Supersonic Baseballs: Characterization and Analysis of Near-Earth Meteoroids via Lunar Impact Observations

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General Interests

- Astrophysics
- Optical Observations
  - Small asteroids
    - Too small to be detected by other means
    - Burn up in Earth's atmosphere
    - Rocky in nature (not icy)

Goals

To utilize the night portion of the lunar surface as a giant detection screen upon which the optical flashes caused by small asteroids striking the surface can be observed in order to obtain an average flux rate for small impactors.

Pros

- Massive amount of available observable area (9-15 million square kilometers)
- Even tiny objects are bright when they smash things going really fast

Cons

- Limited observing times
  - Lunar Phases
  - Daytime lunar transits
- False Positives
  - Airplanes/Satellites
  - Cosmic Rays

Why look at these things?

- Meteors are damaging!
  - Chelyabinsk energy = 20-30 atomic bombs
  - Smaller meteors still go really fast ($17\,\mathrm{km\,s^{-1}}$ to $66\,\mathrm{km\,s^{-1}}$) (Think a baseball at nearly Mach 200!)
  - Small = harder to detect
- Better understanding = Better risk analysis
- Solar System Evolution
  - Collisions and Accretion - small debris is very important!

Background: The Beginnings

- Curiosity about lunar impacts not new (Gordon in 1921) [1]
- Detecting them has taken much longer
  - "Hey, I just saw a flash on the lunar surface!"
    –Harrison Schmitt, Apollo 17, 1972 [2]
  - In 1993, Melosh theorized that rocky debris down to 1 meter should be visible given typical equipment of the time [3]
  - First observed and confirmed during the 1999 Leonid meteor shower by Ortiz and Dunham [4]

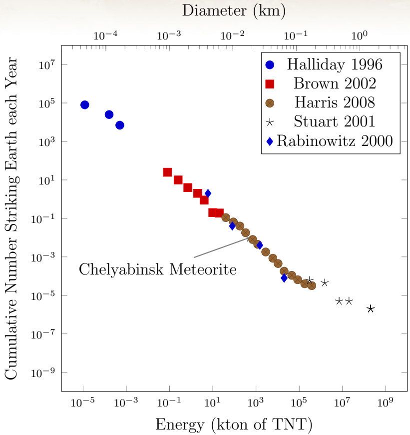
Background: Onward to the Present!

- Meteor Showers easiest to observe
  - Seen again in 2001 Leonids shower by Ortiz and Cudnik [5, 6]
  - First seen in 2004 Perseid shower by Yanagisawa [7]
- Also seen outside of meteor showers
  - Called Sporadics
  - First reported by Ortiz between 2001-2004 [8]
- NASA's Marshall Space Flight Center (MSFC) began observations around 2005 [9]

Background: Energetics

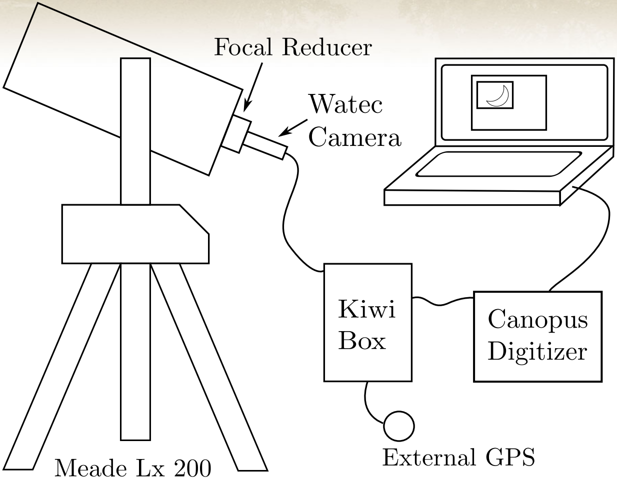
- Only a percentage of kinetic energy converted to visible light (luminous efficiency)
- Not well determined
  - Ortiz modeled off observed to expected impact rate [5]
  - Sigismondi estimated from thermodynamic principles [10]
  - Swift and Moser used the above and gas gun experiments [11]

$$\eta(v) = 1.5\times 10^{-3} e^{-(9.3\,\mathrm{km\,s^{-1}})^2/v^2}$$

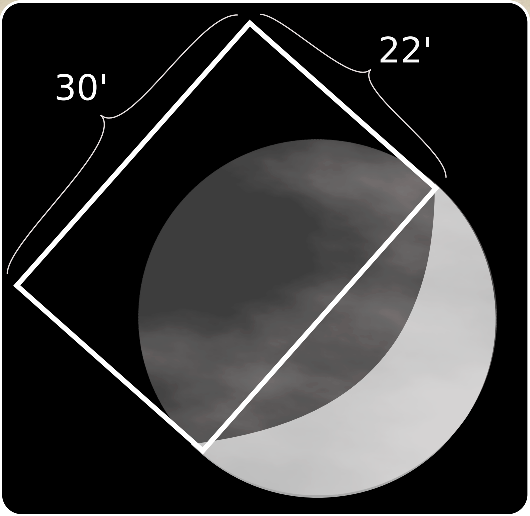


Outline

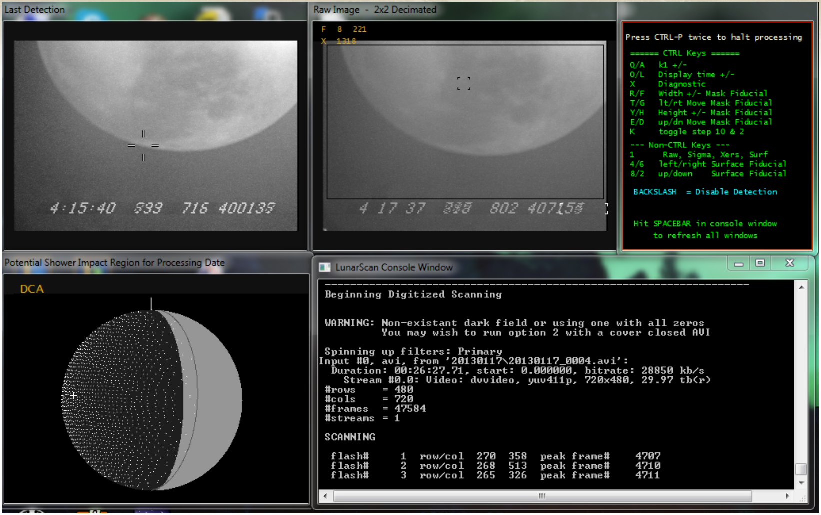
Observational Setup



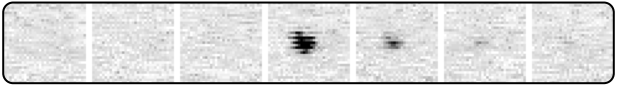
Field of View



LunarScan

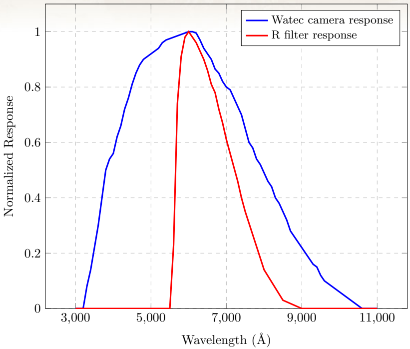

Last Detection
4:15:40 533 716 400133
Raw Image - 2x2 Decimated
F 8 221
X 1318
4 17 37 218 802 40715
Press CTRL-P twice to halt processing
====== CTRL Keys ======
Q/A k1 +/-
O/L Display time +/-
X Diagnostic
R/F Width +/- Mask Fiducial
T/G lt/rt Move Mask Fiducial
Y/H Height +/- Mask Fiducial
E/D up/dn Move Mask Fiducial
K toggle step 10 & 2
--- Non-CTRL Keys ---
1 Raw, Sigma, Xers, Surf
4/6 left/right Surface Fiducial
8/2 up/down Surface Fiducial
BACKSLASH = Disable Detection
Hit SPACEBAR in console window
to refresh all windows
Potential Shower Impact Region for Processing Date
DCA
LunarScan Console Window
Beginning Digitized Scanning
WARNING: Non-existant dark field or using one with all zeros
You may wish to run option 2 with a cover closed AVI
Spinning up filters: Primary
Input #0, avi, from '20130117\20130117_0004.avi':
Duration: 00:26:27.71, start: 0.000000, bitrate: 28850 kb/s
Stream #0.0: Video: dvvideo, yuv411p, 720x480, 29.97 tb(r)
#rows = 480
#cols = 720
#frames = 47584
#streams = 1
SCANNING
flash# 1 row/col 270 358 peak frame# 4707
flash# 2 row/col 268 513 peak frame# 4710
flash# 3 row/col 265 326 peak frame# 4711

LunarScan Example



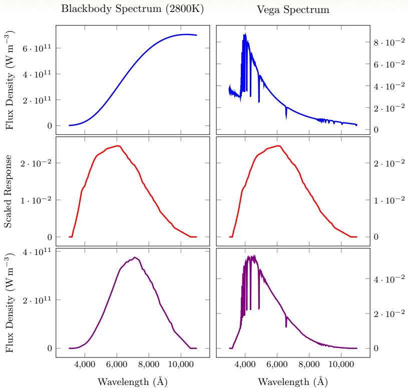
Magnitude Calibration

- Open Filter for sensitivity
  - $\Rightarrow$ Calibrated to R band
- LiMovie used for photometry
- AviSynth used for video decoding

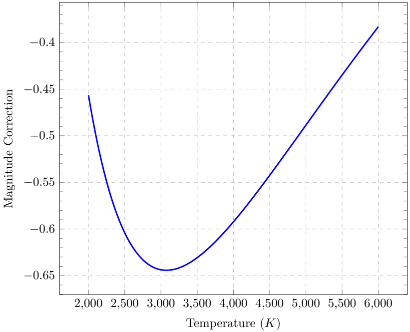


$$m_{act} = -2.5\log(g) - C_{offset} - kx - T(B-V)$$

Impact Color Correction



$$m_{imp} = m_{vega} - 2.5 \log\left(\frac{f_{imp}}{f_{vega}}\right)$$



Magnitude to Energy

- Flux Density (W/cm^2/Å):

$$f_\lambda = 10^{-7} \cdot 10^{-(R+21.1+0.555)/2.5}$$

- Avg Flux (W/cm^2):

$$f = \Delta\lambda f_\lambda$$

- Luminosity (W):

$$L = \frac{\eta(KE)}{\Delta t}$$

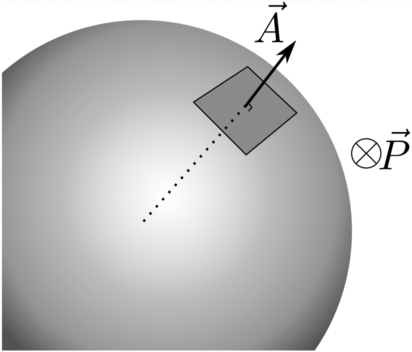
- Flux $\rightarrow$ Luminosity:

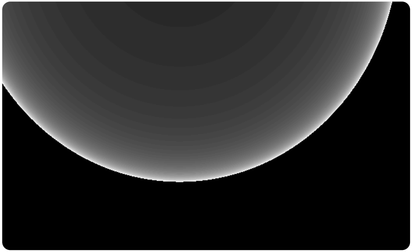
$$f = \frac{L}{2\pi d^2}$$

Impactor Kinetic Energy

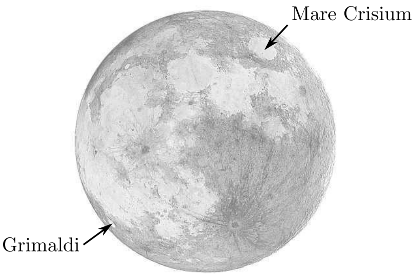
$$KE = \frac{2\pi d^2 f_\lambda \Delta\lambda\Delta t}{\eta}$$

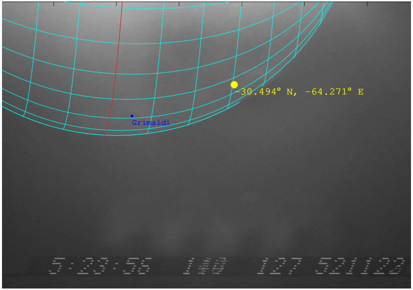
Observed Lunar Area



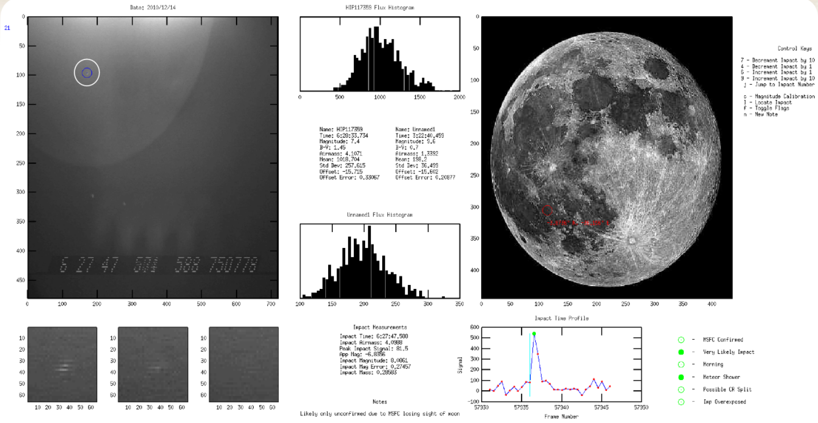


Selenographic Latitude and Longitude





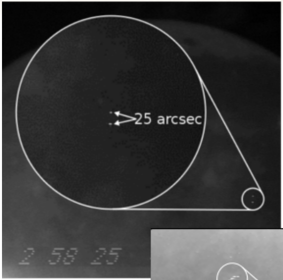
Analysis Command

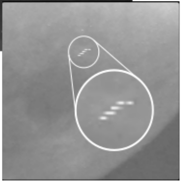


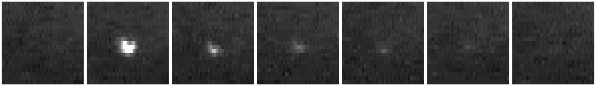
Outline

False Positives

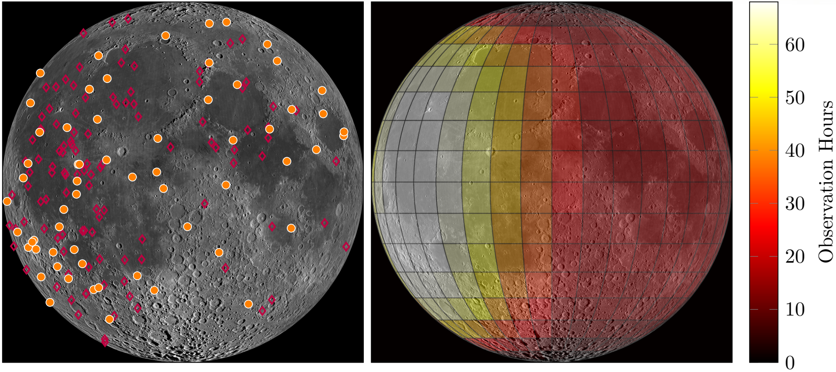
- False Positives
  - Streaks/Movement
  - Doubles/Splits
  - Overexposure
- Positive Signs
  - Extended time signature





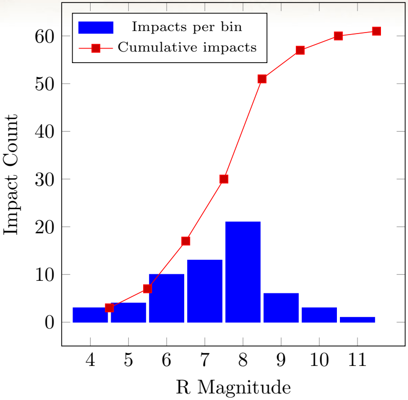


Accepted Impacts



The Completeness Limit

- Dimmer impacts likely not fully sampled
- Expect to see increasingly more small/dim impacts
- Turnover indicates completeness limit
- Taken to correspond to magnitude 8.5



Outline

Impact Flux Rate

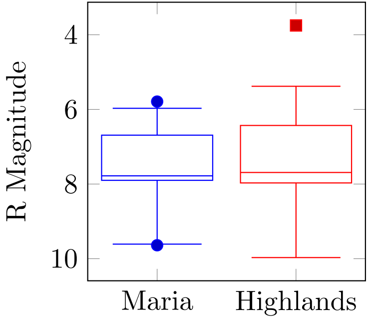
- Average flux rate computed to the completeness limit

$$\frac{51\,\text{Impacts}}{(5.77 \times 10^6\,\text{km}^2)\,(80.97\,\text{h})} = (1.09 \pm 0.02) \times 10^{-7}\text{km}^{-2}\text{h}^{-1}$$

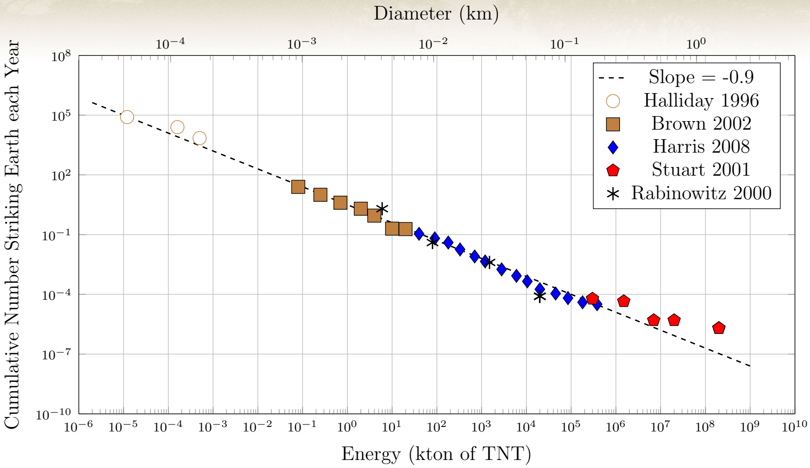
- Slightly higher than MSFC latest value of $1.03 \times 10^{-7}\,\text{km}^{-2}\text{h}^{-1}$ to 9th magnitude [12]
- Corresponds to 9-17 impact difference between databases
- Plausible over multi-year observations with highly variable impact rates, observing times, and conditions

Flash Variations

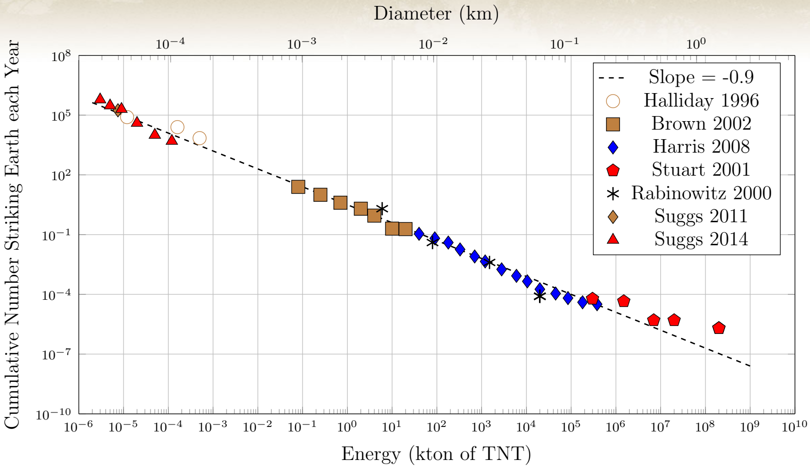
- Photometric evolution may describe unknown impact parameters
  - Impacter composition?
  - Impacted terrain composition?
  - Impact angle?
- Many variables, tough to analyze with limited dataset



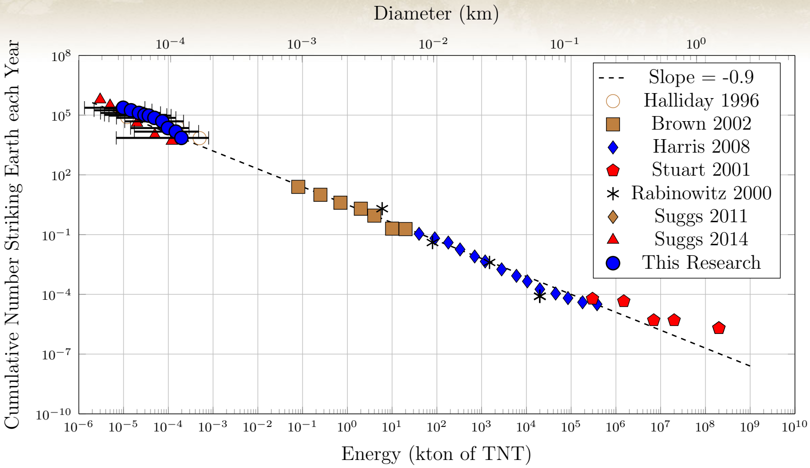
Energy Distribution: The Initial State



Energy Distribution: State this Spring



Energy Distribution



Conclusions: Primary Purpose

To assemble and devise a lunar impact experimental setup capable of observing many lunar impacts over a prolonged time in order to estimate a small debris flux rate near Earth

Result

An experimental setup and analysis pipeline was devised and created which observed 61 accepted lunar impacts over 80 hours of observation between 2010 and 2012. Average impact flux rates to magnitude 8.5 measured 1.09×10^{-7} impact/km^2/h, corresponding to approximately 1 lunar strike every 30 minutes.

Conclusions: Secondary Purposes

To investigate relationships between impact brightness, speed, composition, and impacted terrain

Result

Lunar terrain composition seems to play only a small role in the luminous efficiency, though a larger dataset is needed

To estimate an energy distribution for small size debris near Earth

Result

There is no deviation within error bars from the power law governing the energy distribution of larger asteroids

Future/Current Work

- Working to setup an all-sky camera for fireball detection (with Kyle)
- Fireballs can be analyzed for both orbital information and energetic population density
- Working on code for automatic (hopefully) real-time detection of fireballs/lunar impacts
- Rewritting much of lunar impact analysis code into Python for future ease of use and better automation

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- Rob Suggs (MSFC), for patience and promptness in answering my various questions

References I

[1] J. W. Gordon. Meteors on the Moon. *Nature*, 107(2686):234–235, April 1921.

[2] Apollo Spacecraft Program Office: Test Division NASA. Apollo 17 technical air-to-ground voice transcription. *NASA Mission Report MSC-07629*, page 2461, 1972.

[3] H. Jay Melosh, N. A. Artemjeva, A. P. Golub, I. V. Nemchinov, V. V. Shuvalov, and I. A. Trubetskaya. Remote visual detection of impacts on the lunar surface. In *In Lunar and Planetary Inst.*, 1993.

[4] J. L. Ortiz, P. V. Sada, L. R. Bellot Rubio, F. J. Aceituno, J. Aceituno, P. J. Gutiérrez, and U. Thiele. Optical detection of meteoroidal impacts on the Moon. *Nature*, 405(6789):921–923, 2000.

[5] J. L. Ortiz, J. A. Quesada, J. Aceituno, F. J. Aceituno, and L. R. Bellot Rubio. Observation and Interpretation of Leonid Impact Flashes on the Moon in 2001. *The Astrophysical Journal*, 576(1):567, 2002.

[6] Brian M. Cudnik, David W. Dunham, David M. Palmer, Anthony Cook, Roger Venable, and Peter S. Gural. Ground-Based Observations Of Lunar Meteoritic Phenomena. *Earth, Moon, and Planets*, 93(3):145–161, November 2003.

[7] Masahisa Yanagisawa, Kouji Ohnishi, Yuzaburo Takamura, Hiroshi Masuda, Yoshihito Sakai, Miyoshi Ida, Makoto Adachi, and Masayuki Ishida. The first confirmed Perseid lunar impact flash. *Icarus*, 182(2):489–495, June 2006.

[8] J. L. Ortiz, F. J. Aceituno, J. A. Quesada, J. Aceituno, M. Fernandez, P. Santos-Sanz, J. M. Trigo-Rodriguez, J. Llorca, F. J. Martin-Torres, P. Montañés Rodríguez, and E. Pallé. Detection of sporadic impact flashes on the Moon: Implications for the luminous efficiency of hypervelocity impacts and derived terrestrial impact rates. *Icarus*, 184(2):319–326, October 2006.

[9] W. J. Cooke, R. M. Suggs, R. J. Suggs, W. R. Swift, and N. P. Hollon. Rate and Distribution of Kilogram Lunar Impactors. In *Lunar and Planetary Science Conference*, volume 38 of *Lunar and Planetary Inst. Technical Report*, page 1986, March 2007.

[10] C. Sigismondi and G. P. Imponente. The Observation of Lunar Impacts. Part II. *WGN, Journal of the International Meteor Organization*, 28(6):230–232, May 2001.

References II

[11] W. R. Swift, D. E. Moser, R. M. Suggs, and W. J. Cooke. An Exponential Luminous Efficiency Model for Hypervelocity Impact into Regolith. In W.J. Cooke, D.E. Moser, B.F. Hardin, and D. Janches, editors, *Meteoroids: The Smallest Solar System Bodies*, page 125, 2011.

[12] R. M. Suggs, D. E. Moser, W. J. Cooke, and R. J. Suggs. The flux of kilogram-sized meteoroids from lunar impact monitoring. *Icarus*, 238:23–36, August 2014.

[13] P Brown, R E Spalding, D O ReVelle, E Tagliaferri, and S P Worden. The flux of small near-Earth objects colliding with the Earth. *Nature*, 420(6913):294–6, November 2002.

[14] Ian Halliday, Arthur A. Griffin, and Alan T. Blackwell. Detailed data for 259 fireballs from the Canadian camera network and inferences concerning the influx of large meteoroids. *Meteoritics & Planetary Science*, 31(2):185–217, March 1996.

[15] J S Stuart. A near-Earth asteroid population estimate from the LINEAR survey. *Science (New York, N.Y.)*, 294(5547):1691–3, November 2001.

[16] D Rabinowitz, E Helin, K Lawrence, and S Pravdo. A reduced estimate of the number of kilometre-sized near-Earth asteroids. *Nature*, 403(6766):165–6, January 2000.

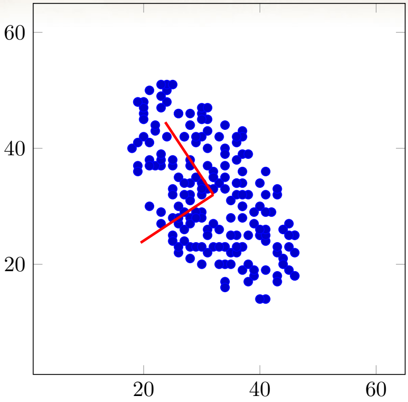
[17] Paul D Strycker, Nancy J Chanover, Charles Miller, Ryan T Hamilton, Brendan Hermalyn, Robert M Suggs, and Michael Sussman. Characterization of the LCROSS impact plume from a ground-based imaging detection. *Nature communications*, 4:2620, January 2013.

Questions

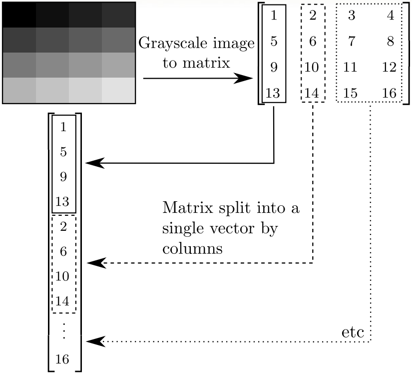
Questions? Comments?

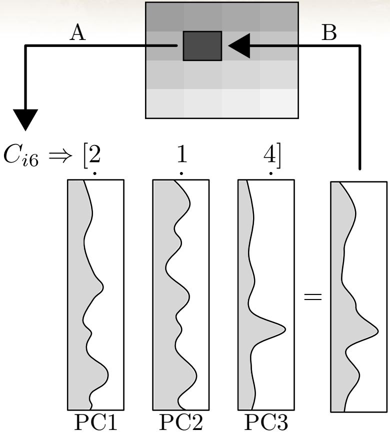
PCA Basics

- Some missed impacts after comparing to MSFC
- LunarScan higher sensitivity failed to find
- PCA showed promise in LCROSS observations [17]
- Extract the principal components from an image stack
    - Order of greatest covariation

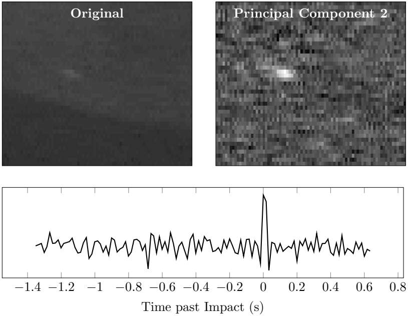


Dealing with an Image Stack





PCA Effectiveness



- Pros:
  - Enhanced impact image
- Cons:
  - Requires localized region and time
  - Which PC's show impact signatures can vary
  - Not a miracle worker