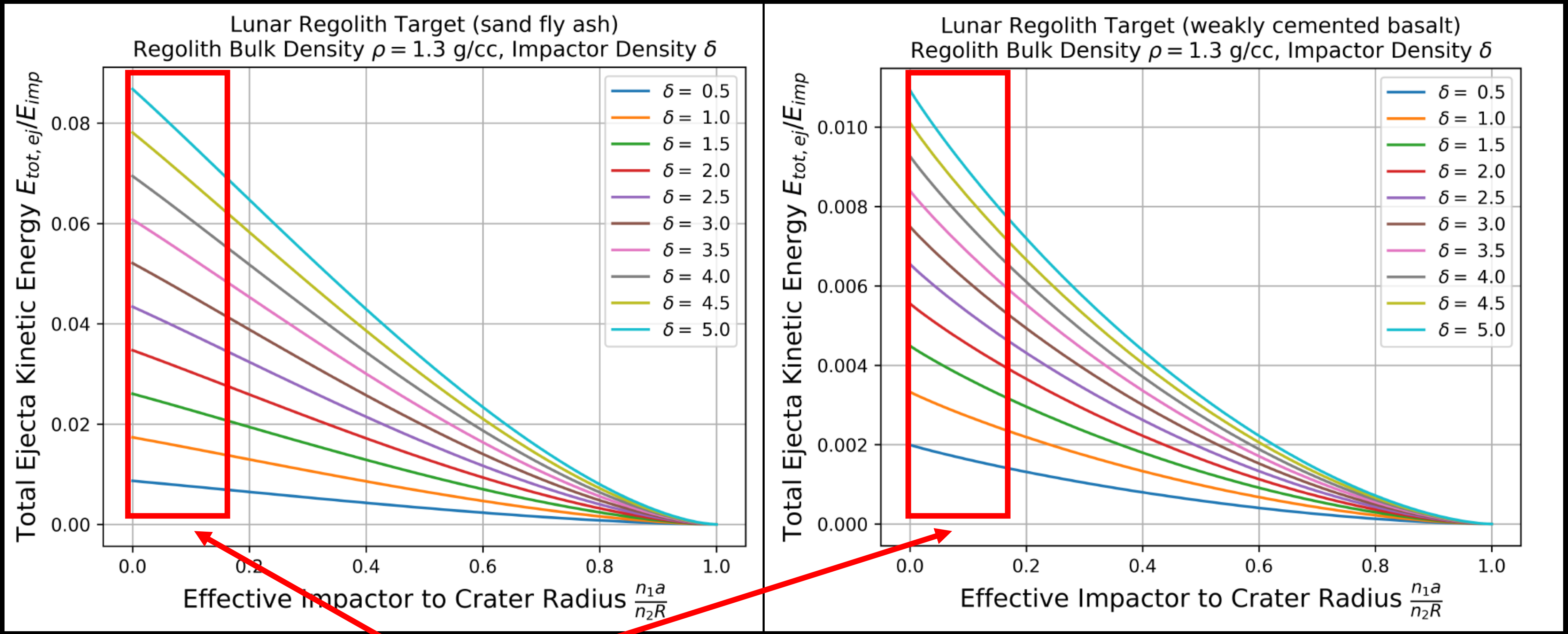
Cratering Efficiency
Ejecta Yield = Ejected Mass / Impactor Mass





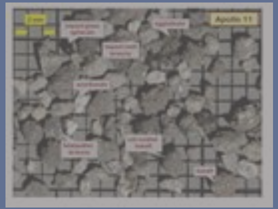
Cratering Efficiency: Total Kinetic Energy of Ejecta

Roughly 91-99.9% of the impactor kinetic energy is lost to inelastic cratering processes

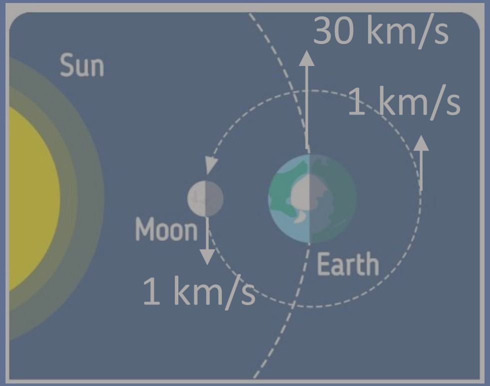


Where most of the craters are made

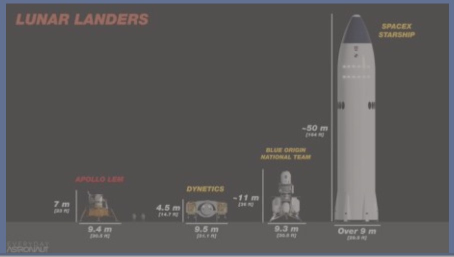
Input
Lunar Surface Properties



Meteoroids & Near-Earth Objects



Asset Definition



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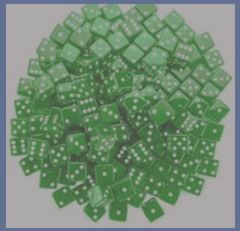
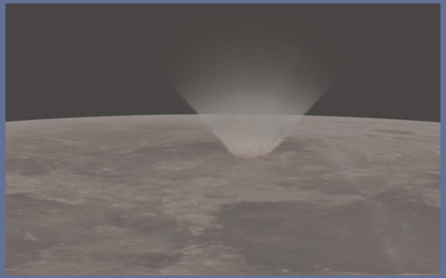
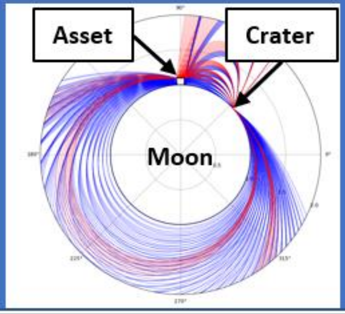


Crater Generation & Ejecta Distribution

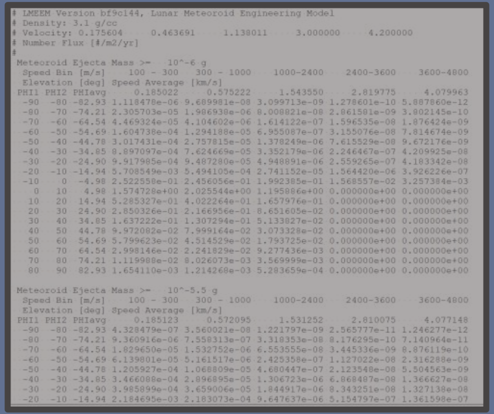


Ejecta Trajectory Mapping & Asset Collision Detection



Output
Ejecta Particle Fluxes at Asset

Post-Processing
DSNE Formatting



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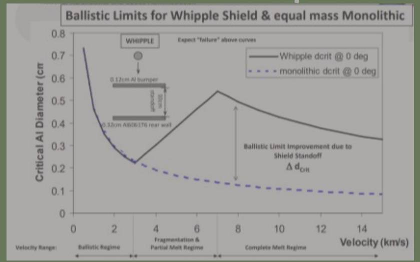
Input
Ballistic Limit Equations



Ejecta Particle Fluxes

Function
Bumper

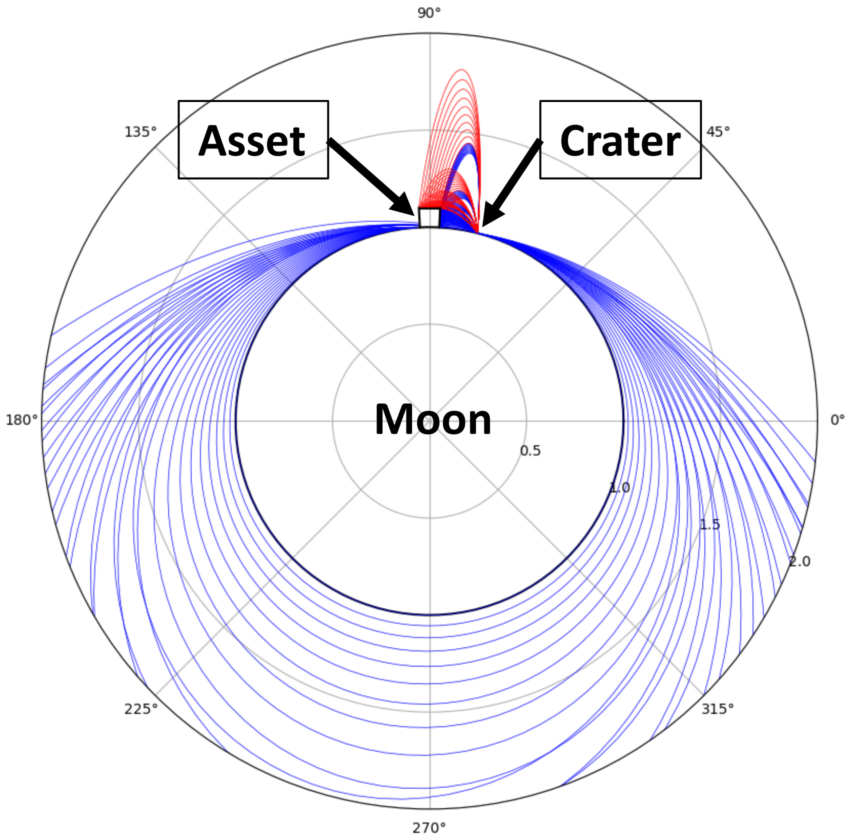
Output
Impact Fluxes & Probability-of-no-penetration

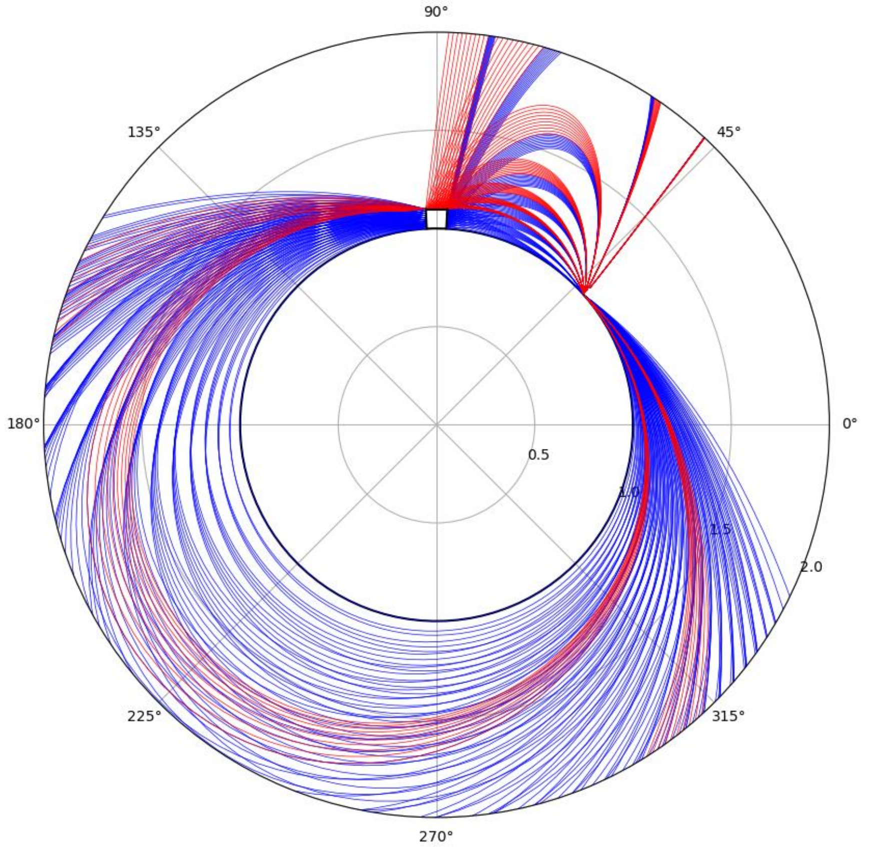
Risk Assessment

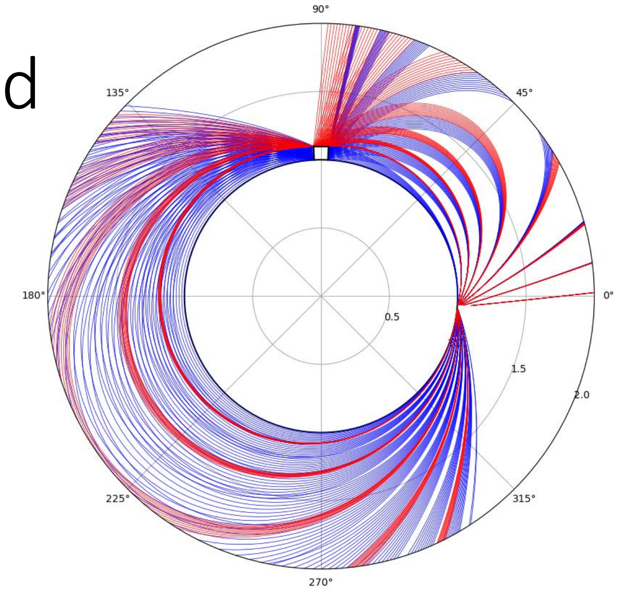
Example Ejecta Trajectories

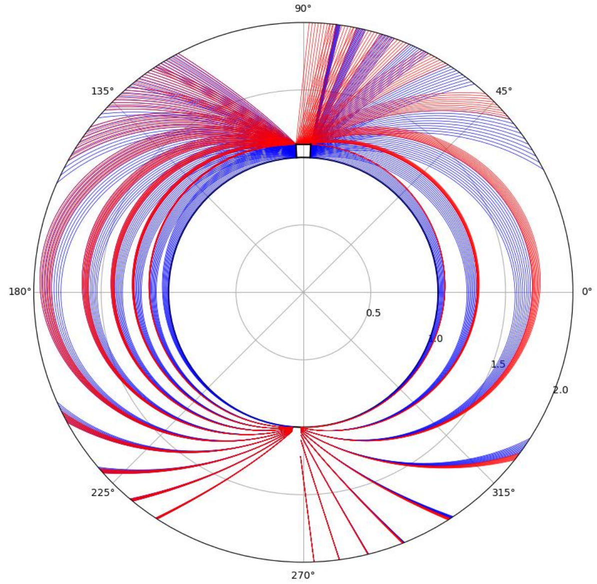
For each crater distance, only ejecta with certain speeds and angles can hit the asset

Red = top hit
Blue = side hit



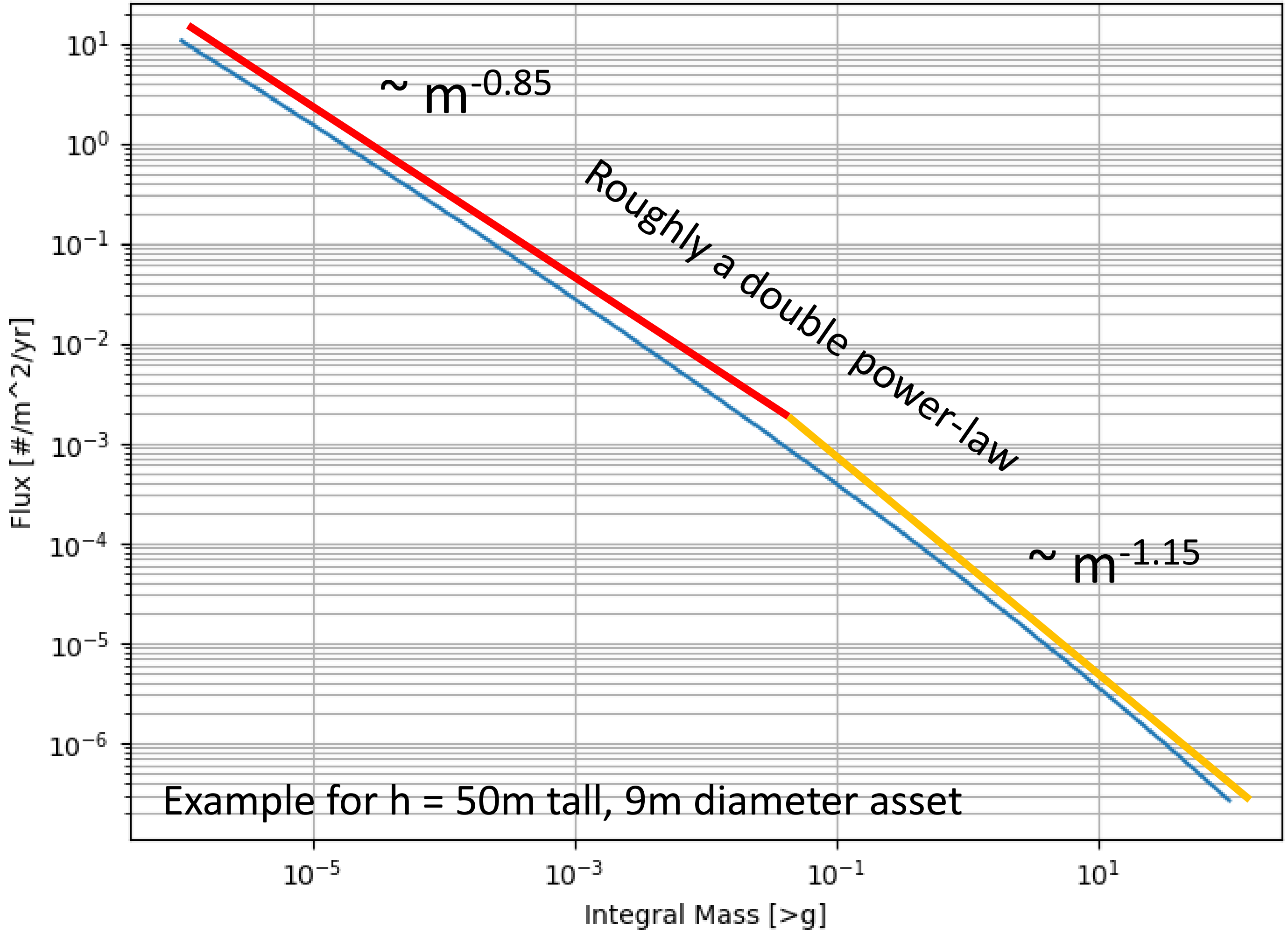


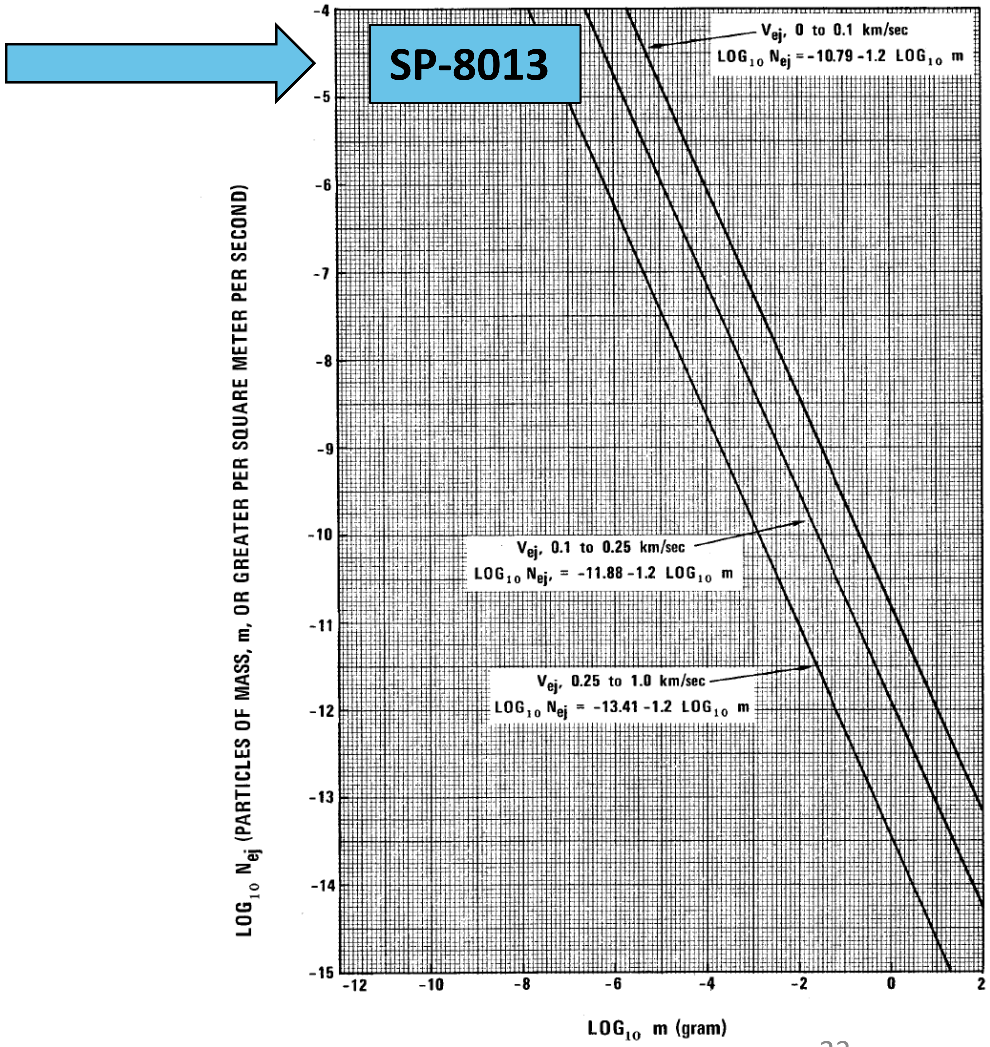




Results: Mass Distribution
Agrees with observations for larger particles

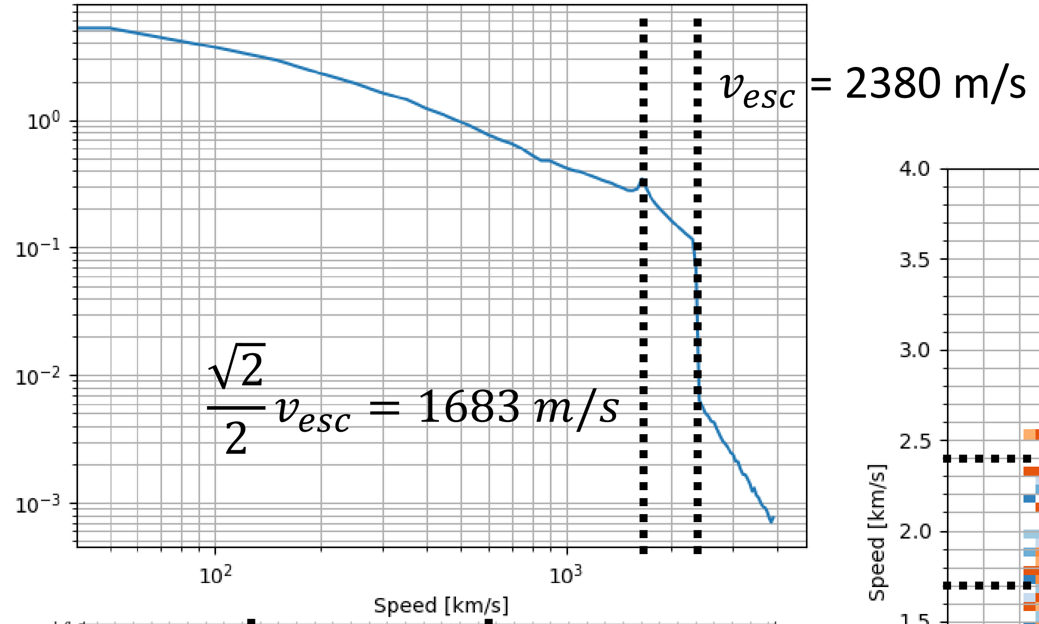
- Compare with SP-8013: all mass slopes are -1.2
- Carrier 2003 (observations) fits to a slope of about -1.18

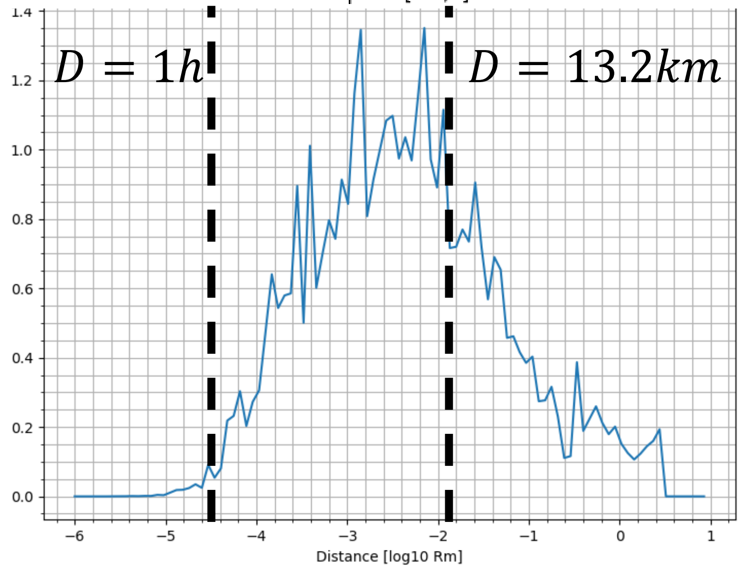


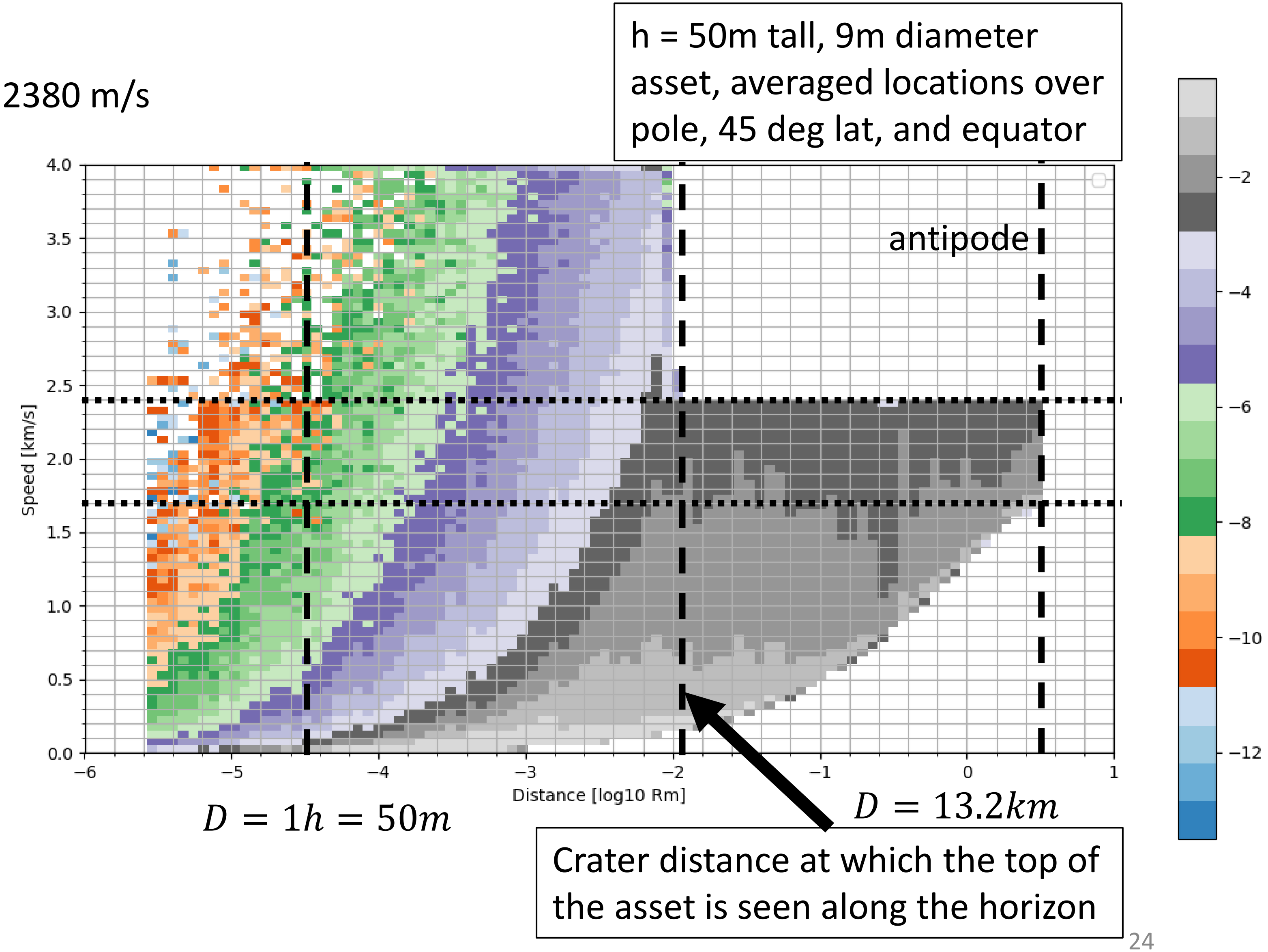


How far did the ejecta travel and at which speeds?

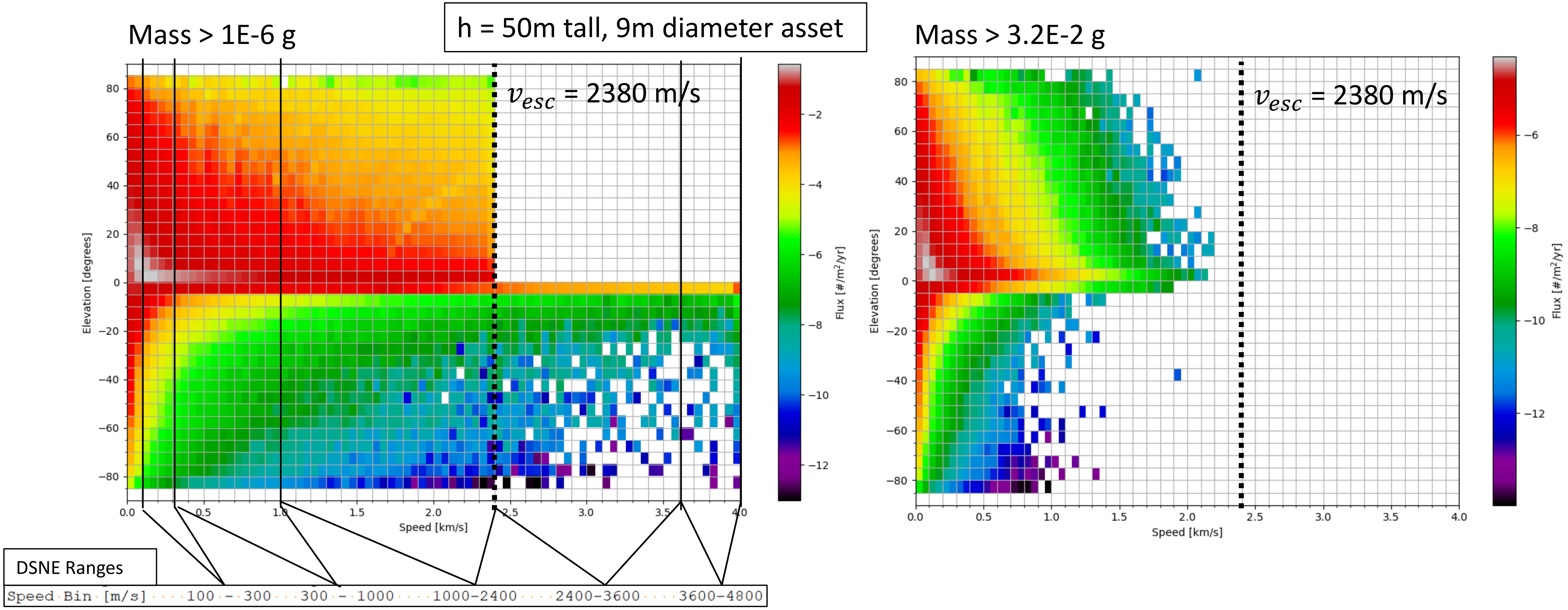
Slow < 1.7 km/s: 100 m to 50 km away, **Medium** 1.7 – 2.4 km/s: > 10 km away,
Fast > 2.4 km/s: 4.5 – 13 km away





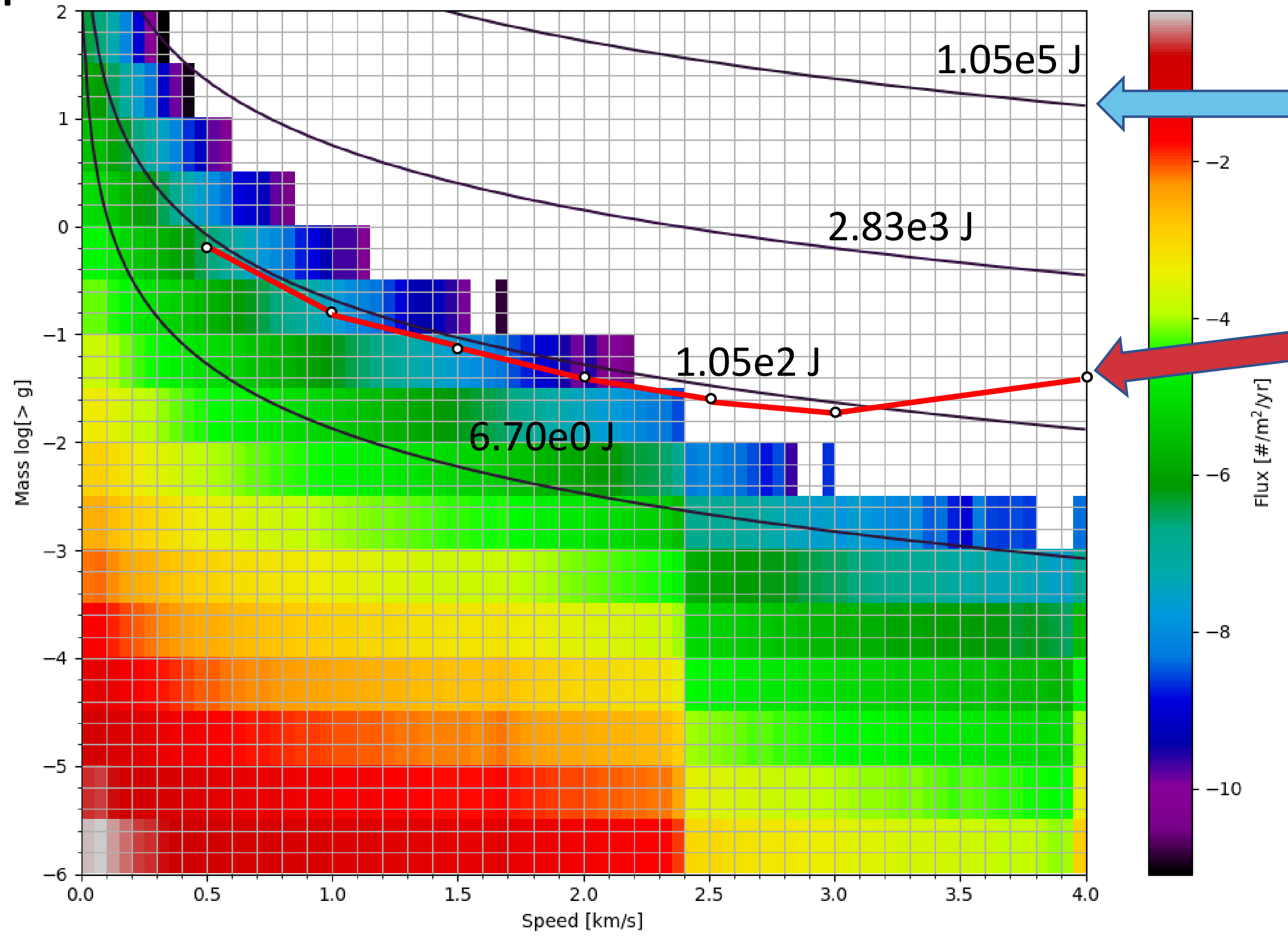


Elevation vs Speed Distribution, most ejecta flux occurs at low horizon angles and slow speeds



Ejecta Energy compared to Ballistic Limit Equations
The more flux above the BLE curve, the more penetrations

h = 50m tall, 9m diameter asset



Iso-energy contours

(KE = $\frac{1}{2}mv^2$)

Example ballistic limit equation

(failure is expected above BLE curve)