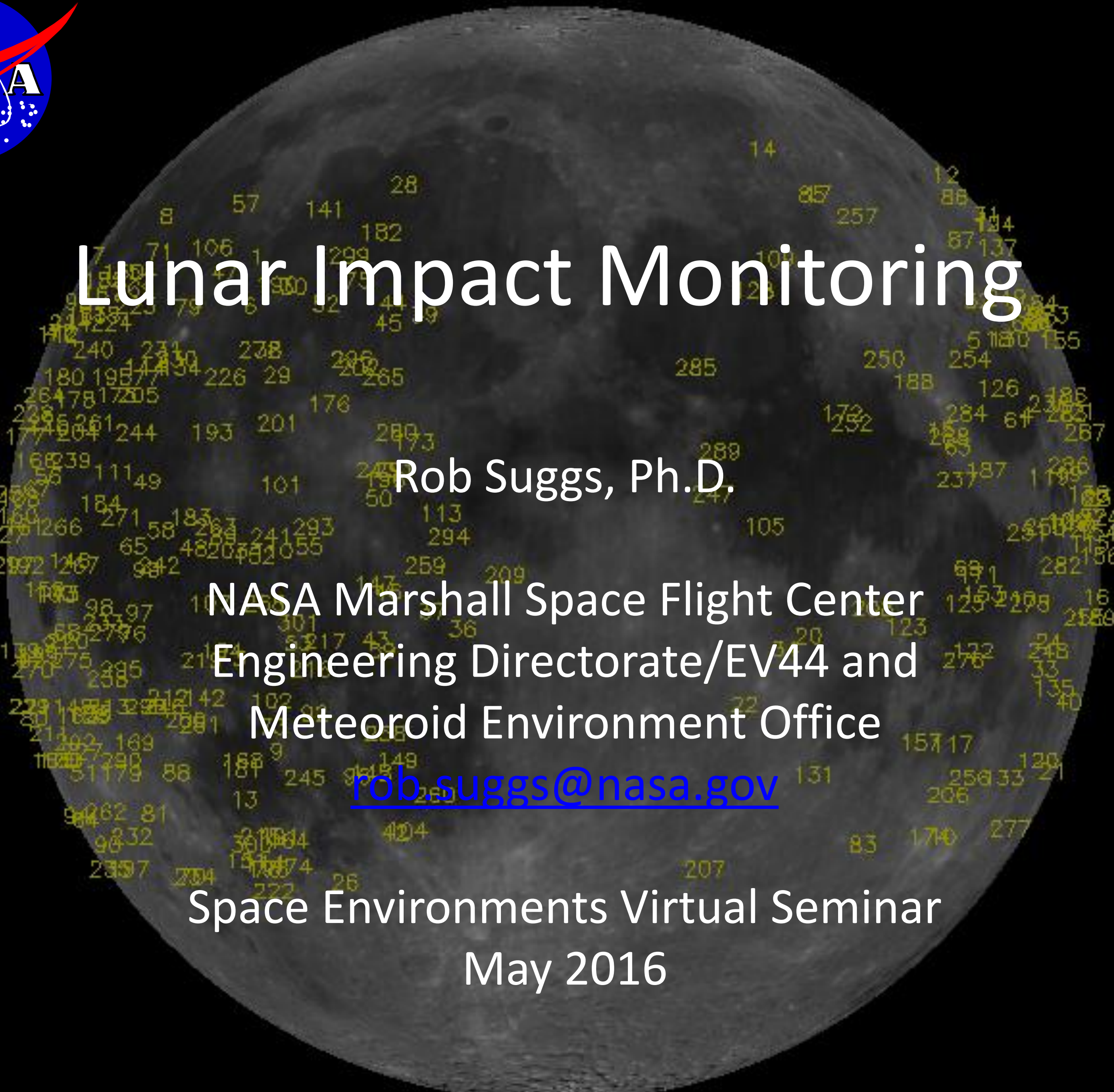

Lunar Impact Monitoring

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Meteoroid Environment Office
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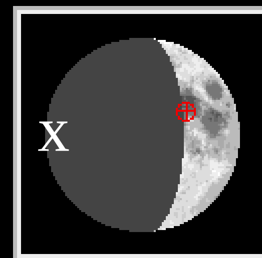
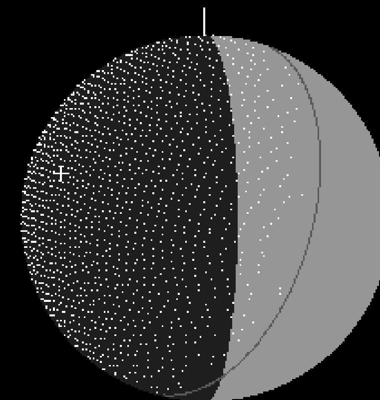
Space Environments Virtual Seminar
May 2016

Outline

- Observational Technique
- Photometric Calibration and Energy Calculation
- Meteoroid Flux
- A Crater is Born

Jack Schmitt/Apollo 17 observation of lunar impact





Geminid visiblity

"NASA Apollo 17 transcript" discussion is given below (before descent to lunar surfac

----

03 15 38 09 (mission elapsed time)
(10 Dec 1972, 21:16:09 UT – possible Geminid)

LMP Hey, I just saw a flash on the lunar surface!

CC Oh, yes?

LMP It was just out there north of Grimaldi [mare]. Just north of Grimaldi. You might see if you got anything on your seismometers, although a small impact probably would give a fair amount of visible light.

CC Okay. We'll check.

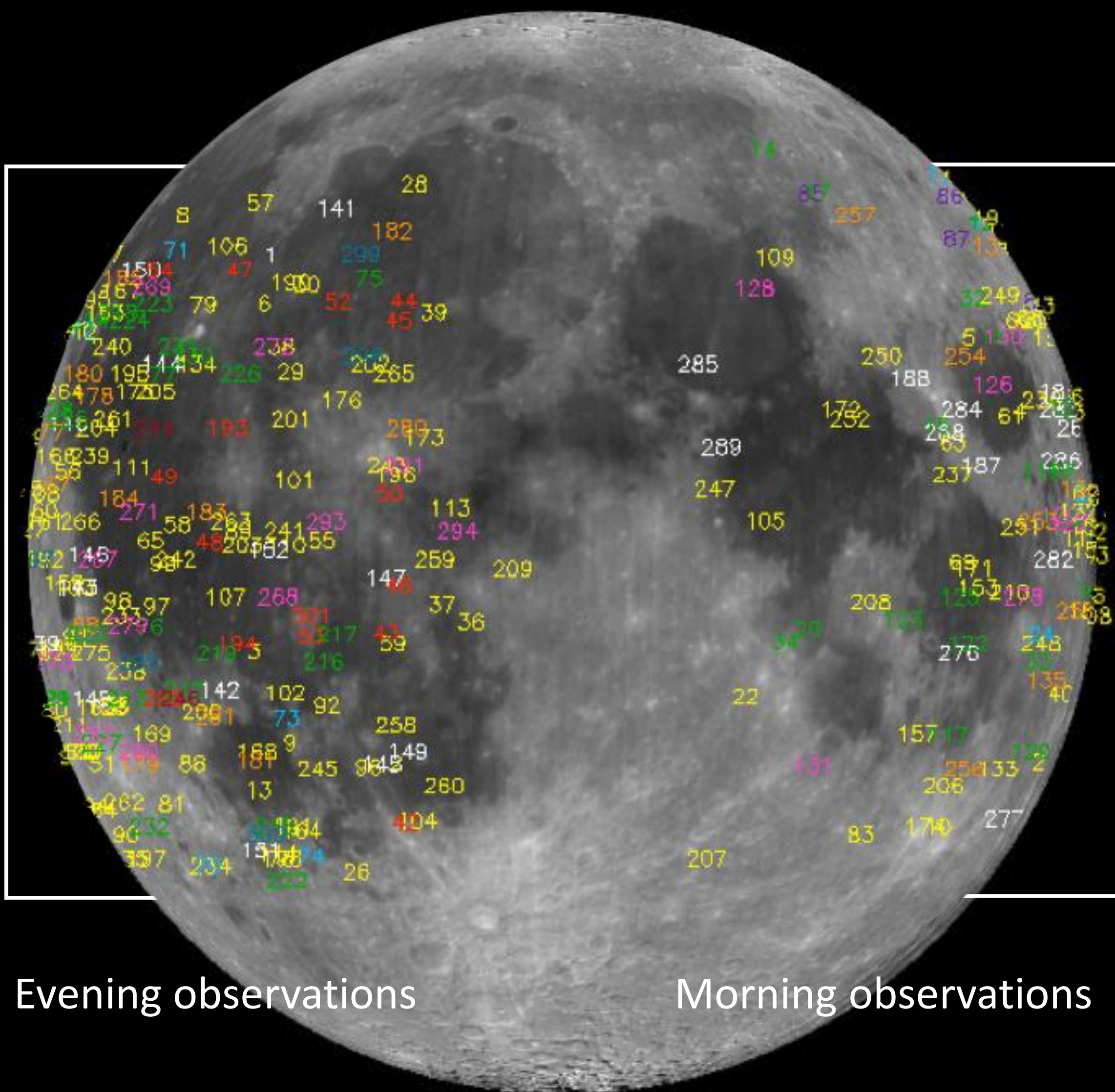
LMP It was a bright little flash right out there near that crater. See the [sharp rimed] crater right at the [north] edge of [the] Grimaldi [mare]? Then there is another one [i.e., sharp rimed crater] [directly] north of it [about 50km]- fairly sharp one north of it. [That] is where there was just a thin streak [pin prick] [flash?] of light.

CC How about putting an X on the map where you saw it?

9 Years of Observations

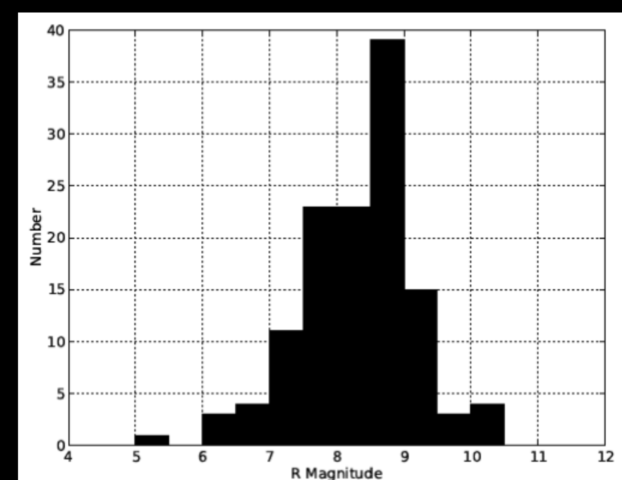
- The MSFC lunar impact monitoring program began in 2006 in support of environment definition for the Constellation Program
  - Needed a model/specification for impact ejecta risk
- Work continued by the Meteoroid Environment Office after Constellation cancellation
  - Lunar impact monitoring allows measurement of fluxes in a size range not easily observed (10s of grams to kilograms)
- A paper published in Icarus reported on the first 5 years of observations
  - **Icarus:** http://www.sciencedirect.com/science/article/pii/S0019103514002243
  - **ArXiv:** http://arxiv.org/abs/1404.6458

Observation Summary



394 impacts since 2005

Subset of 126 flashes on photometric nights to 2011
141 hrs evening - 81 flashes
126 hrs morning - 45 flashes
Average: 2.1 hrs/flash
evening/morning = 1.6:1



Photometric error ~0.2 mag

When We Observe

- Initially, it was anytime the glare from the sunlit face did not completely wash out the earthshine face
  - Typically between 10% illuminated (crescent) and 50% (quarter)
- Impact rate is higher during meteor showers and we are focusing on those now after 7 years of observing anytime
- Observe from nautical twilight to moonset – evening
- Observe from moonrise to nautical twilight – morning
- Generate a schedule each year with dates, times, and shower visibilities

Camera Field of View and Processing

Approximately 20 arcminutes horizontal, 3.8×10^6 km^2 on the Moon

Approximately 1m effective focal length with ½ inch CCD

Good compromise between collecting area and glare

Use stars for photometric calibration

Two telescopes are needed to discriminate cosmic ray flashes in the CCD

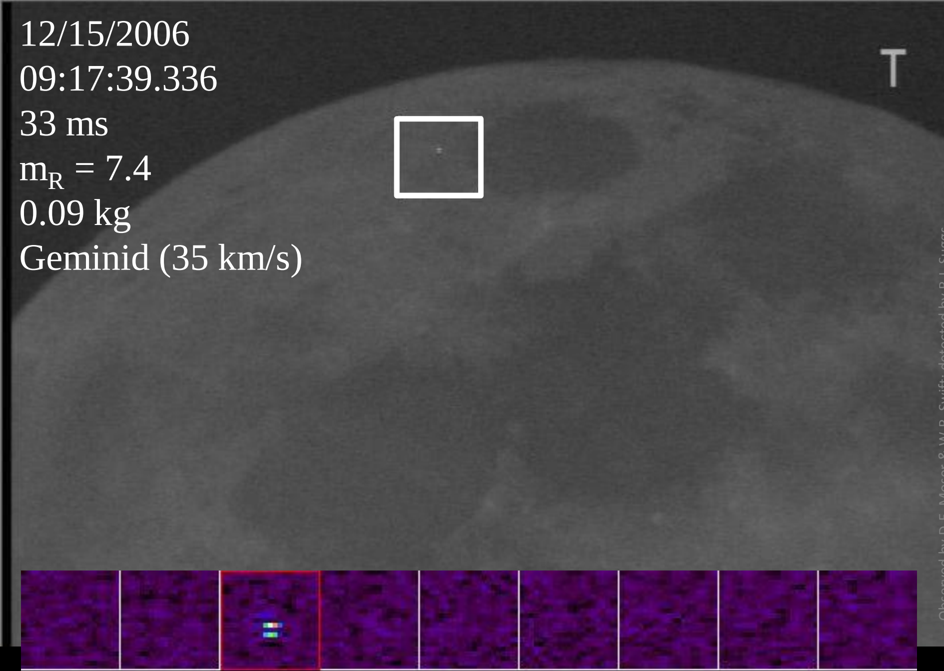
A third telescope 100 km away helps discriminate orbital debris sun-glints

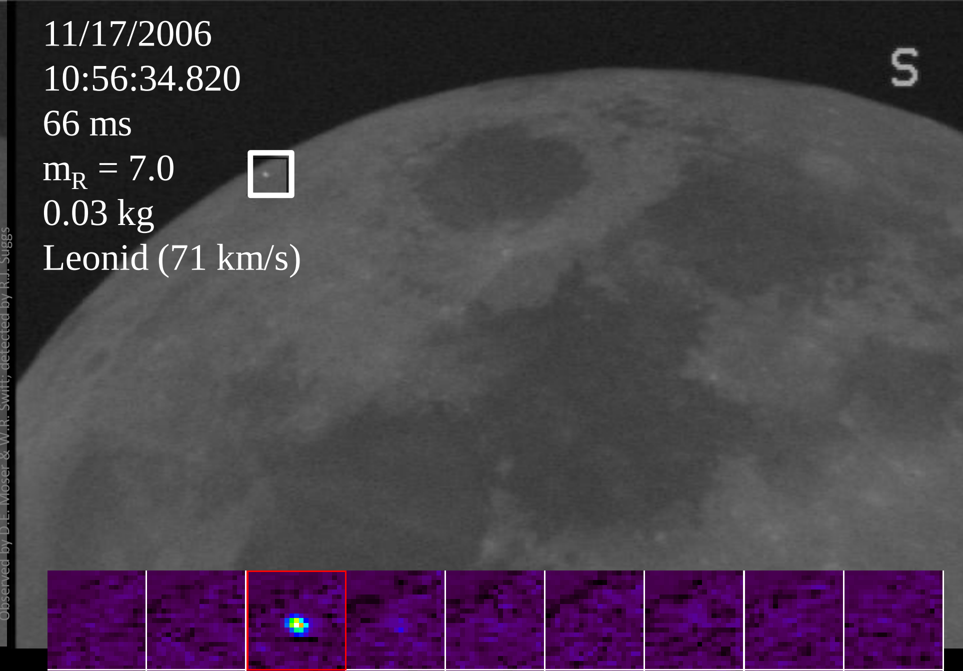
Software finds the flashes and a human correlates them

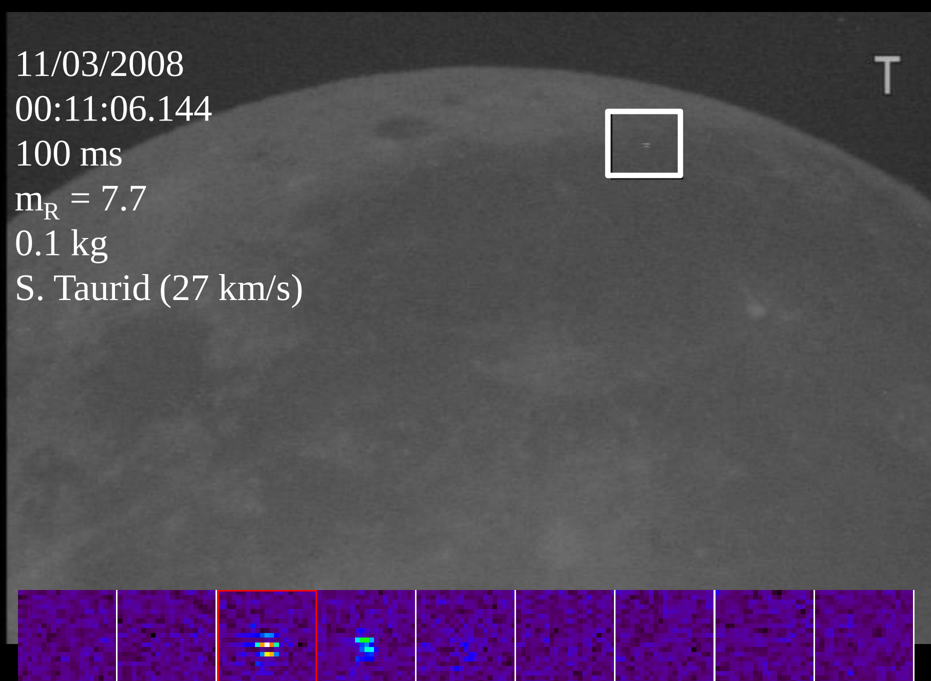
Automated Lunar and Meteor Observatory (MPC H58)

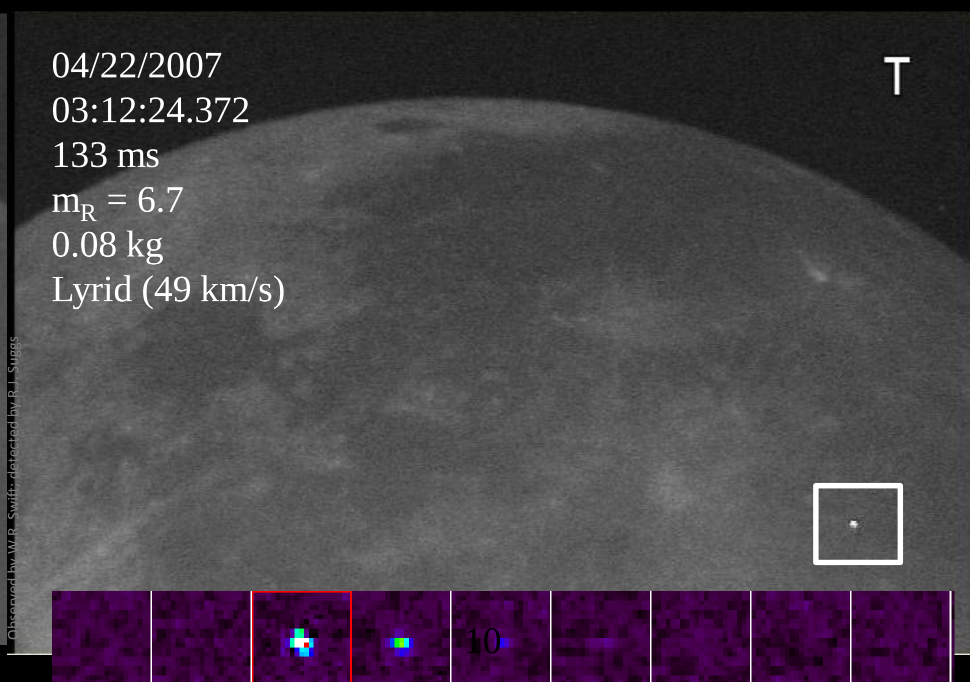
- Telescopes
  - 14” (0.35m)
    - Meade, Celestron
  - Paramount (ME, MX)
- Detectors
  - Sony HAD EX – based video
  - Gamma=0.45, man. gain, shutter off

Operator position


12/15/2006
09:17:39.336
33 ms
m_R = 7.4
0.09 kg
Geminid (35 km/s)
T
Observed by D.E. Moser & W.R. Swift; detected by R.J. Suggs


11/17/2006
10:56:34.820
66 ms
m_R = 7.0
0.03 kg
Leonid (71 km/s)
S
Observed by V. Coffey, D.E. Moser & W.R. Swift; detected by R.J. Suggs


11/03/2008
00:11:06.144
100 ms
m_R = 7.7
0.1 kg
S. Taurid (27 km/s)
T
Observed by W.R. Swift; detected by R.J. Suggs


04/22/2007
03:12:24.372
133 ms
m_R = 6.7
0.08 kg
Lyrid (49 km/s)
T
Observed by R.M. Suggs; detected by R.J. Suggs

Video

Calibration: Magnitude Equation

Parameters determined by observing stars with known magnitudes

$$R = -2.5\ log_{10}(S) - k'\ X + T\ (B\text{-}V) + ZP$$

R = Johnson-Cousins R magnitude

k' = extinction coefficient

X = airmass (zenith = 1.0)

T = color response correction term

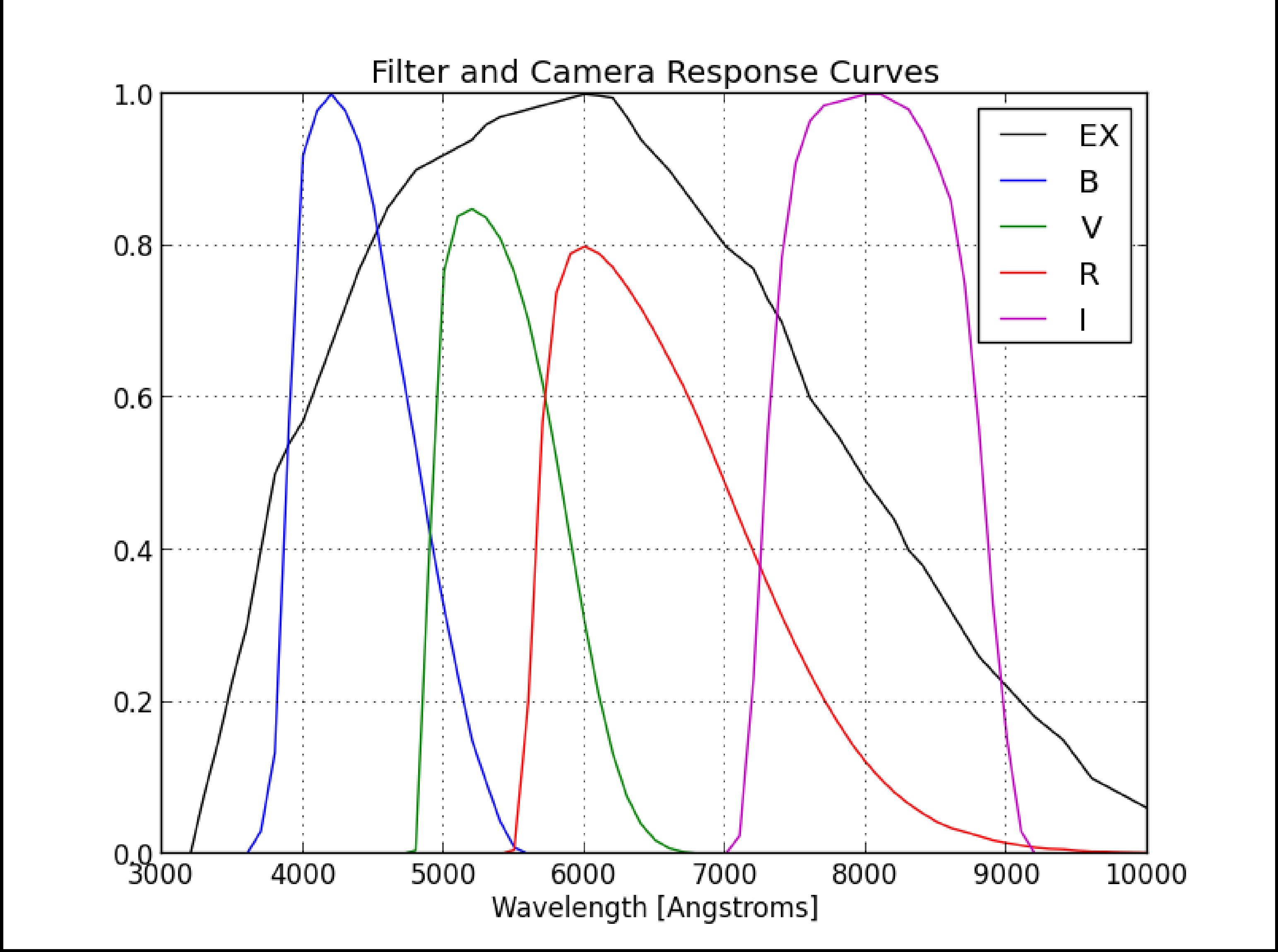
$(B\text{-}V)$ = color index

ZP = zero point for the night

$S = DN^{1/0.45}$ if camera gamma set to 0.45 which extends dynamic range (faintest flash to saturation)

DN = pixel value 0 – 255

Sony HAD EX response compared to Johnson-Cousins filters



Mass of the impactor assuming impact speed (shower or sporadic)

Luminous efficiency

$$\eta = 1.5\times10^{-3} \exp(-9.3^2/v^2)$$

v = impact speed in km/s

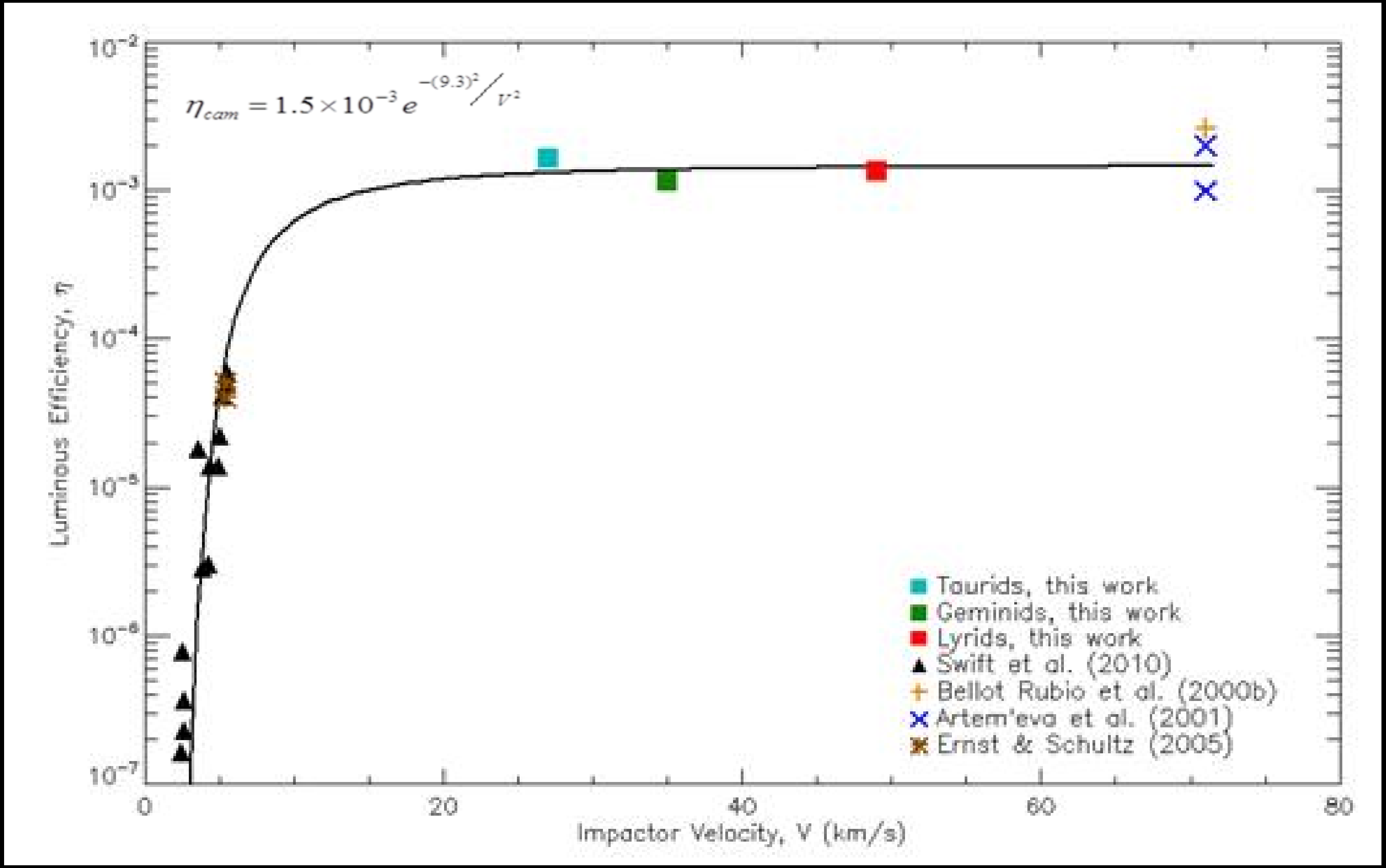
Kinetic Energy

$$KE = E_{lum} / \eta$$

Mass

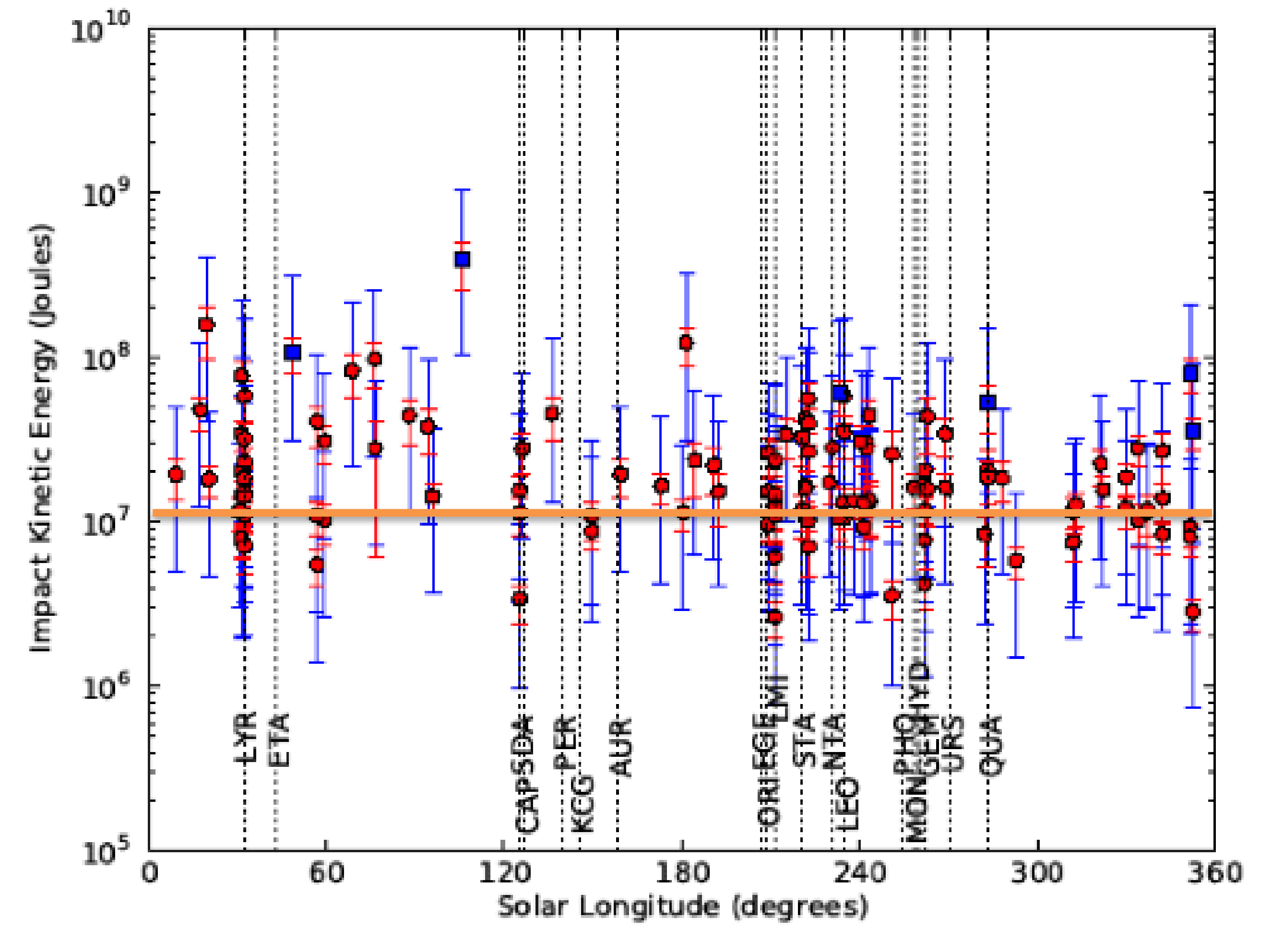
$$M = 2\,KE / v^2$$

Luminous Efficiency



From Moser et al. (2011)

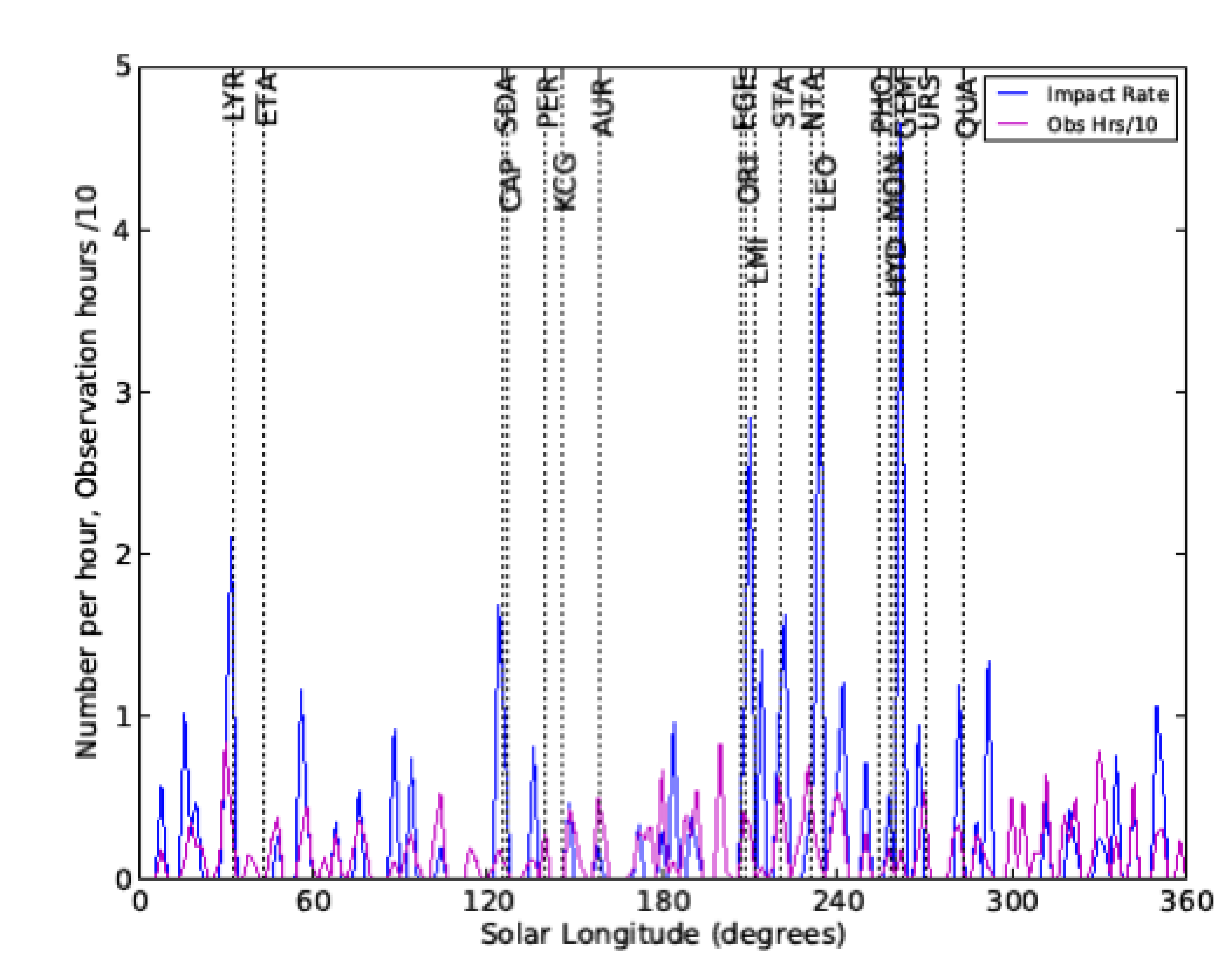
Impact Energies



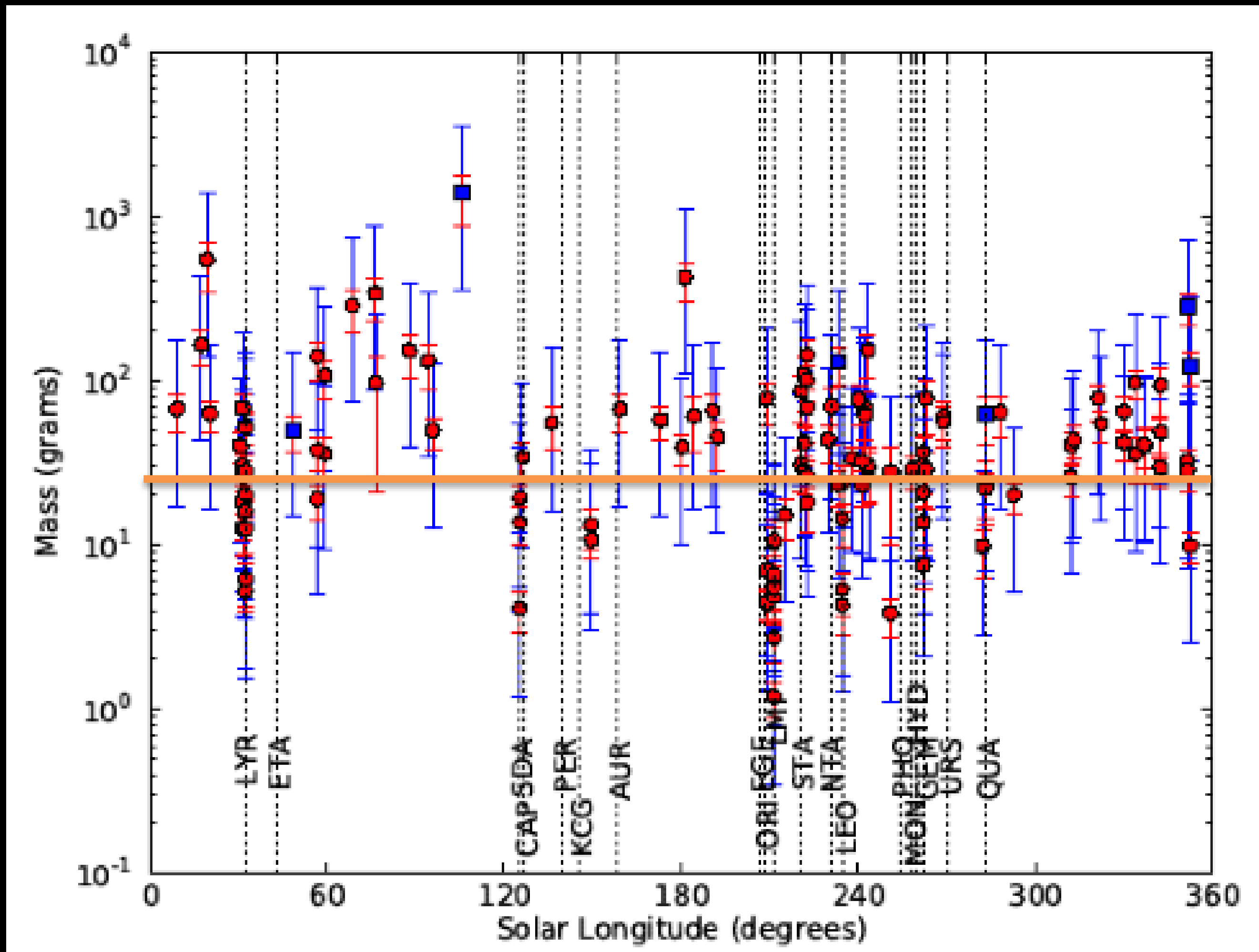
Red error bars - photometric uncertainty; Blue error bars - luminous efficiency uncertainty
Squares indicate saturation

The flux to a limiting energy of 1.05×10^{7} J is 1.03×10^{-7} km^{-2} hr^{-1}

Shower Correlation



Meteoroid Masses



Red error bars - photometric uncertainty; Blue error bars - range of reasonable luminous efficiencies
Squares indicate saturation

The flux to a limiting mass of 30 g is 6.14×10^{-10} m^{-2} yr^{-1}

Comparison with Grün Flux

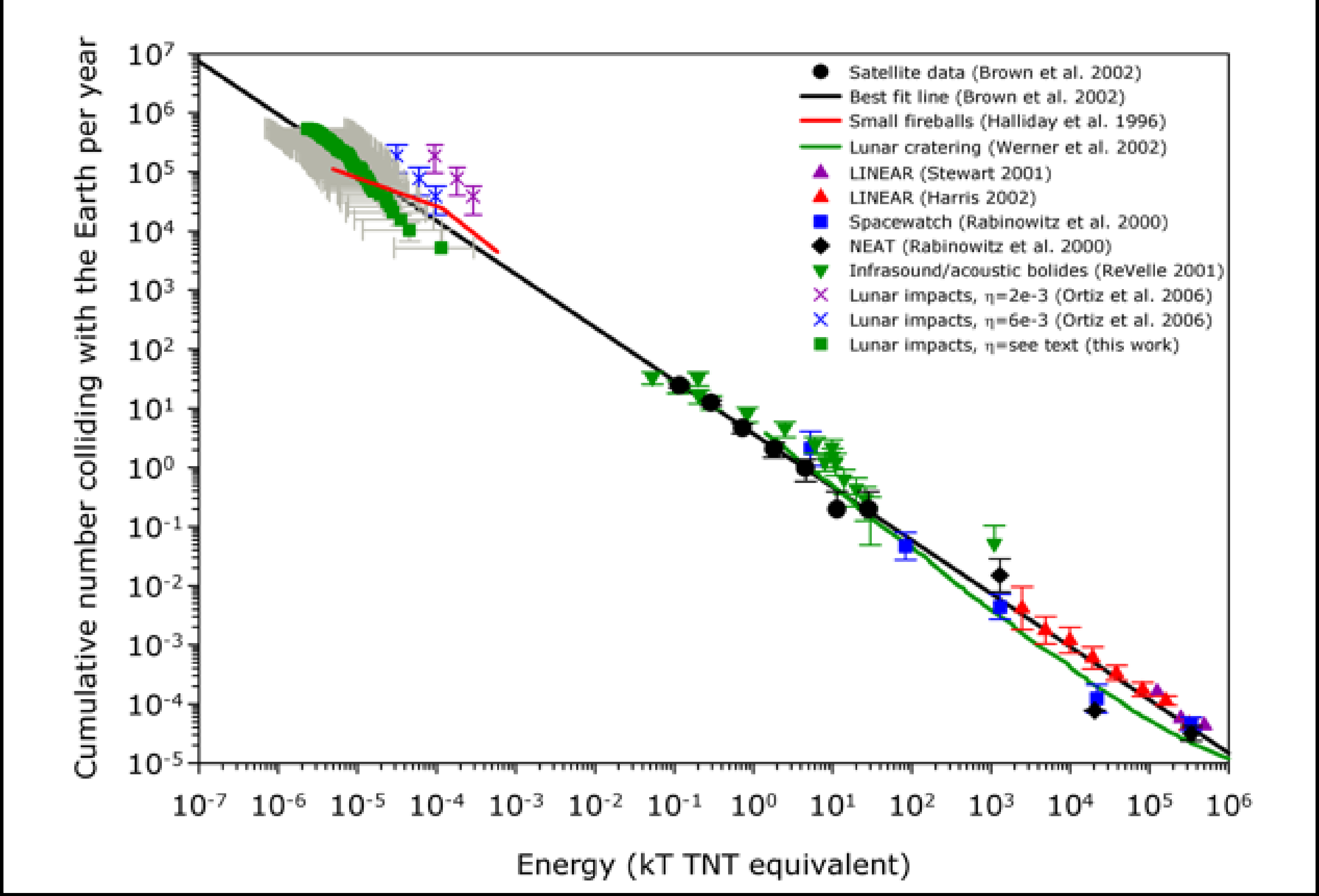
- For our completion limit of 30g we saw 71 impacts for a flux of

  $6.14 \times 10^{-10}\ m^{-2}\ yr^{-1}$

- The Grün et al. (1985) flux above a mass of 30g is

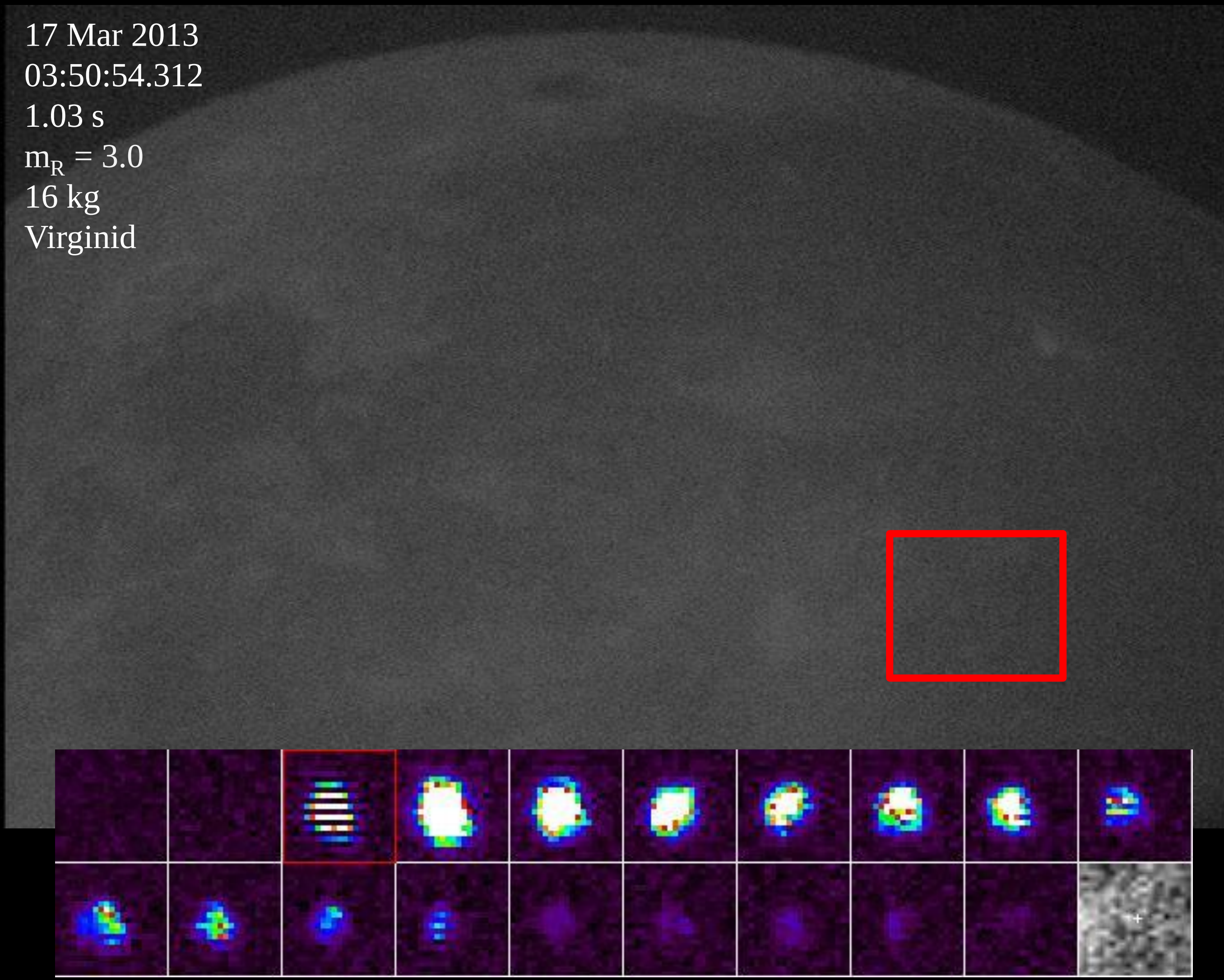
  $7.5 \times 10^{-10}\ m^{-2}\ yr^{-1}$

Impact Flux at Earth Compared with Other Measurements



After Brown et al. (2002)
with adjustments for gravitational focusing and surface area of Earth at 100km altitude

Bright flash on 17 March 2013



Observed by A. Kingery & R.M. Suggs; detected by R.J. Suggs

Flash info

Detected with two 0.35 m telescopes

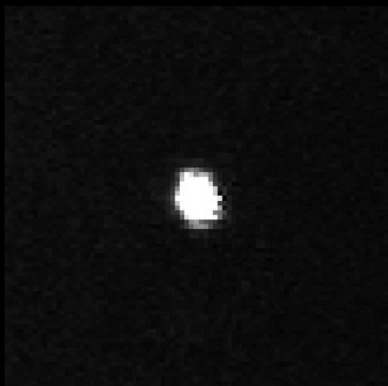
Watec 209H2 Ult monochrome CCD cameras

- Manual gain control
- No integration
- $\Gamma = 0.45$

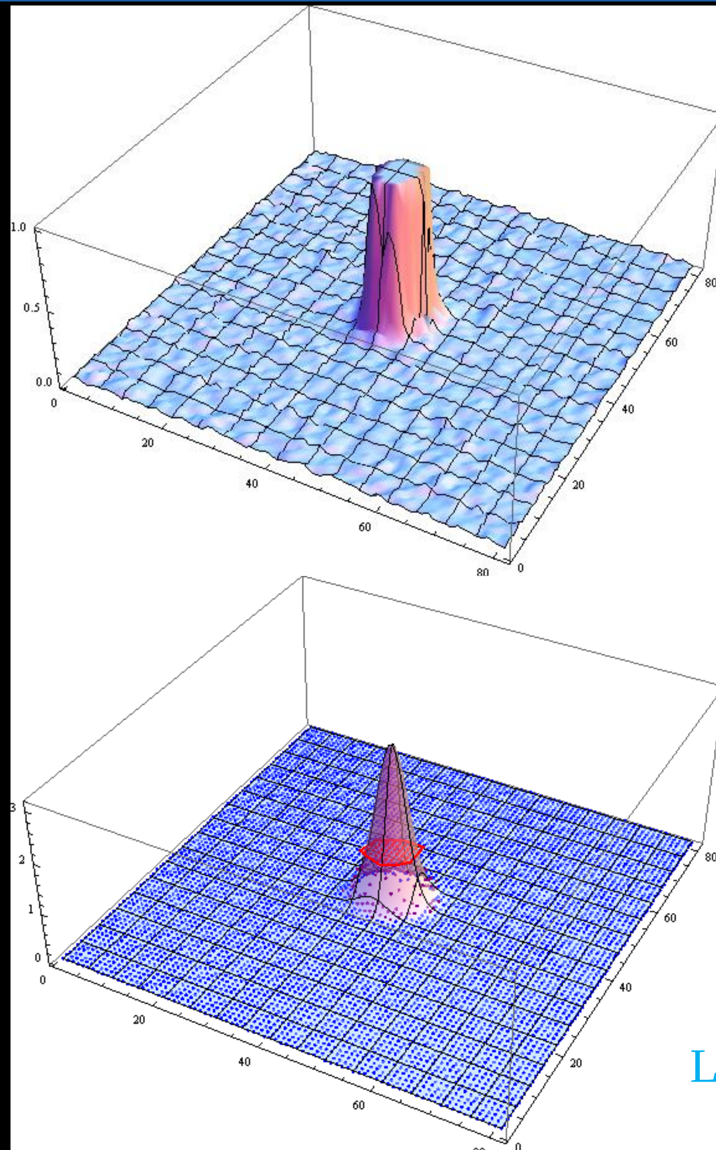
Interlaced 30 fps video

Saturated → needed saturation correction!

Peak R magnitude saturation correction



Photometry performed using comparison stars
(see Suggs et al. 2014)



Saturated

Peak $m_R = 4.9$

UNDERESTIMATED!

⬇

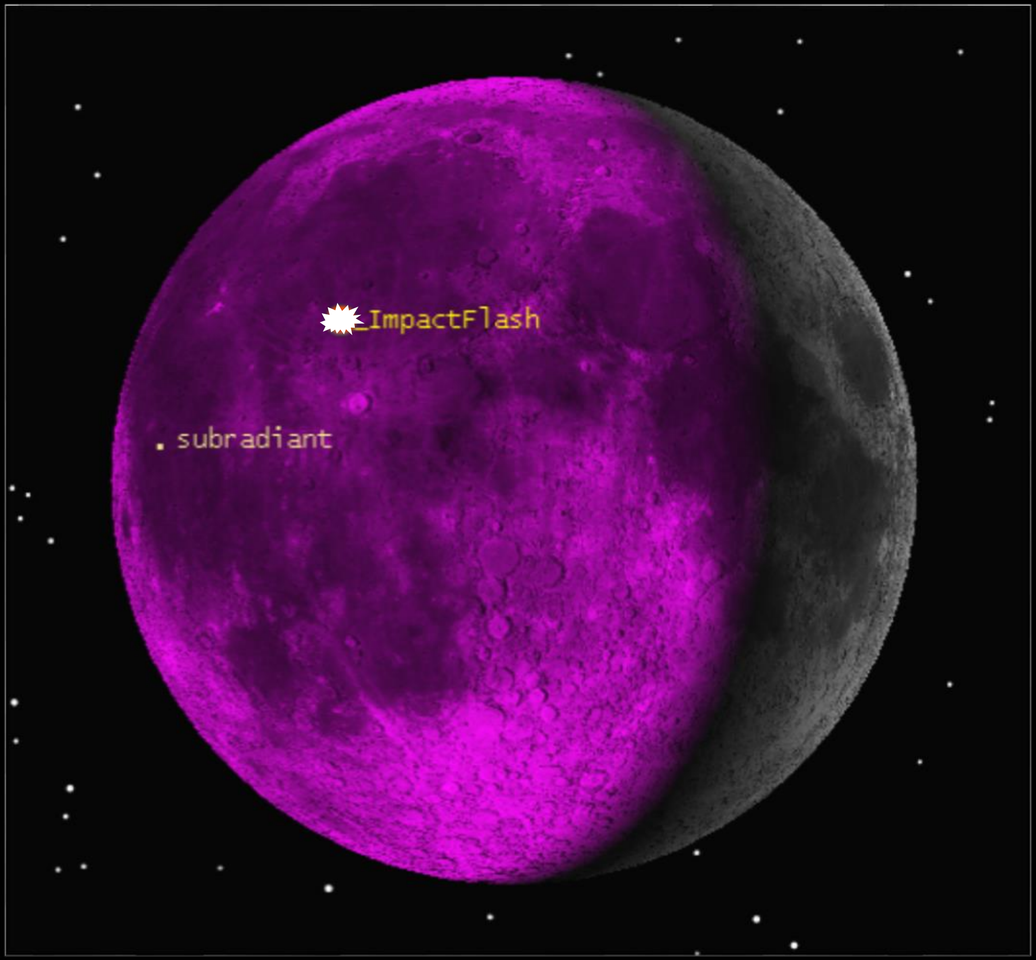
CORRECTION:

2D elliptical Gaussian fit to the unsaturated wings

Peak $m_R = 3.0 \pm 0.4$

Luminous energy = $7.1^{+3.9}_{-2.4} \times 10^6$ J

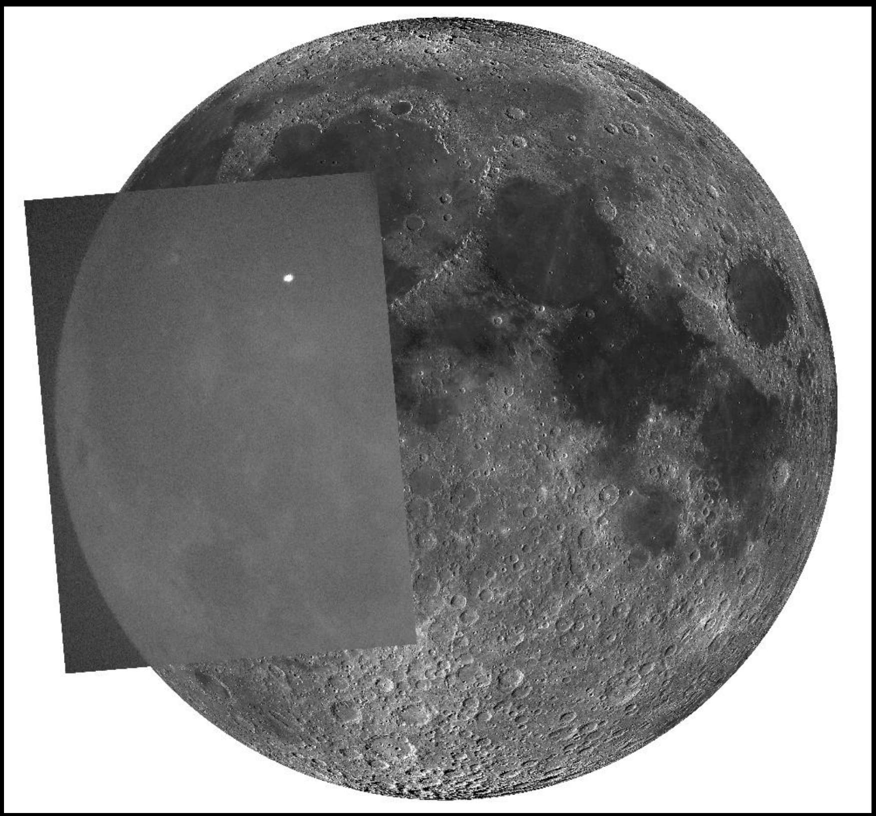
Favorable Virginid radiant geometry



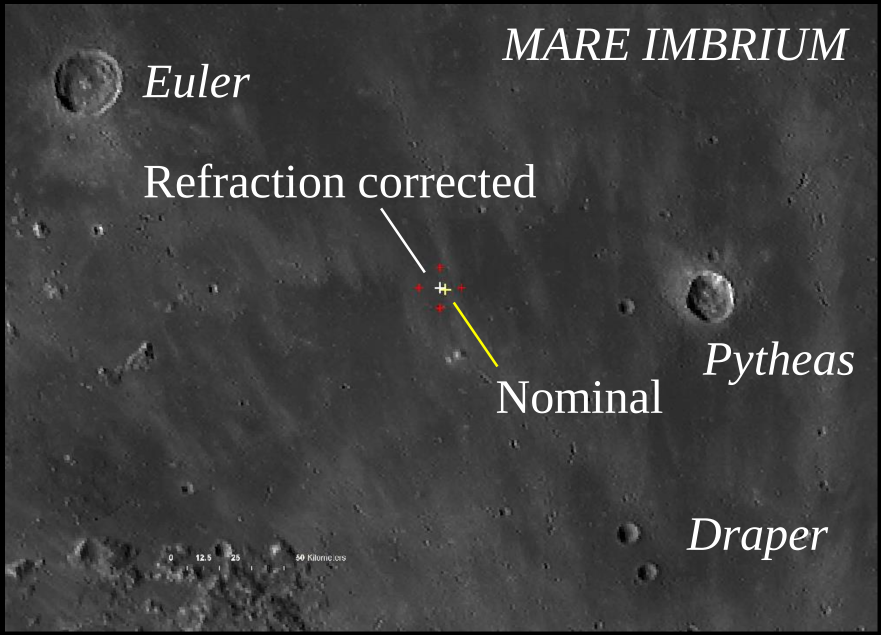
Pink indicates the portion of the moon visible to the radiant.
Impact angle ~56° from horizontal.

Mapping the impact location

LRO basemap



ArcMap was used to georeference the lunar impact following the geolocation workflow.



Nominal predicted crater position
20°.6644 N, 24°.1566 W

Refrac corr:

$$20°.6842^{+0.2585}_{-0.2581}\ \text{N},\ 24°.2277^{+0.2881}_{-0.2887}\ \text{W}$$

Impact crater found by LRO!
Robinson et al. (2014)

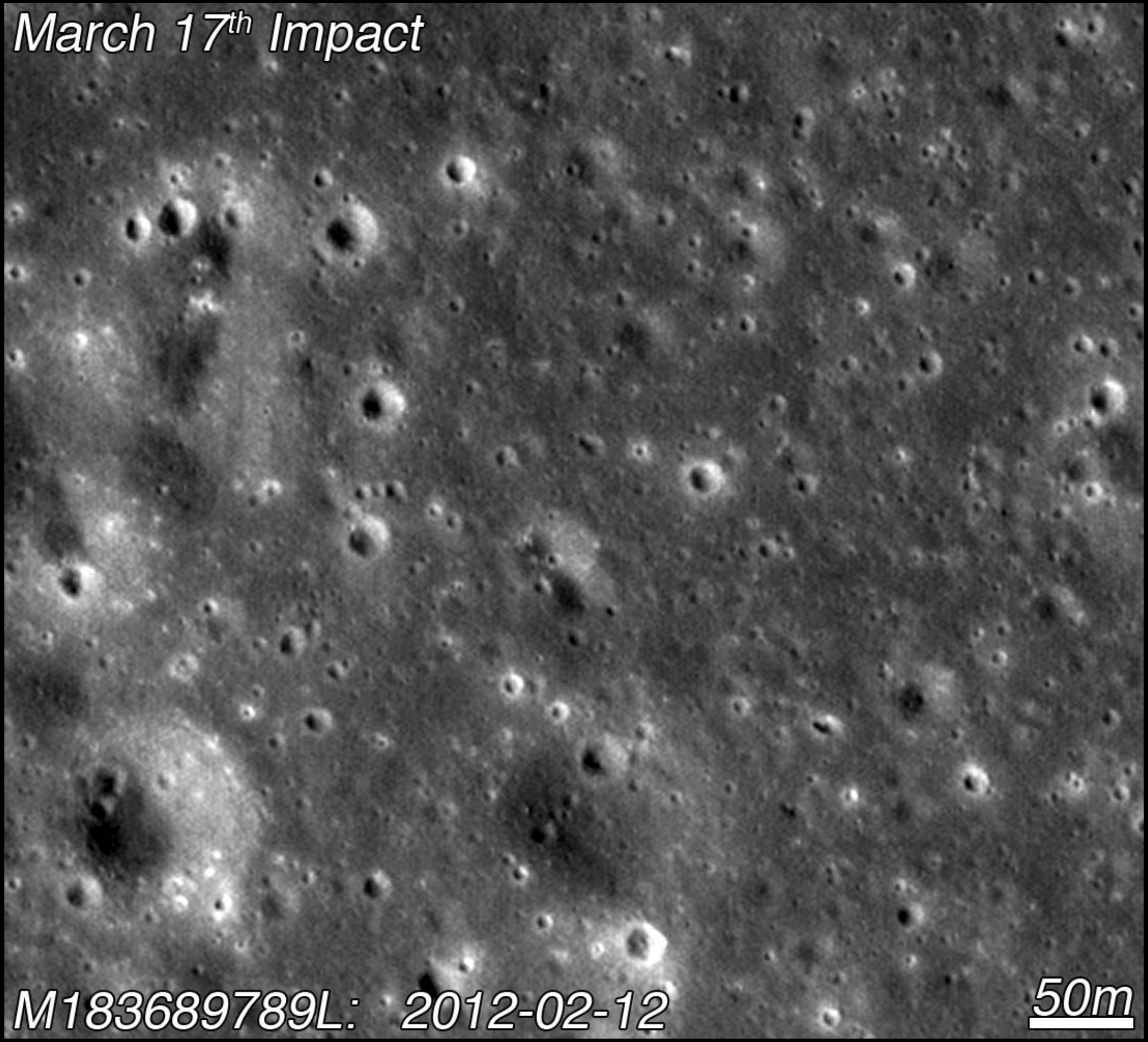


Image from Robinson (2013)

NASA/GSFC/Arizona State University

Features
- Fresh, bright ejecta
- Circular crater
- Asymmetrical ray pattern

Crater info
- Rim-to-rim diameter = 18 m
- Inner diameter = 15 m
- Depth ≈ 5 m

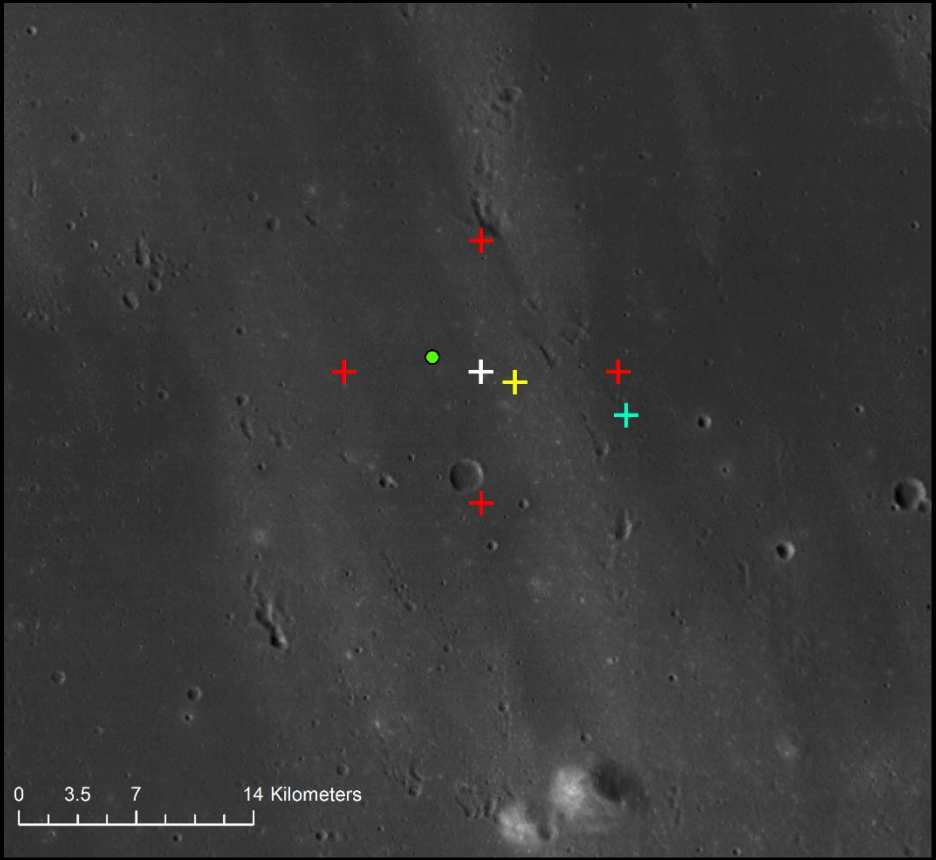
Actual crater location
- 20.7135°N, 24.3302°W

Impact Constraints

➡ Circular crater, impact angle constrained θ_h >15°

➡ Ejecta gives no azimuth constraint (Robinson, personal comm.)

Comparison of geolocation results to obs crater location



Method	Longitude (° W)	Latitude (° N)	Angular distance from observed (°)	Surface distance from observed (km)
Rough workflow	23.922	20.599	0.39875	12.096
Refined workflow	24.1566	20.6644	0.169665	5.1469
Refined, with refraction correction	$24.2277^{+0.2881}_{-0.2887}$	$20.6842^{+0.2585}_{-0.2581}$	0.100261	3.0415
LRO observed	24.3302	20.7135	-	-

Transient crater diameter estimates

Assumptions: Virginid v_{gfoc}=25.7 km/s, θ_h = 56°; ρ_t = 1500 kg/m^3 (regolith)

Model	Lum eff. η	KE ×10^9 (J)	Mass (kg)	ρ_p (kg/m^3)	D_{calc} (m)	D_{obs} (m)	% Err
Gault's crater scaling law (Gault 1974)	5×10^{-4} (Bouley et al. 2012)	14 [9.4,22]	42 [28,66]	1800	18.5 [16.5,21.1]	15	23%
				3000	20.2 [18.0,23.0]	15	35%
	1.3×10^{-3} (Moser et al. 2011)	5.4 [3.6,8.4]	16 [11,26]	1800	14.1 [12.5,16.0]	15	6%
				3000	15.3 [13.6,17.4]	15	2%
Holsapple's online calculator (Holsapple 1993)	5×10^{-4}	14 [9.4,22]	42 [28,66]	1800	12.2 [10.9,13.8]	15	19%
				3000	12.5 [11.1,14.2]	15	17%
	1.3×10^{-3}	5.4 [3.6,8.4]	16 [11,26]	1800	9.3 [8.3,10.5]	15	38%
				3000	9.5 [8.5,10.8]	15	37%

Two example values of η from the literature yield large ranges for KE and mass. Consequently, model results are highly dependent on luminous efficiency η.

Assuming a velocity dependent η = 1.3×10^{-3}, these model results are consistent with the observed crater diameters.

D_{calc} = 8-18 m transient crater
D_{calc} = 10-23 m rim-to-rim

D_{obs} = 15 m inner ('transient')
D_{obs} = 18 m rim-to-rim

Summary

- 10 years of routine observations have yielded nearly 400 lunar impact flashes confirmed by at least 2 telescopes
- Photometric calibration of the flashes and determination of luminous efficiency give impact energies
- Impact energy distribution compares favorably with other measurements
- The large impact of 17 March 2013 created a new crater observed by LRO – estimates of crater size were surprisingly close
- Ground-based observations of lunar impacts with accurate ejecta models can give us a handle on ejecta risk to lunar surface operations

Backup

References

Bessell, M.S., Castelli, F., Plez, B., 1998. Model atmospheres broad-band colors, bolometric corrections and temperature calibrations for O-M stars. Astron.m Astrophys. 333, 231-250.

Brown, P.G., Spalding, R., ReVelle, D., Tagliaferri, E., Worden, S., 2002. The flux of small near-Earth objects colliding with the Earth. Nature 420, 294-296.

Grün, E., Zook, H.A., Fechtig, H., Giese, R.H., 1985. Collisional balance of the meteoritic complex, Icarus 62, 244-272.

Moser, D.E. , Suggs, R.M., Swift, W.R., Suggs, R.J., Cooke, W.J., Diekmann, A.M., Kohler, H.M., 2011., "Luminous Efficiency of Hypervelocity Meteoroid Impacts on the Moon Derived from the 2006 Geminids, 2007 Lyrids, and 2008 Taurids", Meteoroids 2010 Proceedings (NASA CP-2011-216469)

Nemtchinov, I.V., Shuvalov, V.V., Artemieva, N.A., Ivanov, B.A., Kosarev, I.B., Trubetskaya, I.A., 1998. Light impulse created by meteoroids impacting the Moon. Lunar Planet. Sci. XXIX. Abstract 1032.

Suggs, R.M., Moser, D.E., Cooke, W.J., Suggs, R.J., 2014. The flux of kilogram-sized meteoroids from lunar impact monitoring. Icarus 238, 23-36.

Luminous energy from impact peak magnitude

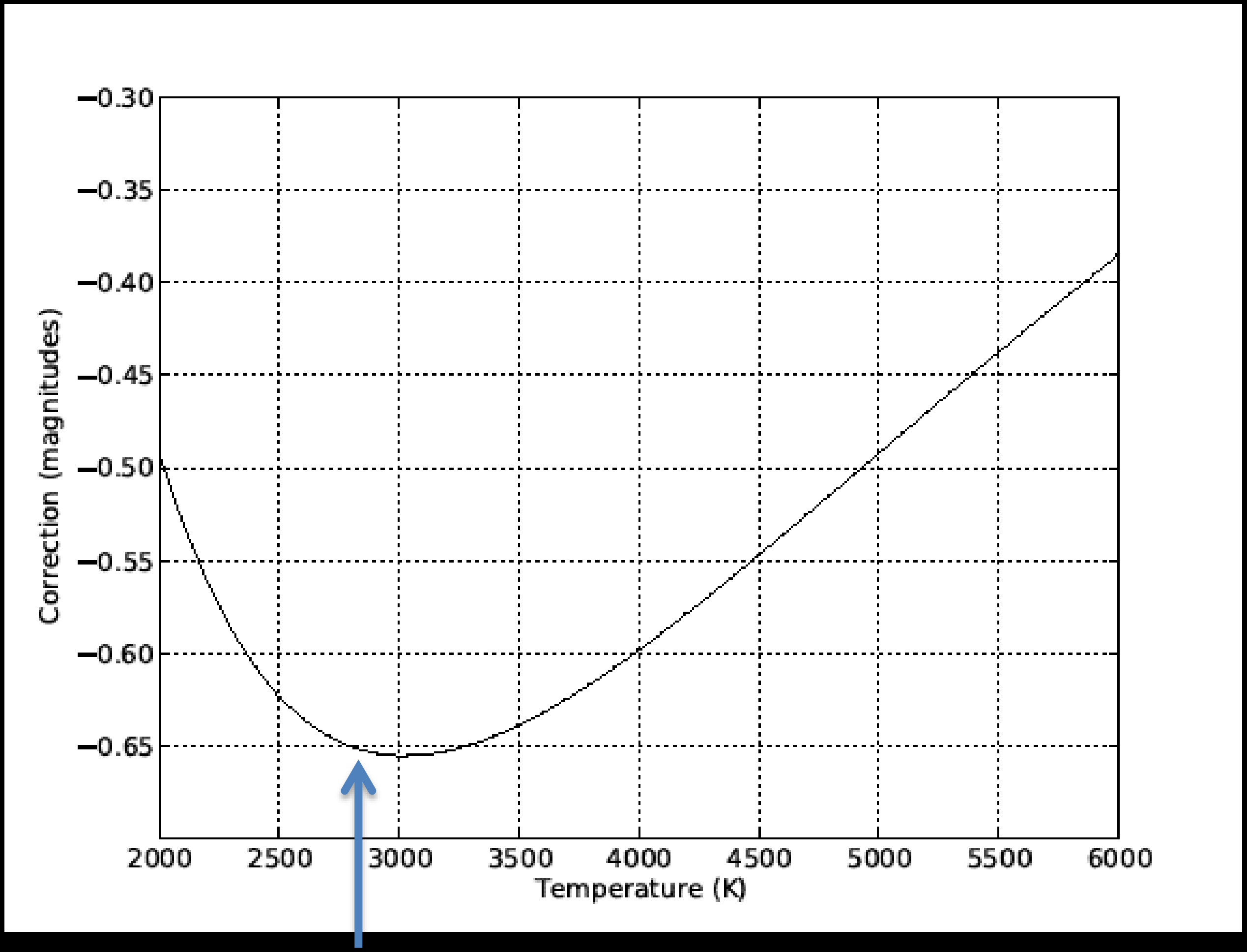
$$E_{lum} = f_\lambda \, \Delta\lambda \; f \; \pi \; d^2 \; t$$ Joules

- E_{lum} = luminous energy
- $\Delta\lambda$ = filter half power width, 1607 Ångstroms for R
- f = 2 for flashes near the lunar surface
- d = distance from Earth to the Moon
- t = exposure time, 0.01667 for a NTSC field

$$f_\lambda = 10^{-7} \times 10^{(-R + 21.1 + zp_R)/2.5}$$ J cm^{-2} s^{-1} Å^{-1}

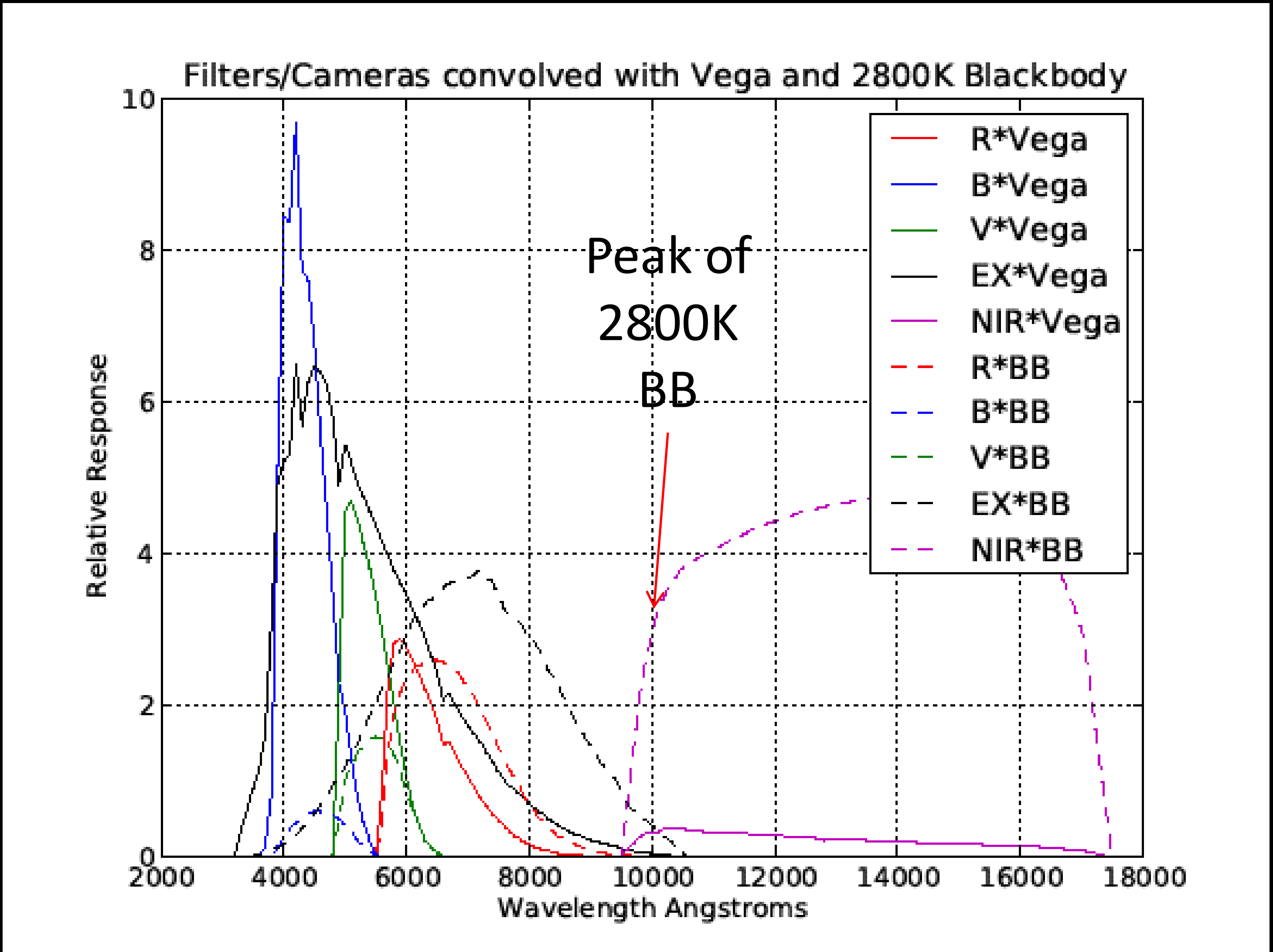
- R = the R magnitude
- zp_R = 0.555, photometric zero point for *R* (not the same as *ZP* in magnitude equation) from Bessell et al. (1998)

Correction from HAD EX to R filter vs blackbody temperature
R-EX replaces T(B-V)

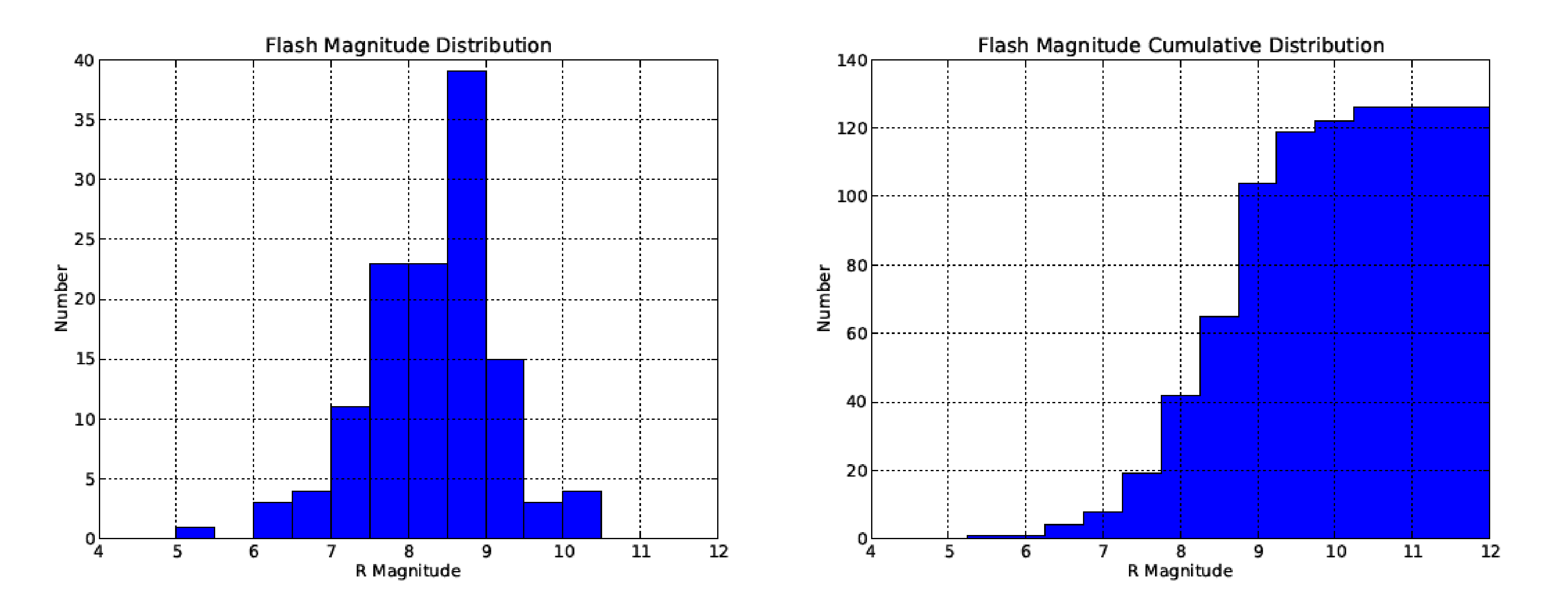


Theoretical peak flash temperature 2800K Nemtchinov et al. (1998)

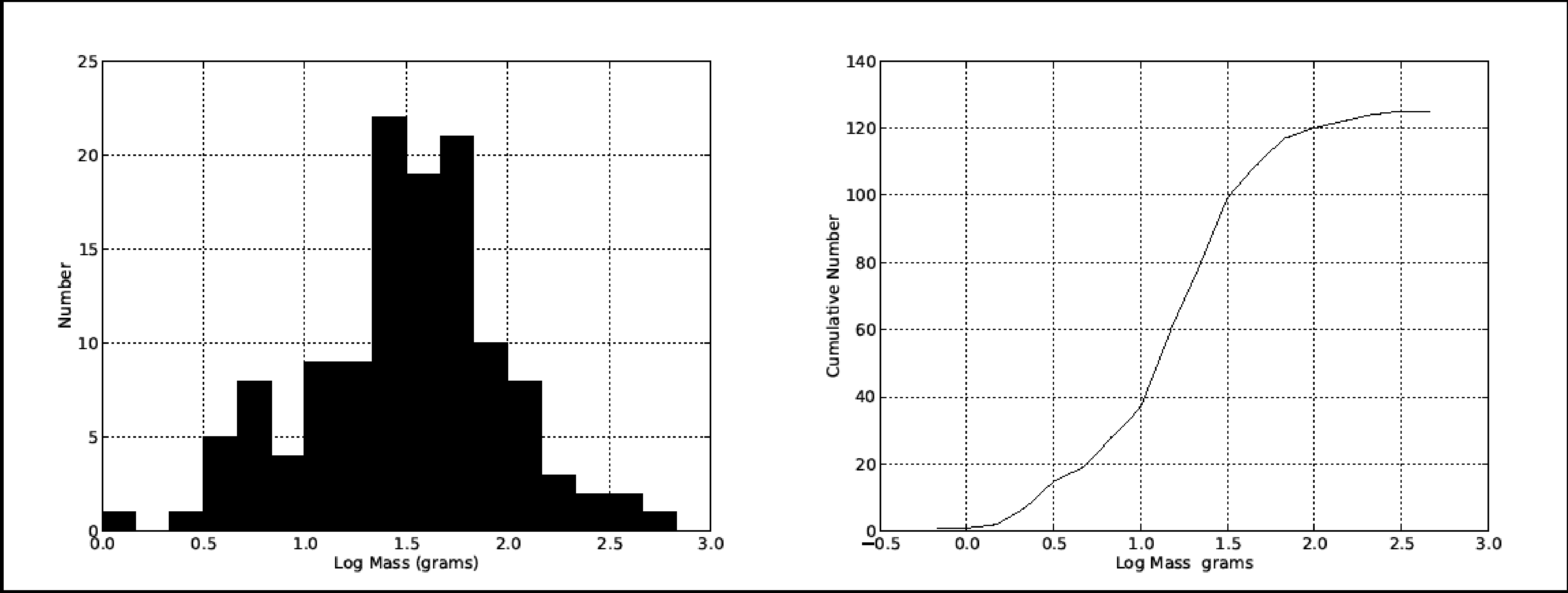
Filter and camera responses depend on color of object



Limiting Magnitude

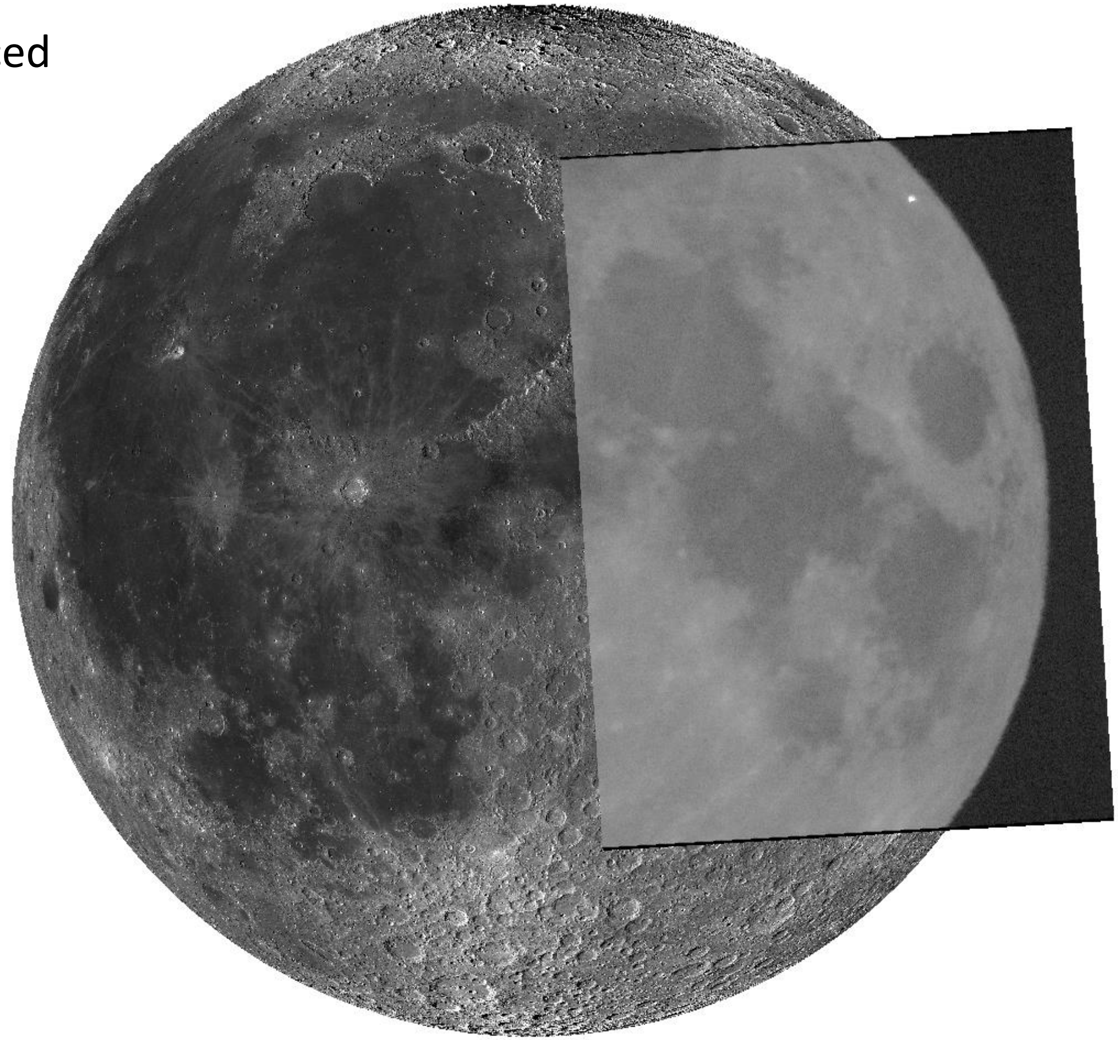


Limiting Mass



4. Georeference flash image

Final georeferenced impact image

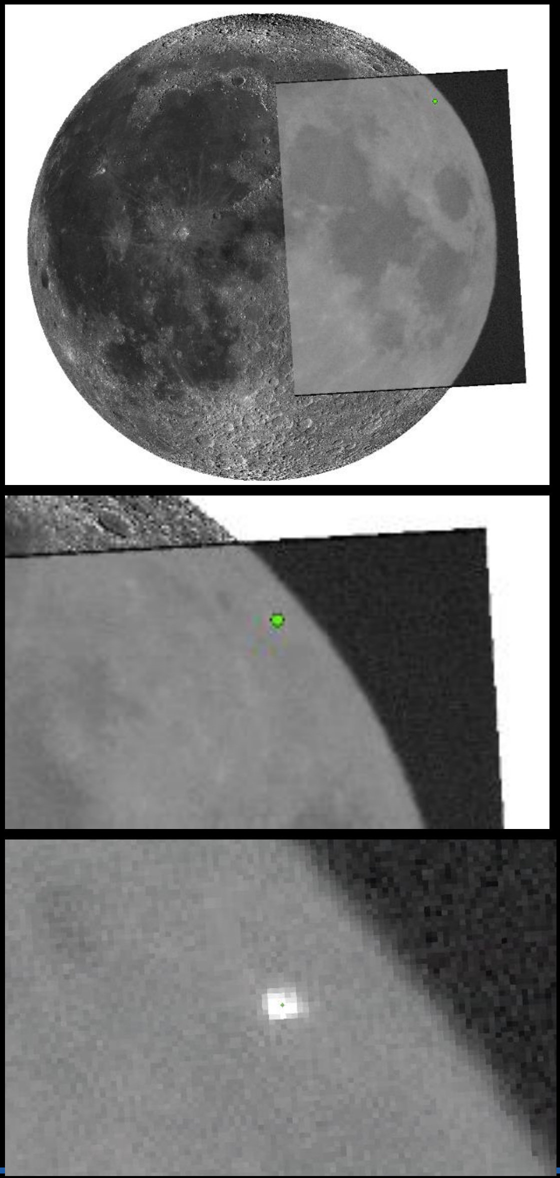


6. Determine flash location

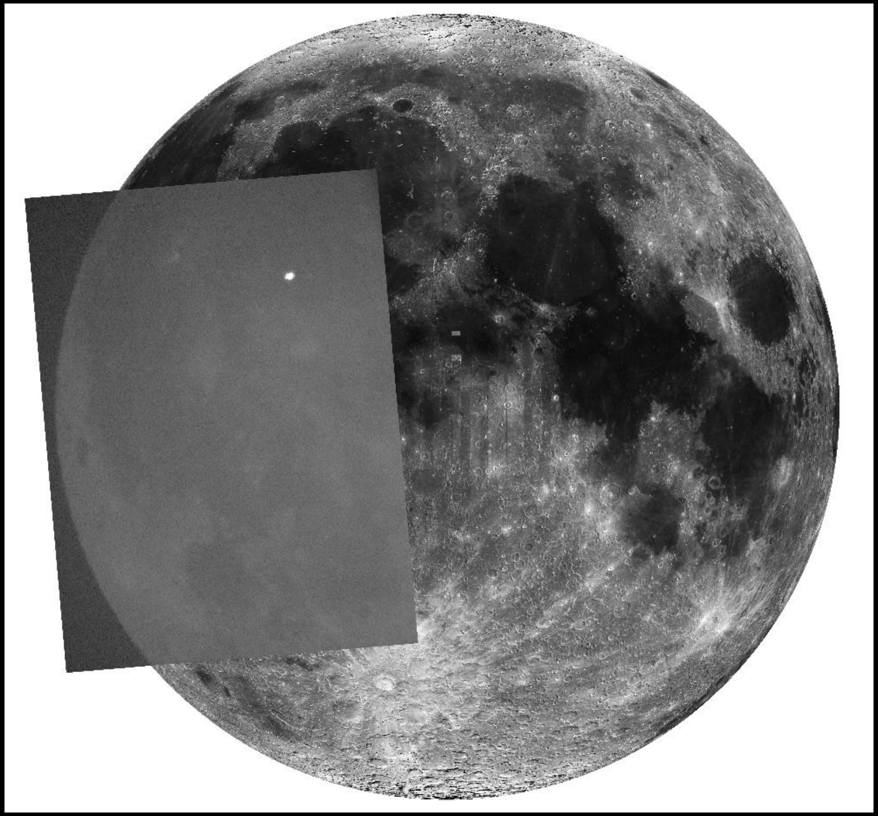
- Input flash location ($\bar{x}_f{}'$,$\bar{y}_f{}'$) to ArcMap's "Go to XY" tool

- Read & record selenographic coordinates (λ, φ) transformed by ArcMap

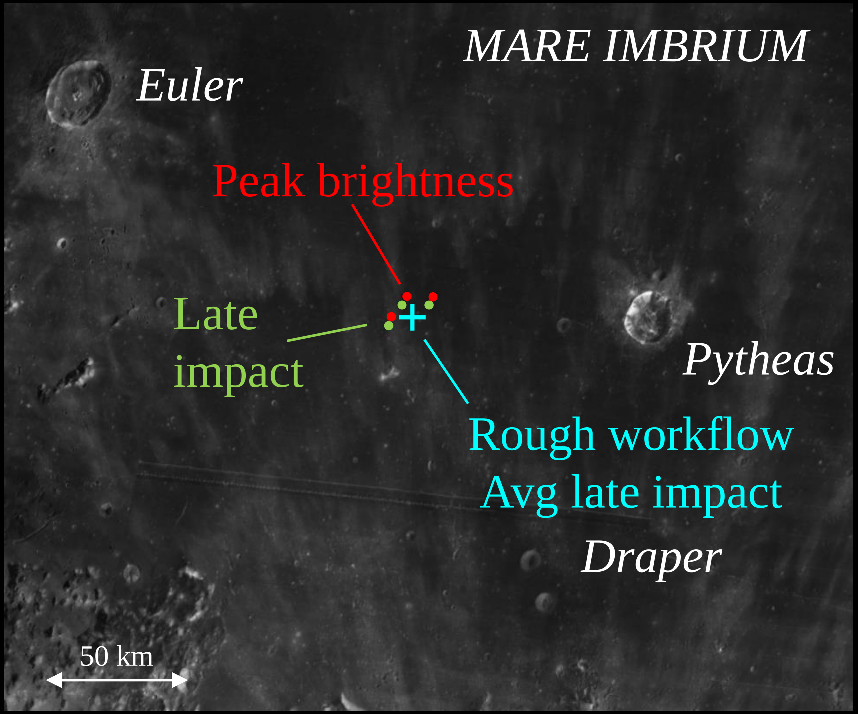
- Place marker at flash location, add point to database and shapefile



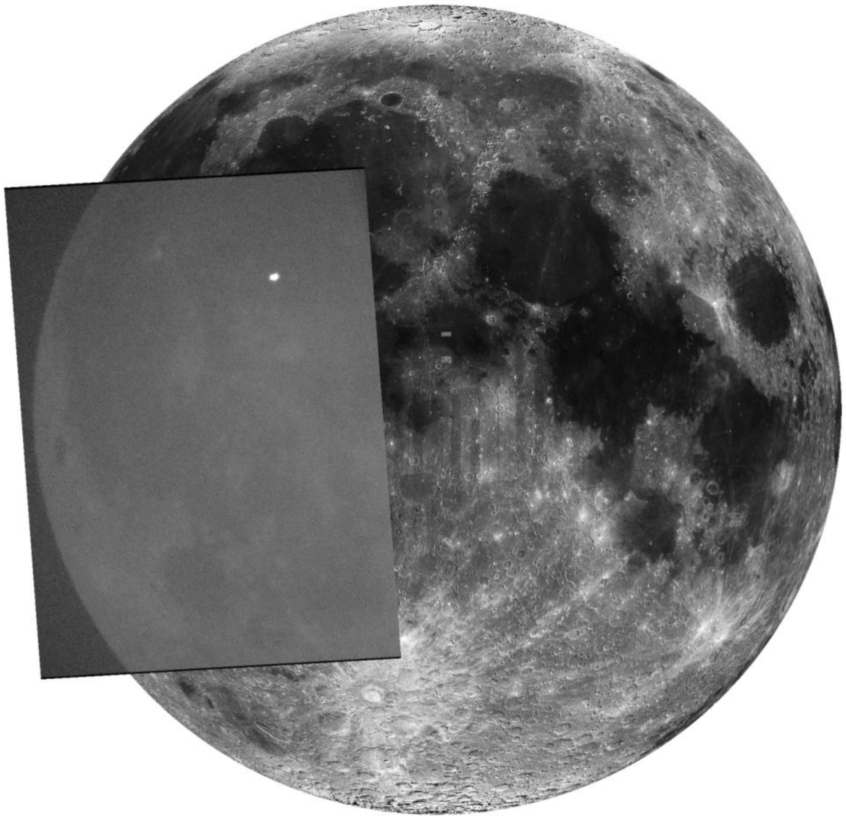
Mapping the impact location
"Rough workflow"

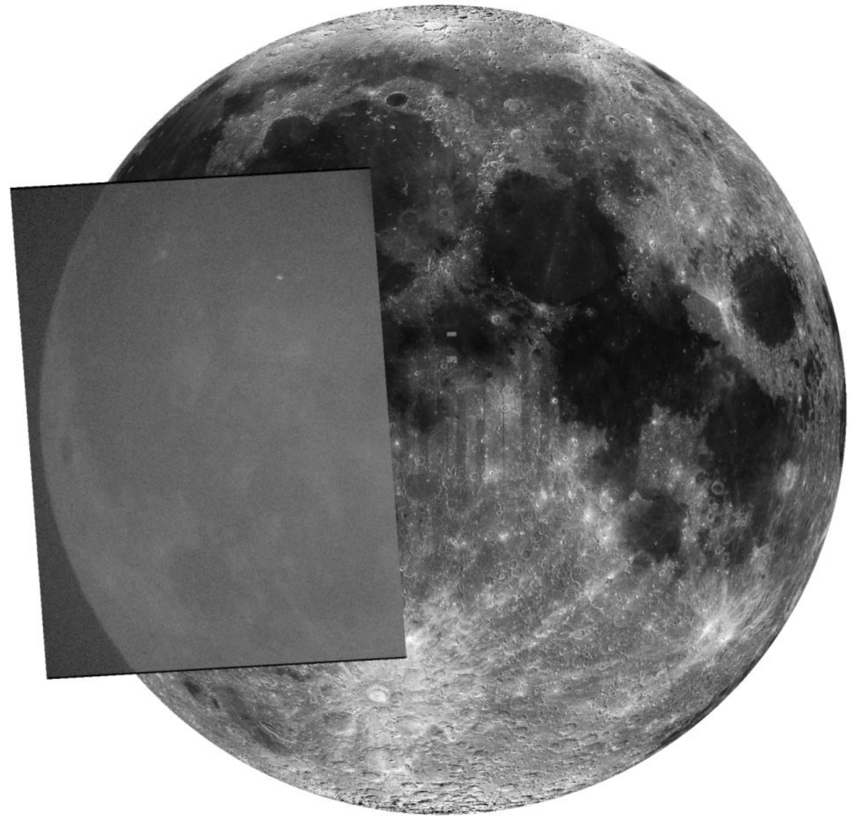


ArcMap was used to georeference the lunar impact 3 times, at peak brightness and late impact.



Mapping the impact location

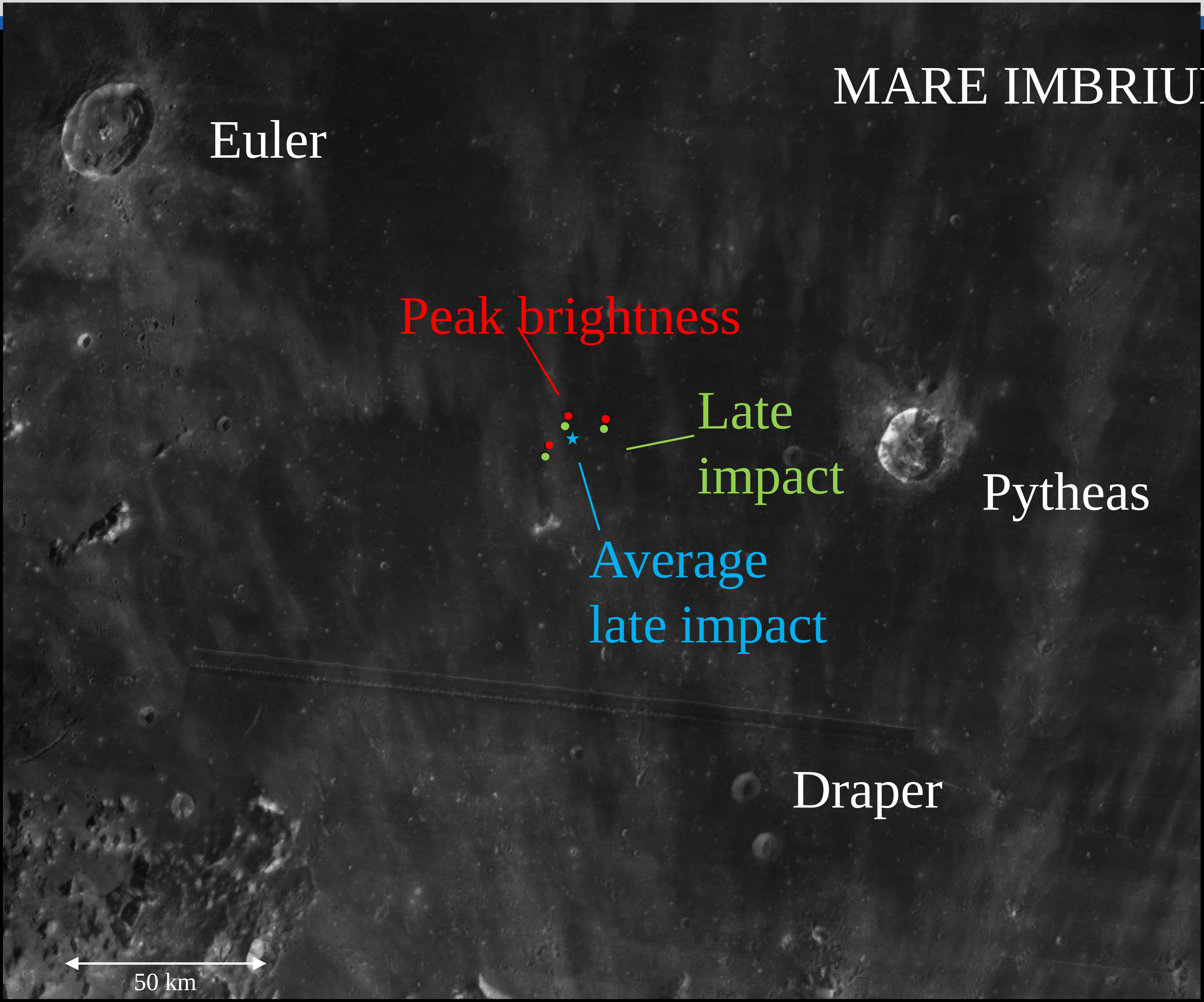




[redacted]

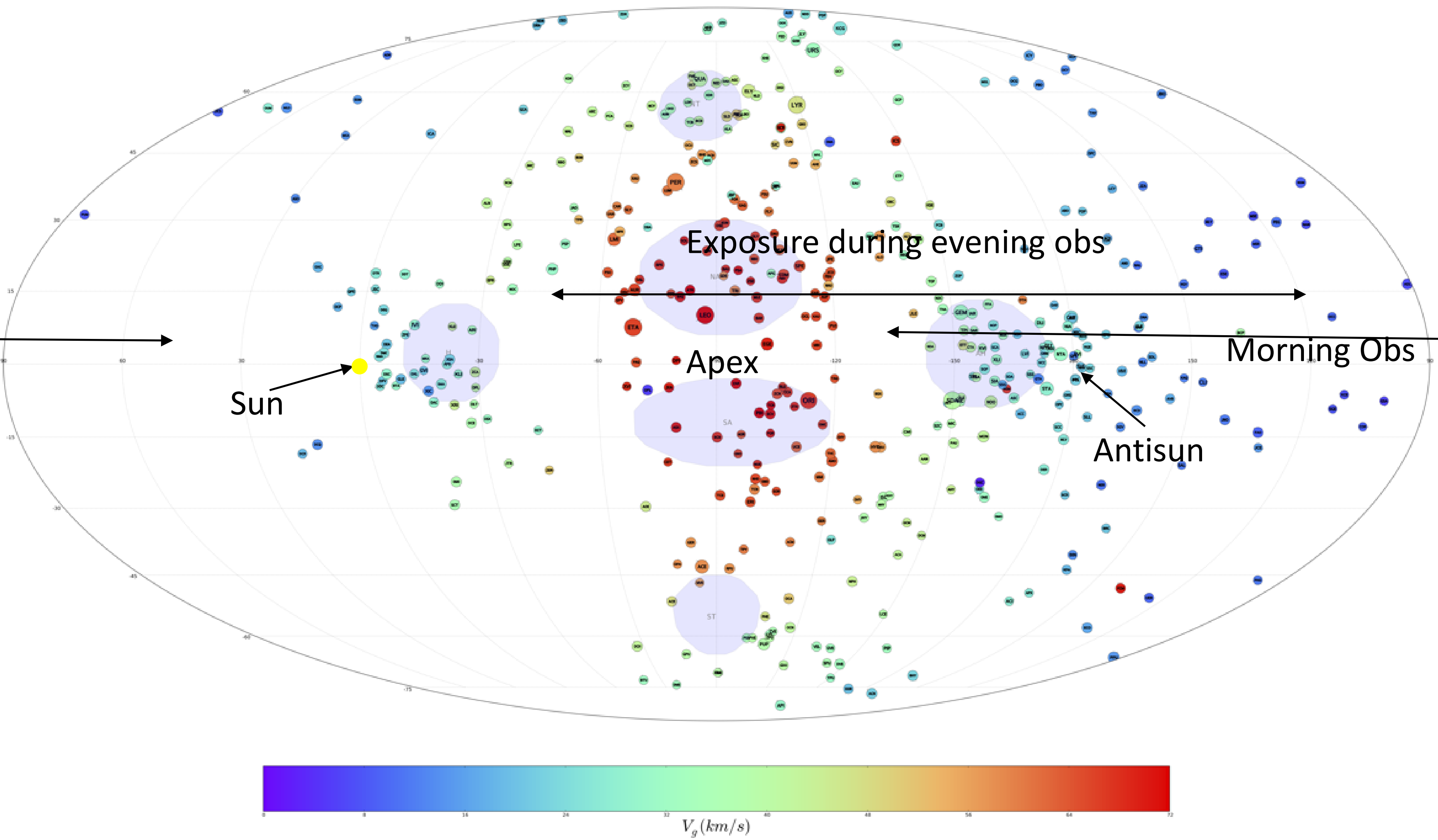
Impact location

Results of several attempts with different features and frames



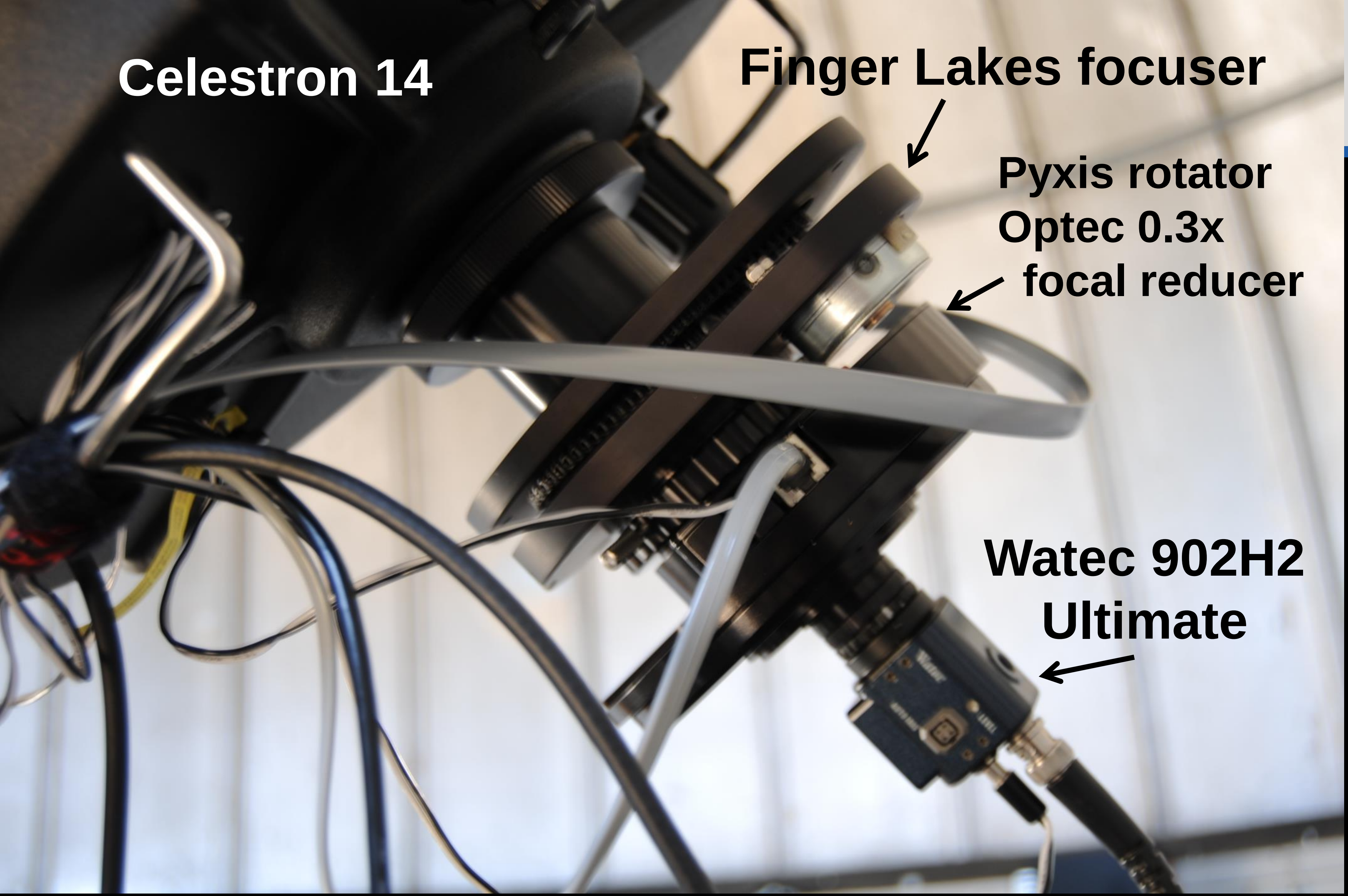
Average location: 20.599 ± 0.172° N, 23.922 ± 0.304° W

Meteor Shower and Sporadic Source Radiants



Equipment

- Telescopes – 14 inch (0.35m), have also used 0.5m and 0.25m
- Camera – B&W video 1/2inch Sony HAD EX chip (Watec 902H2 Ultimate is the most sensitive we have found)
- Digitizer – preferably delivering Sony CODEC .AVI files if using LunarScan (Sony GV-D800, many Sony digital 8 camcorders, Canopus ADVC-110)
  - This gives 720x480 pixels x8 bits
- Time encoder – GPS (Kiwi or Iota)
  - Initially used WWV on audio channel with reduced accuracy
- Windows PC with ~500Gb fast harddrive (to avoid dropped frames)
  - Firewire card for Sony or Canopus digitizers


Celestron 14
Finger Lakes focuser
Pyxis rotator
Optec 0.3x
focal reducer
Watec 902H2
Ultimate

Software we have used

- WinDV for recording windv.mourek.cz
- LunarScan detection software (Gural will discuss) www.lunarimpacts.com/lunarimpacts.htm
- VirtualDub for slicing out relevant sections of video and converting to "Old AVI" for reading into Limovie www.virtualdub.org/download.html
- Limovie for checking photometry of flashes and calibration stars www005.upp.so-net.ne.jp/k_miyash/occ02/limovie_en.html
- MaximDL can convert video segments to FITS
  - Don't use the aperture photometry tool until after each pixel is gamma corrected by $S = DN^{1/0.45}$ if camera gamma set to 0.45
- Python and Pyraf may be used for aperture photometry www.stsci.edu/institute/software_hardware/pyraf/current/download