Lunar Meteoroid Impact Observations and the Flux of Kilogram-sized Meteoroids

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Why is lunar impact monitoring useful?

- Started the project to develop a better meteoroid ejecta model for use by the Constellation Program in shielding design and risk assessments
  - Existing spec is for Apollo – circa 1969, probably overly conservative
- We realized that the flux we were measuring is important to understanding the meteoroid environment in this size range
  - The collecting area is much larger than that available for all-sky cameras
  - Allows better determination of meteor shower population indices
- Future application to lunar seismic stations and dust experiments

Observation and Analysis Process

Night side only

- Earthshine illuminates lunar features
- FOV is approximately 20 arcmin – covering 3.8 million square km ~ 12% of the lunar surface
- 12th magnitude background stars are easily visible at video rates

Crescent to quarter phases – 0.1 to 0.5 solar illumination

- 5 nights waxing (evening, leading edge)
- 5 nights waning (morning, trailing edge)

Have taken data on about half of the possible nights, > 212 hours of photometric quality data in first 3 years.

Analysis procedure

- Use LunarScan to detect flashes
- Use LunaCon to perform photometry, measure collecting area

Automated Lunar and Meteor Observatory

- Telescopes
  - 2 Meade RCX400 14” (0.35m)
  - RCOS 20 inch (0.5m)
- Detectors
  - Watec 902H2
  - Astrovid Stellacam EX
  - Goodrich SU640KTSX near-infrared

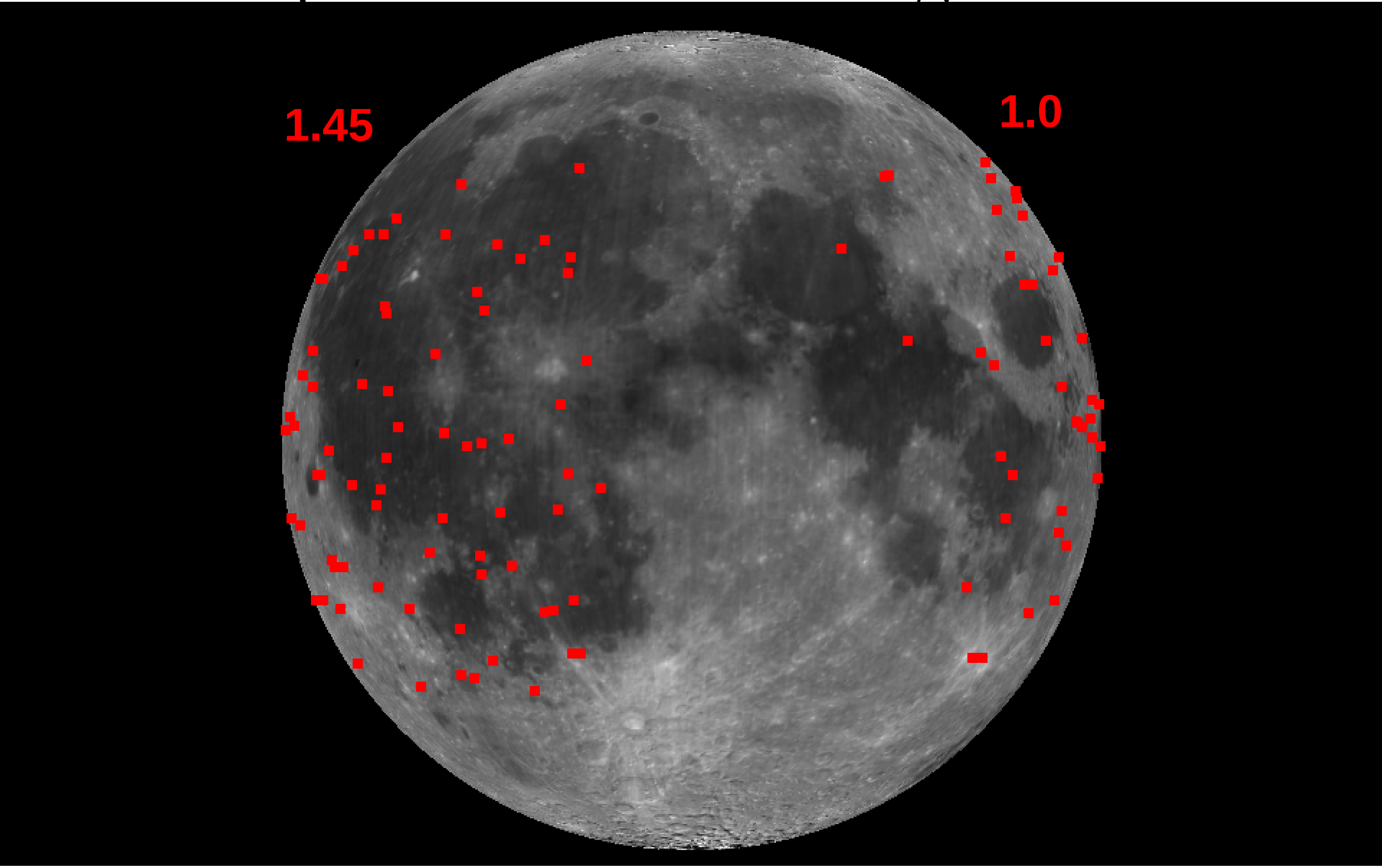
Huntsville, Alabama

Chickamauga, Georgia

Probable Leonid Impact
November 17, 2006

Video is slowed by a factor of 7

108 Impacts used in this study, 212 hours



Flux asymmetry – 1.55×10^{-7} evening (left), 1.07×10^{-7} morning (#/km^2/hr)

Results

- Flux is 1.34×10^{-7} km^{-2} hr^{-1}

Approximate detectable mass limit is 100g

Ratio of leading to trailing edge is 1.45:1

212.4 total observing hours (photometric quality)

115 total impacts in this period, 108 to our completeness limit

3.8×10^{6} km^{2} average collecting area

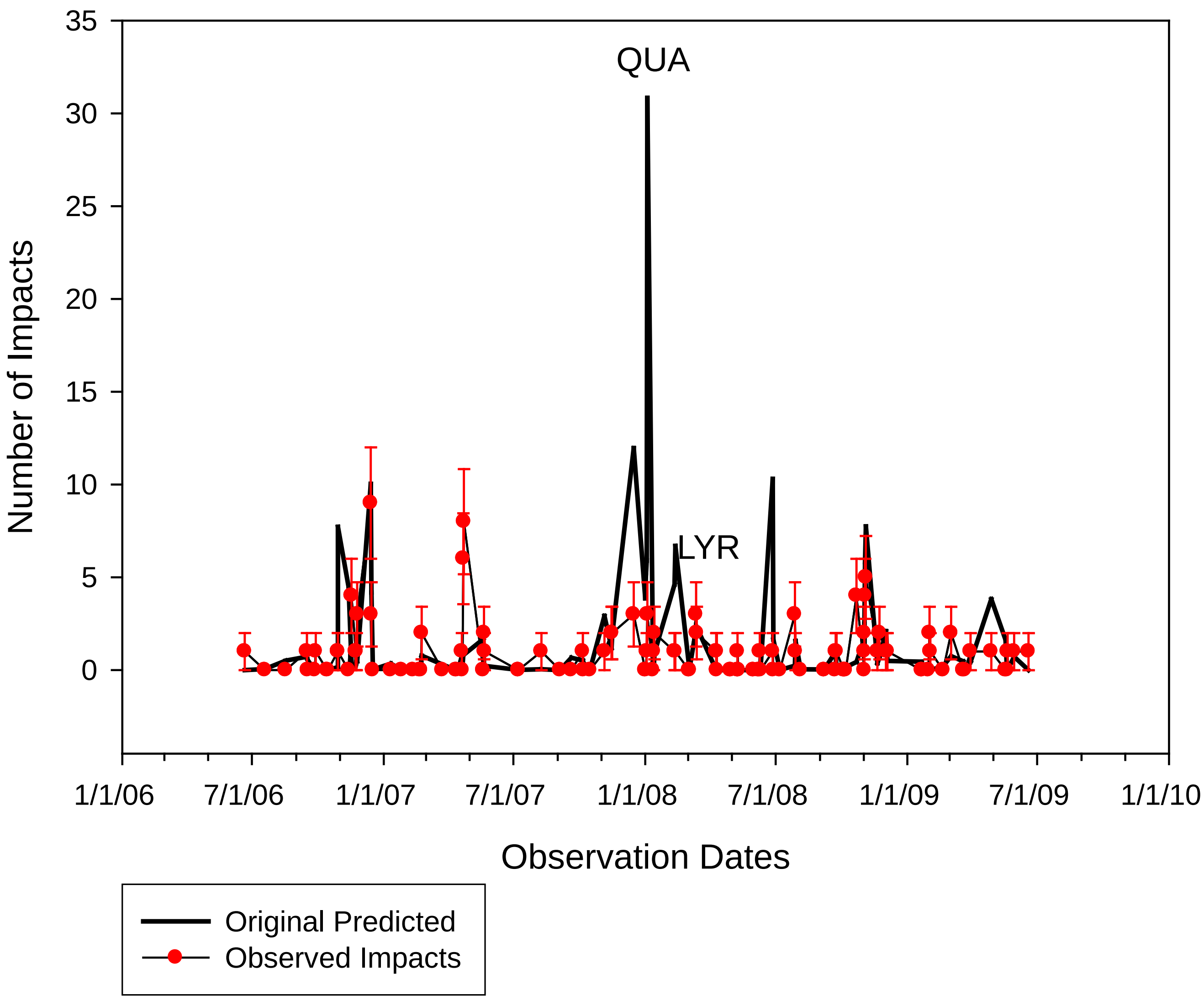
Sporadic Modeling Results

- Used Meteoroid Engineering Model to attempt to reproduce the morning/evening flux asymmetry
  - Hypothesis was that Apex + Antihelion impacts visible in evening, Antihelion only in morning explained asymmetry
- Modeled ratio is 1.02:1 versus observed ratio of 1.45:1
- Since sporadic population indices are steeper (more small particles) than showers, the showers should dominate at larger particle sizes

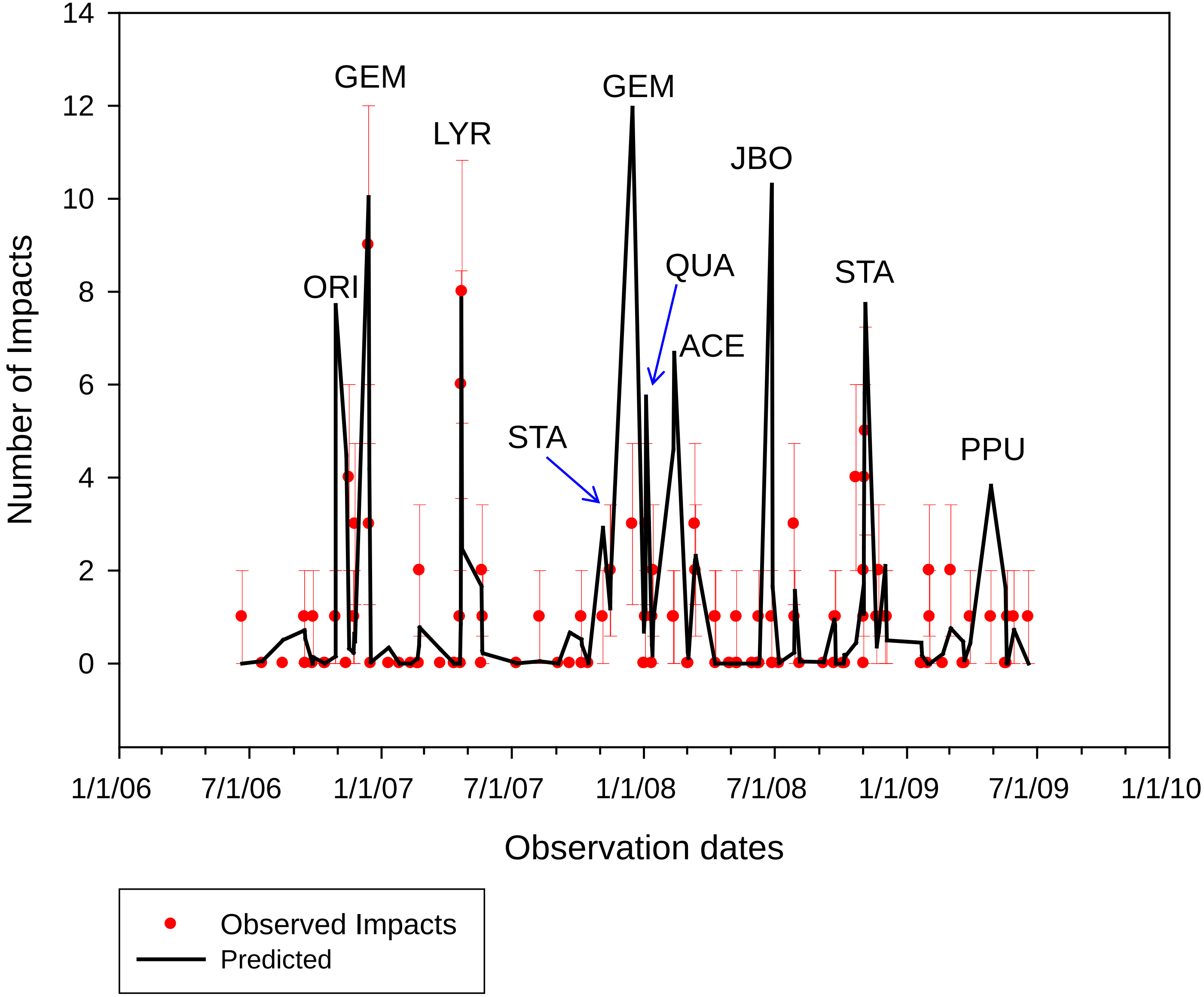
Shower Modeling Results

- Determined radiant visibility for the FOV of each night of observations
- Computed an expected flash rate using
  - Reported ZHR at time of observations from International Meteor Organization (corrected for location of the Moon and FOV visibility of radiant)
  - Population index from IMO
  - Shower speed
  - Luminous efficiency vs. speed from Swift, et al., this conference
- Had to adjust population index for Lyrids and Quadrantids to match observed rates
  - Modeled 2008 Lyrids were too weak
    - IMO says 2.9, better fit with 2.5,2.3, 2.6 (4/21-23/2007)
  - Modeled 2008 Quadrantids were too intense (30 impacts vs 3)
    - IMO says 2.1, better fit with 2.6

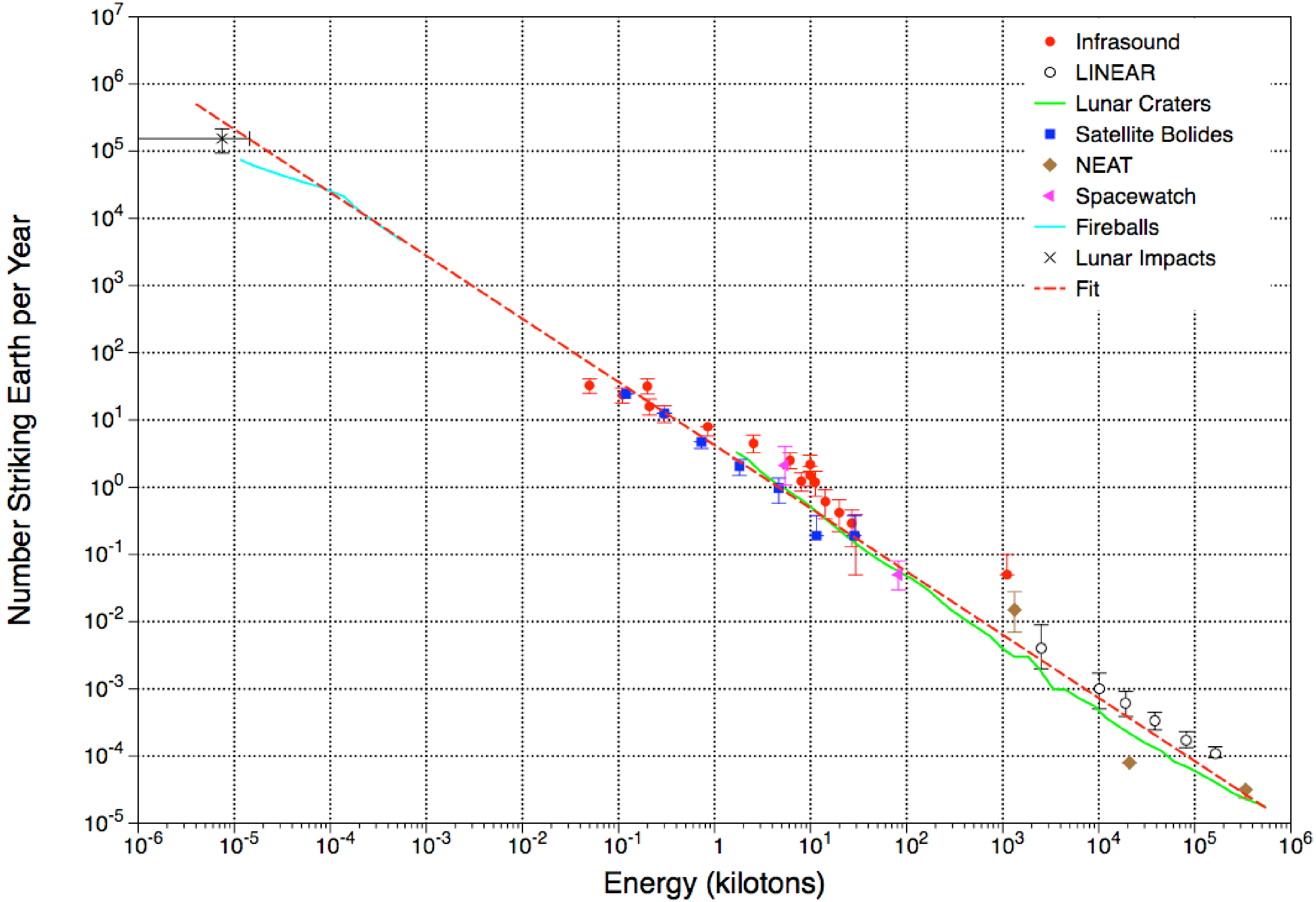
Meteor Shower Correlation
Predicted and Observed – IMO Population Indices



Meteor Shower Correlation
Predicted and Observed – Adjusted Population Indices



Flux Comparison with Other Measurements



After Silber, ReVelle, Brown, and Edwards, 2009, JGR, 114, E08006

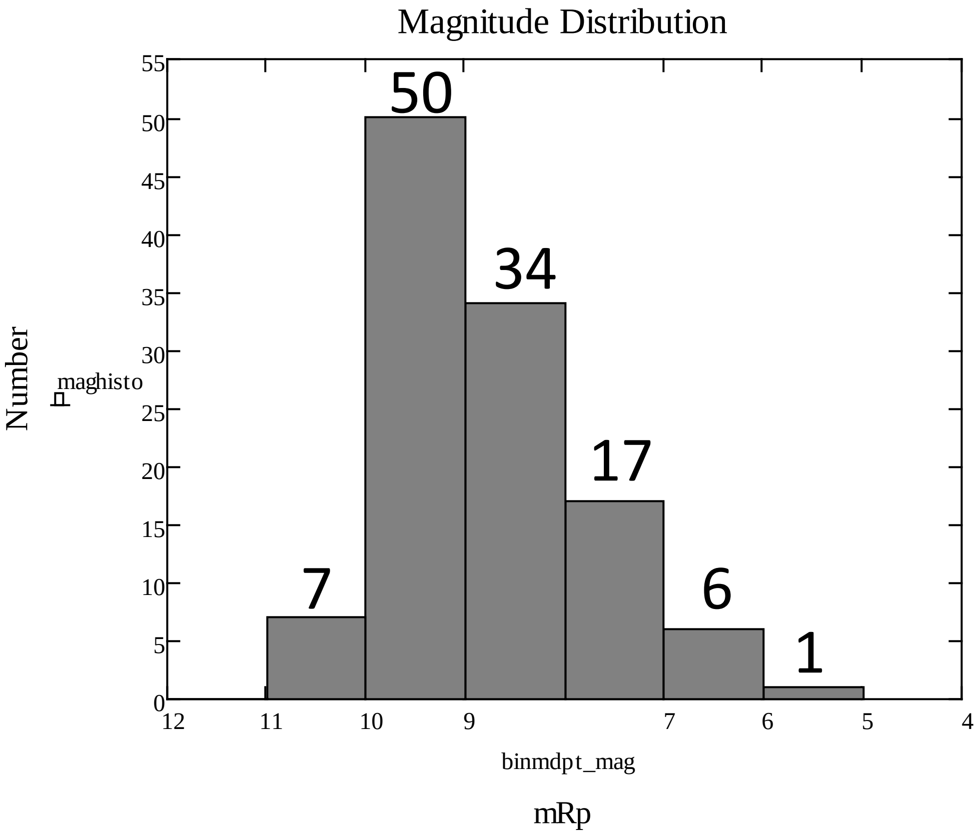
Summary

- Meteor showers dominate the environment in this size range and explain the evening/morning flux asymmetry of 1.5:1
- With sufficient numbers of impacts, this technique can help determine the population index for some showers
- Measured flux of meteoroids in the 100g to kilograms range is consistent with other observations
- We have a fruitful observing program underway which has significantly increased the number of lunar impacts observed
  - Over 200 impacts have been recorded in about 4 years
  - This analysis reports on the 115 impacts taken under photometric conditions during the first 3 full years of operation.
- We plan to continue for the foreseeable future
  - Run detailed model to try explain the concentration near the trailing limb
  - Build up statistics to better understand the meteor shower environment
  - Provide support for robotic seismometers and dust missions
  - Deploy near-infrared and visible cameras with dichroic beamsplitter to 0.5m telescope in New Mexico

The authors thank the Meteoroid Environment Office and the MSFC Engineering Directorate for support of this project

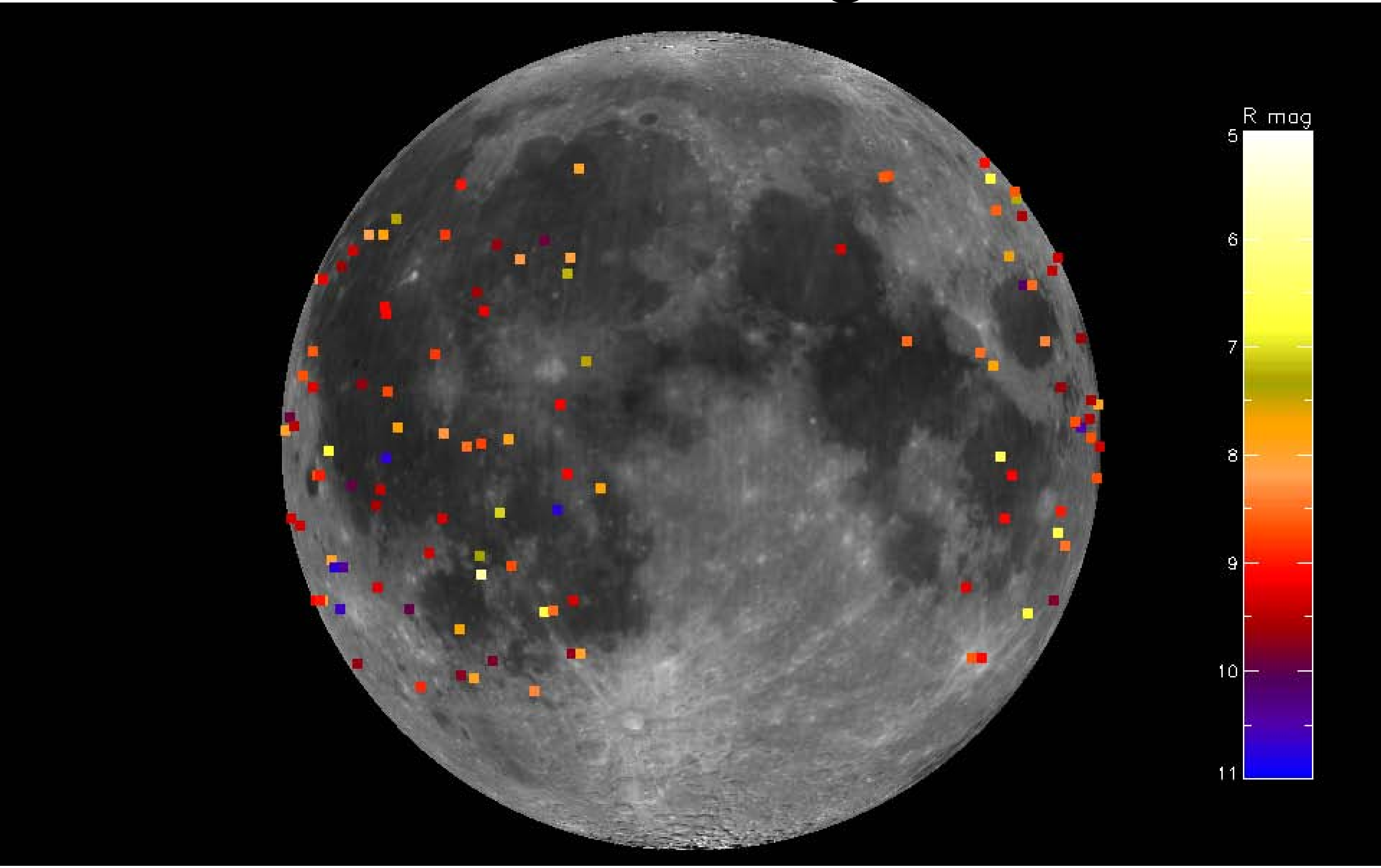
Backup

Magnitude Distribution

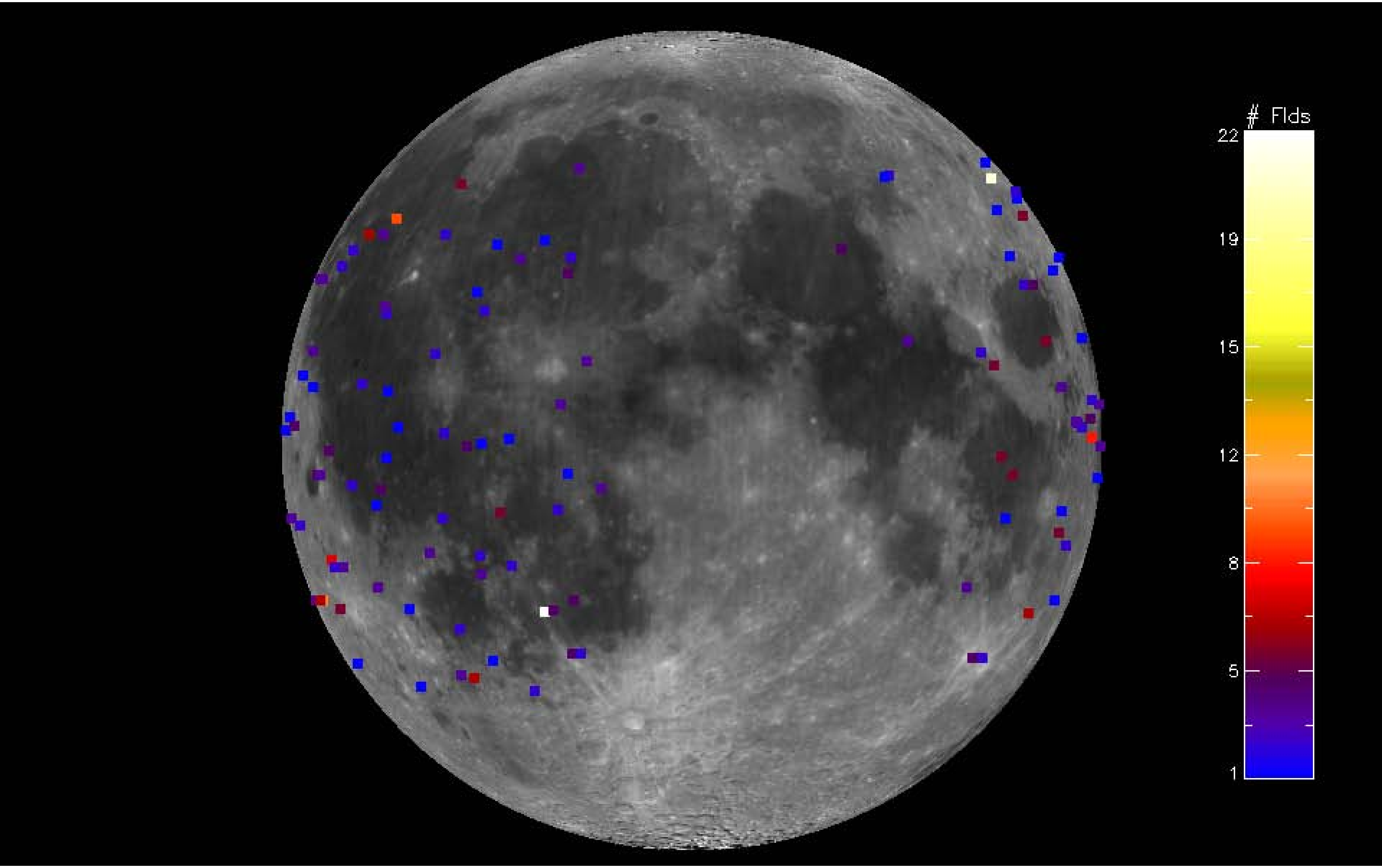


- Complete to 9th magnitude, approximately 100g for average shower meteoroid

Peak Flash Magnitude



Flash Duration – Video Fields

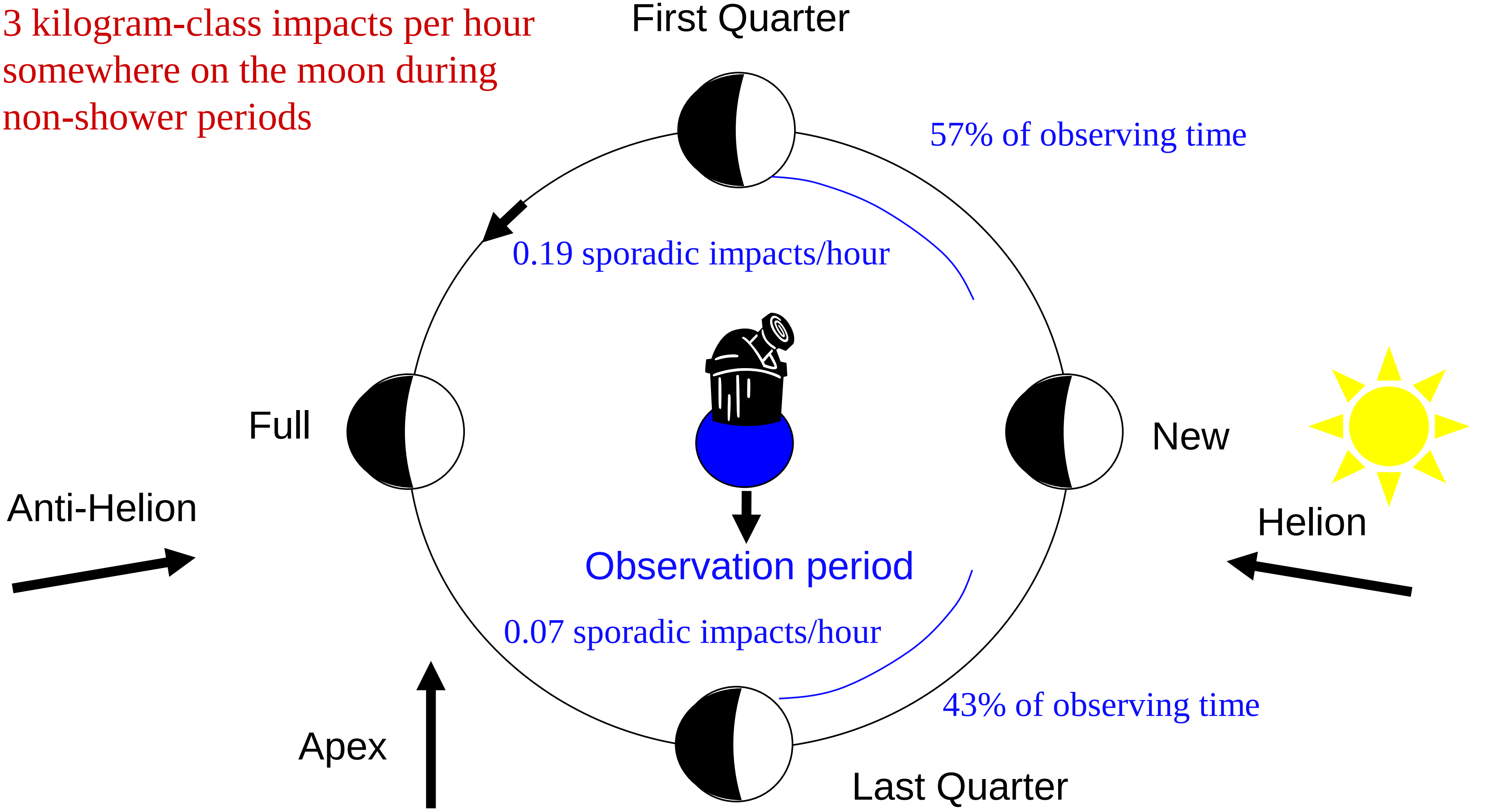


Observing Sites

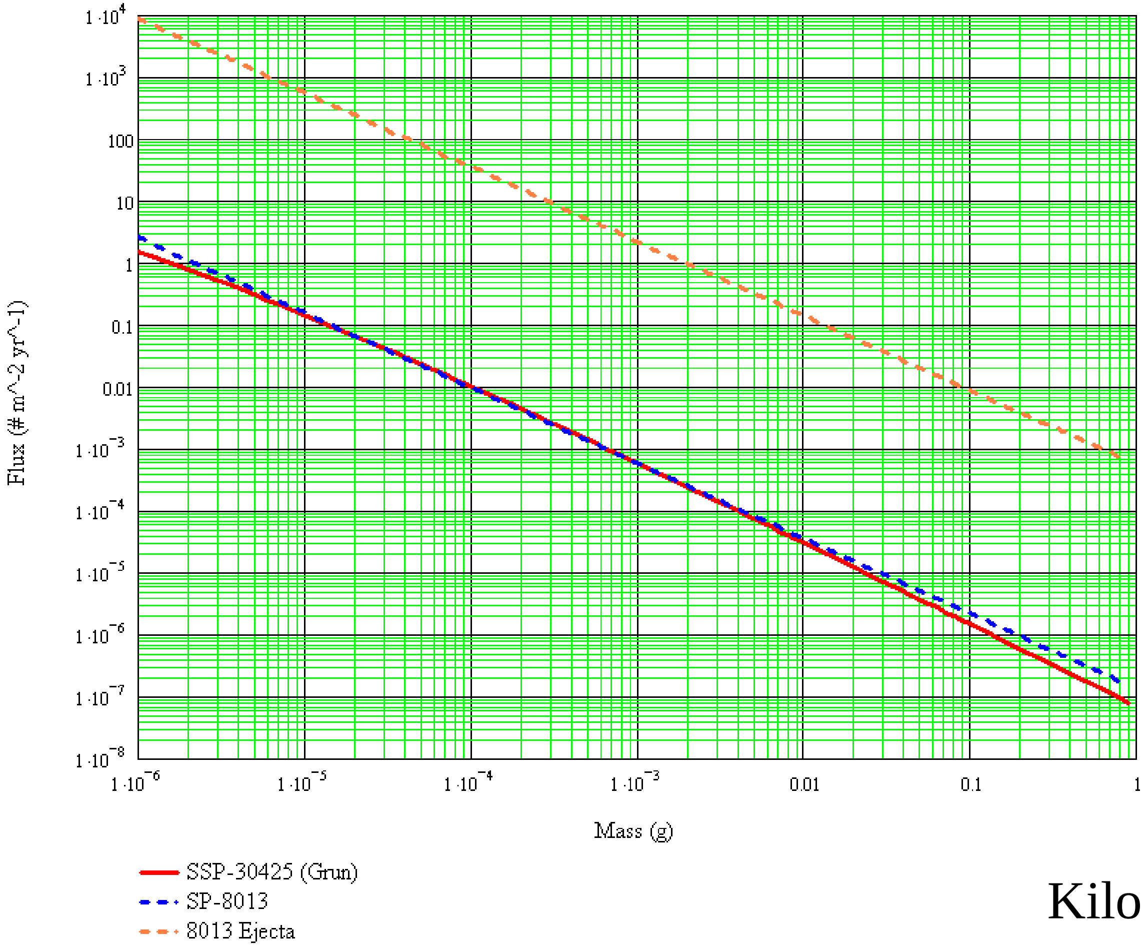
- MSFC ALAMO (Alabama)
  - Two 14 inch telescopes
  - 20 inch telescope moved to New Mexico after 2 years of operation at ALAMO – several months of operation with near-infrared camera
- Walker County Observatory (Georgia)
  - One 14 inch telescope
  - Used to discriminate orbital debris sunglints

Lunar Viewing and Impact Geometry from 3 Strongest Sporadic Sources

Implies an average of more than 3 kilogram-class impacts per hour somewhere on the moon during non-shower periods



Current (1969) Ejecta Model from SP-8013



Ejecta

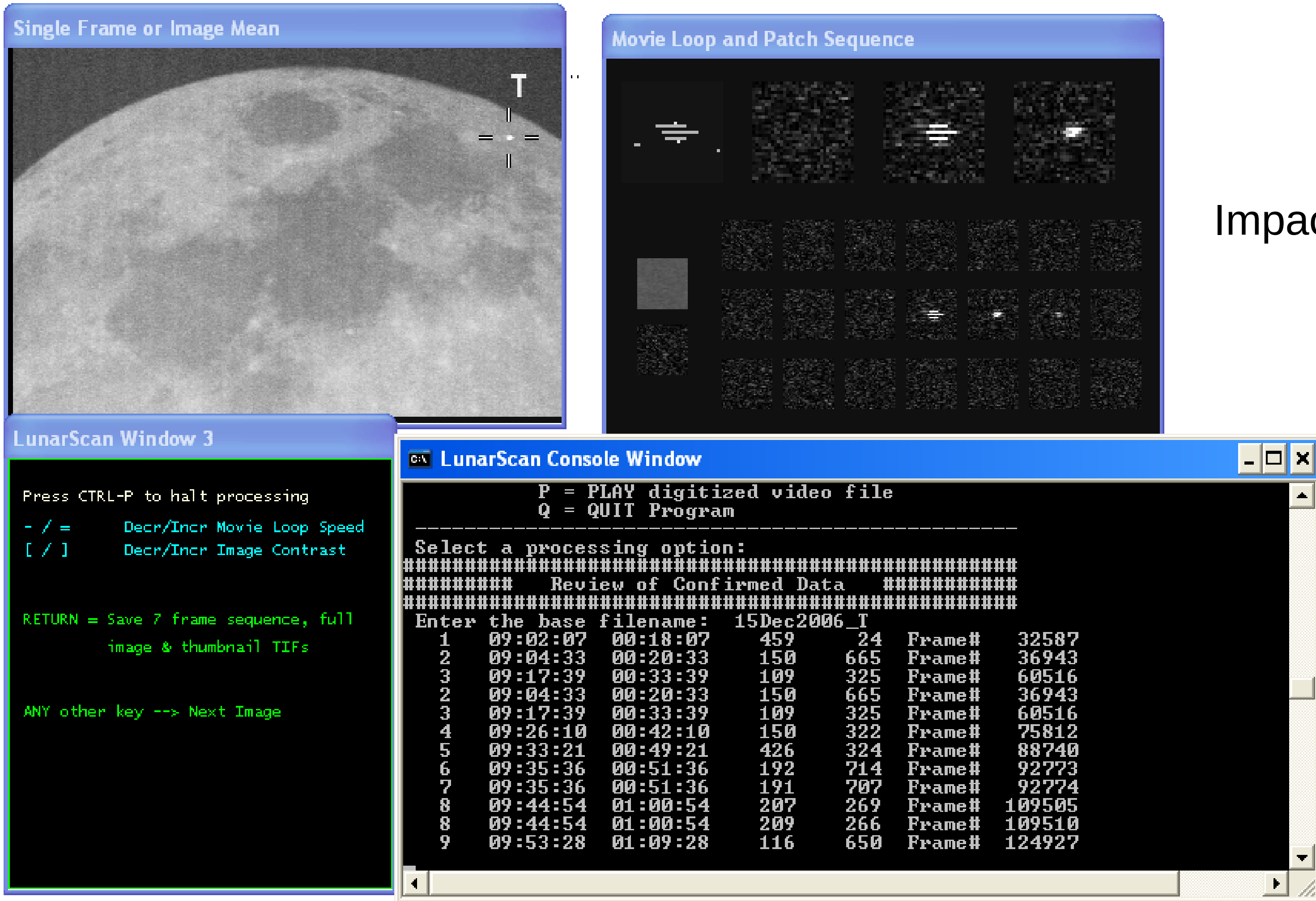
Primaries

Kilogram primaries >

Ejecta particles are 10,000 times as abundant as primaries of same size!

This curve is *probably* overly conservative.

LunarScan (Gural)



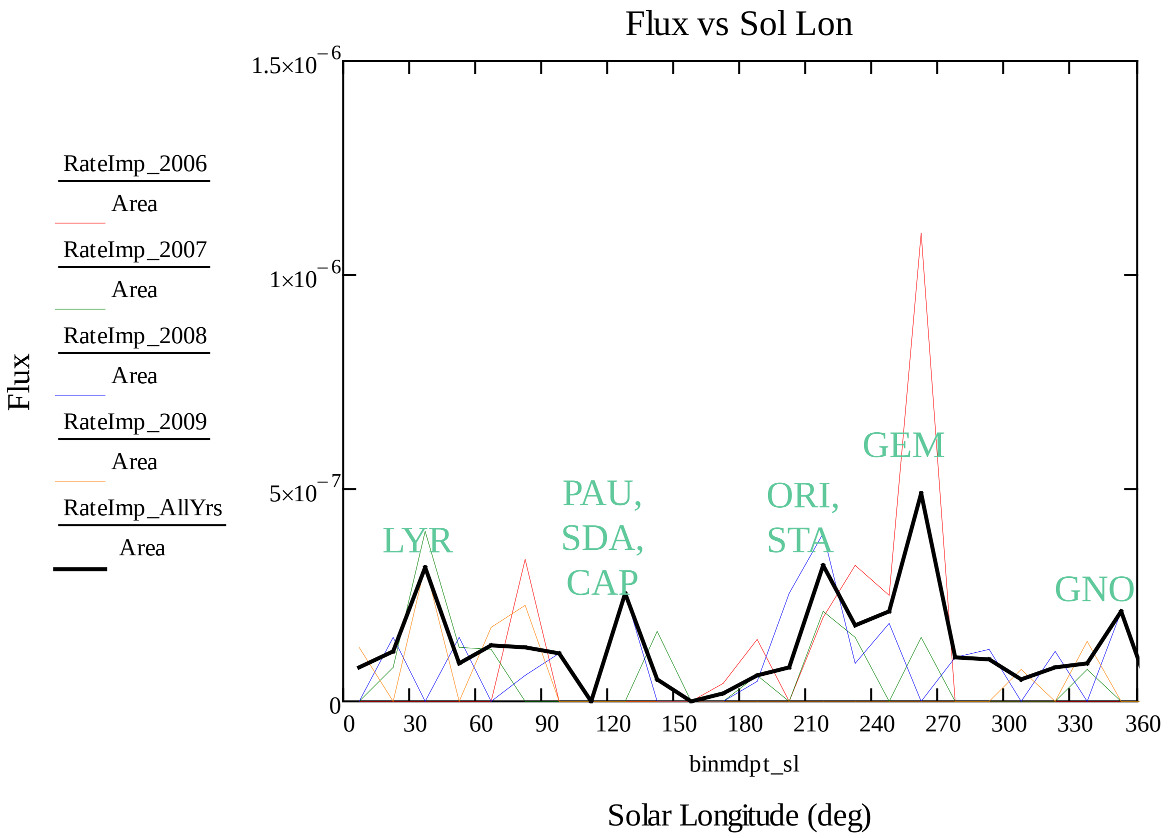
Impact 15 Dec 2006

Photometric analysis is performed by LunaCon (Swift, poster paper)
Currently adding collecting area and “limiting magnitude” determination to LunaCon

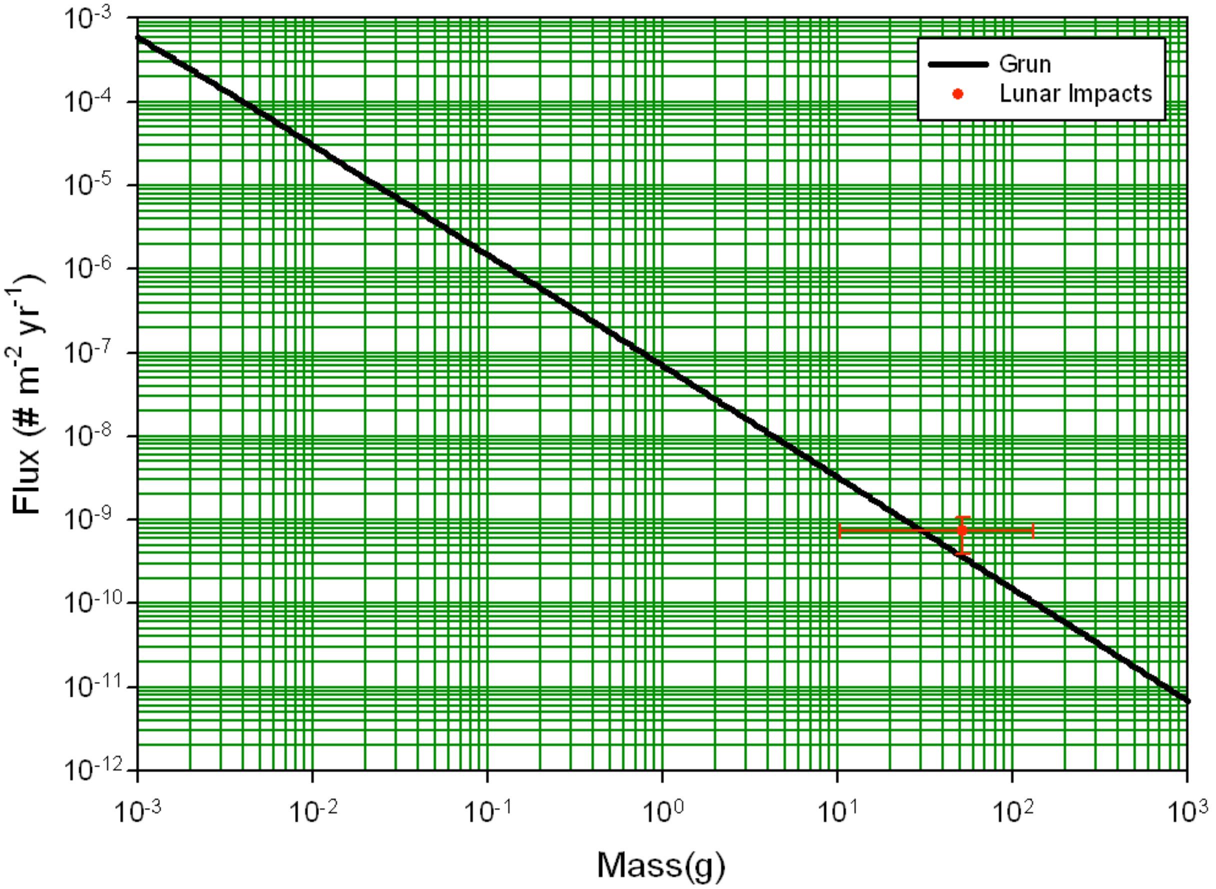
Example of a Moderate-Sized Impactor - May 2, 2006

Duration of flash:	~500 ms
Estimated peak magnitude:	6.86
Peak power flux reaching detector:	$4.94 * 10^{-11}$ W/m^2
Total energy flux reaching detector:	$4.58 * 10^{-12}$ J/m^2
Detected energy generated by impact:	$3.394 * 10^{7}$ J
Estimated kinetic energy of impactor:	$1.6974 * 10^{10}$ J (4.06 tons of TNT)
Estimated mass of impactor:	17.5 kg
Estimated diameter of impactor:	32 cm (ρ = 1 g/cm^3)
Estimated crater diameter:	13.5 m

Meteor Shower Correlation with Flux



Comparison With Grun Flux



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6) Ortiz, J.L. et al., “Detection of sporadic impact flashes on the Moon: Implications for the luminous efficiency of hypervelocity impacts and derived terrestrial impact rates”, Icarus 184 (2006) 319–326
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