Large Meteoroid Impact on the Moon 17 March 2013

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7-year observing program

Goal: Monitor the Moon for impact flashes produced by meteoroids striking the lunar surface.

Observation from MSFC

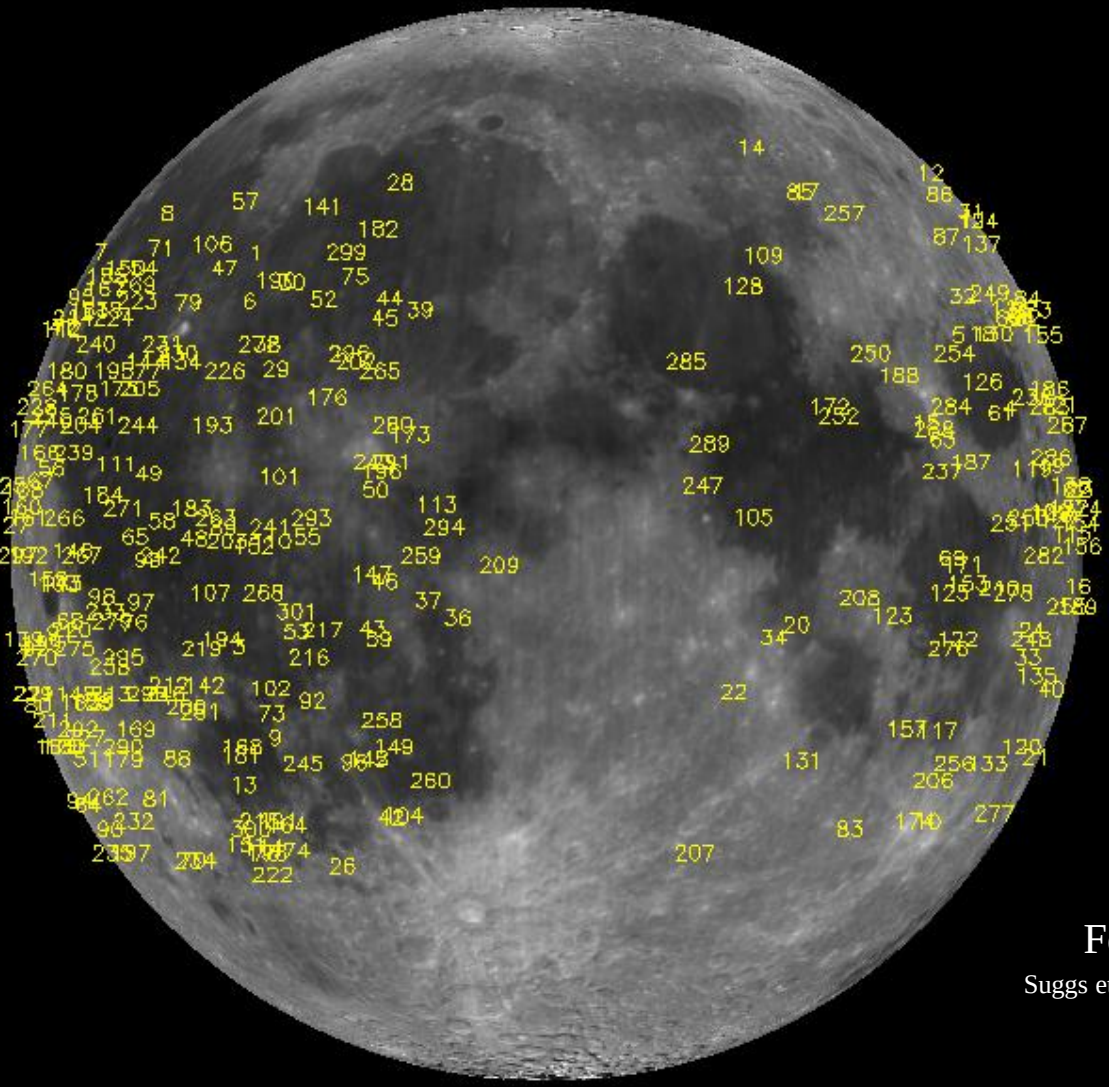
Field of View

- Two 0.35m telescopes simultaneously
- Black & white CCD video cameras
- Interleaved 30fps video digitized, recorded
- Video analyzed with custom software

- FOV covers approx. 20 arcmin
- 4×10^6 km^2 on the leading or trailing edge
- Observing when illumination 10-50%
- Maximum 10 observing nights/month

300+ lunar impacts observed

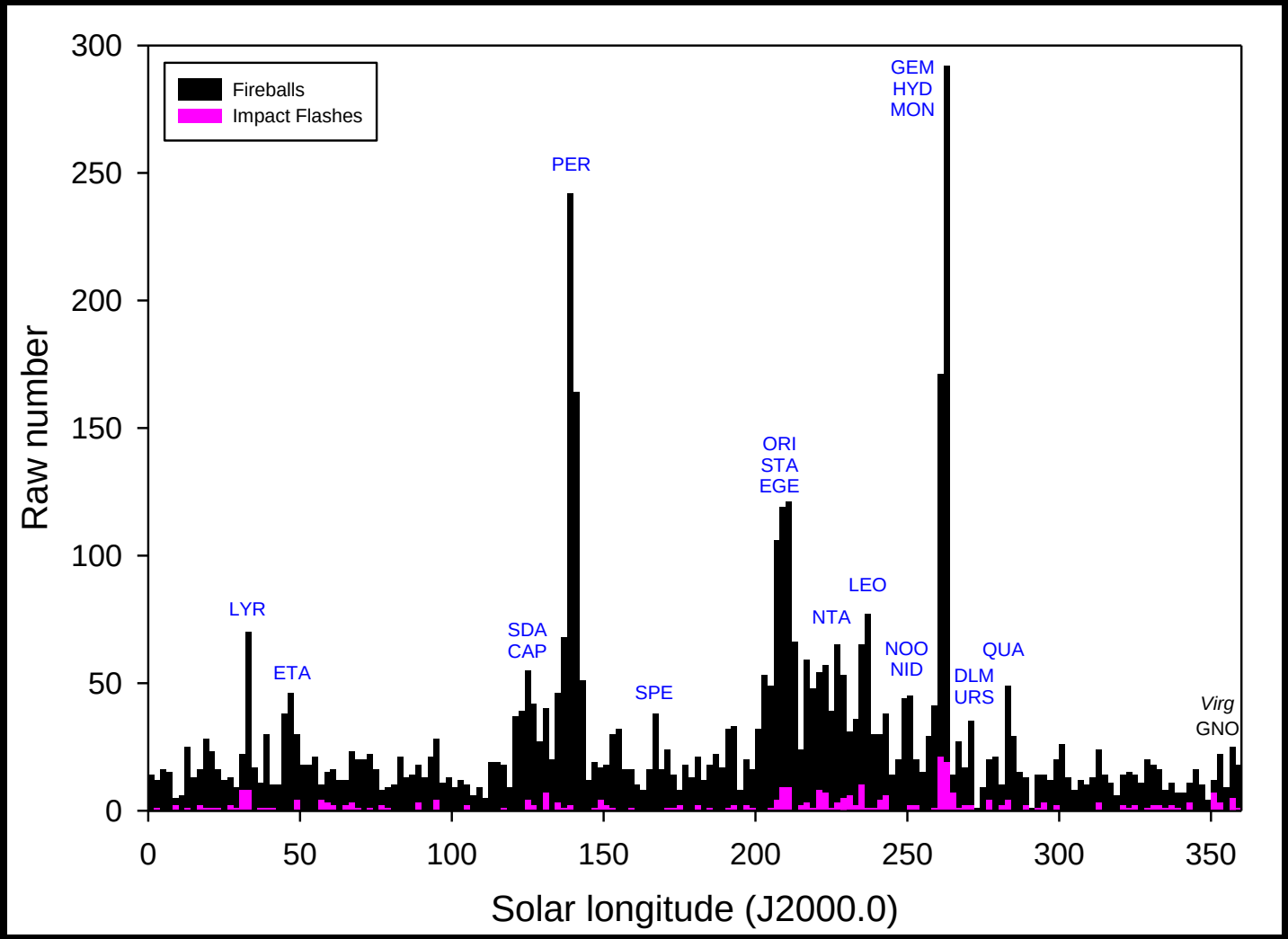
2005-present



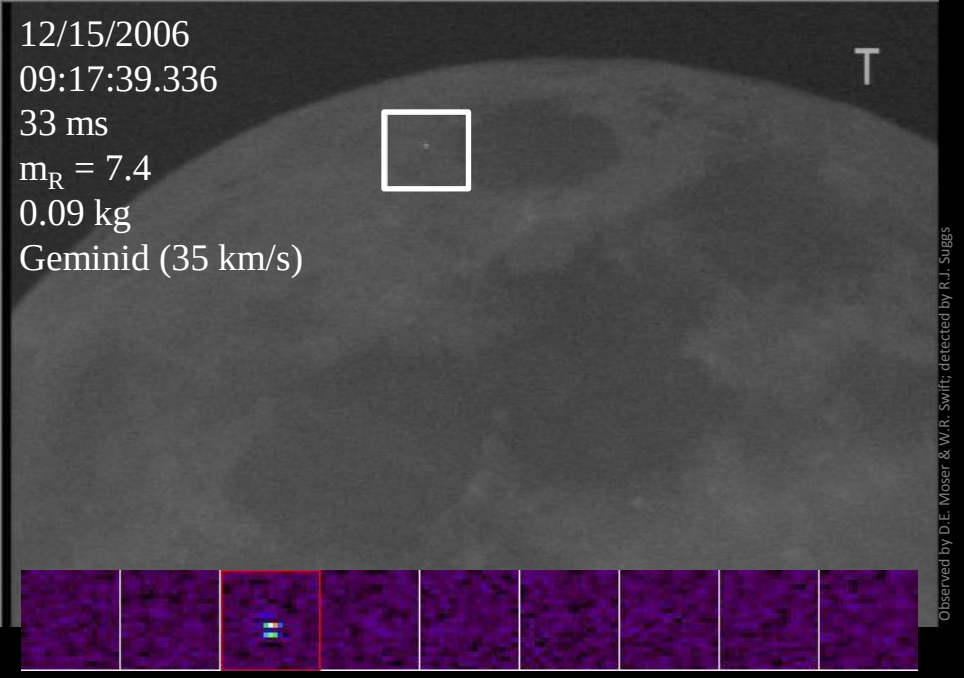
For more info:

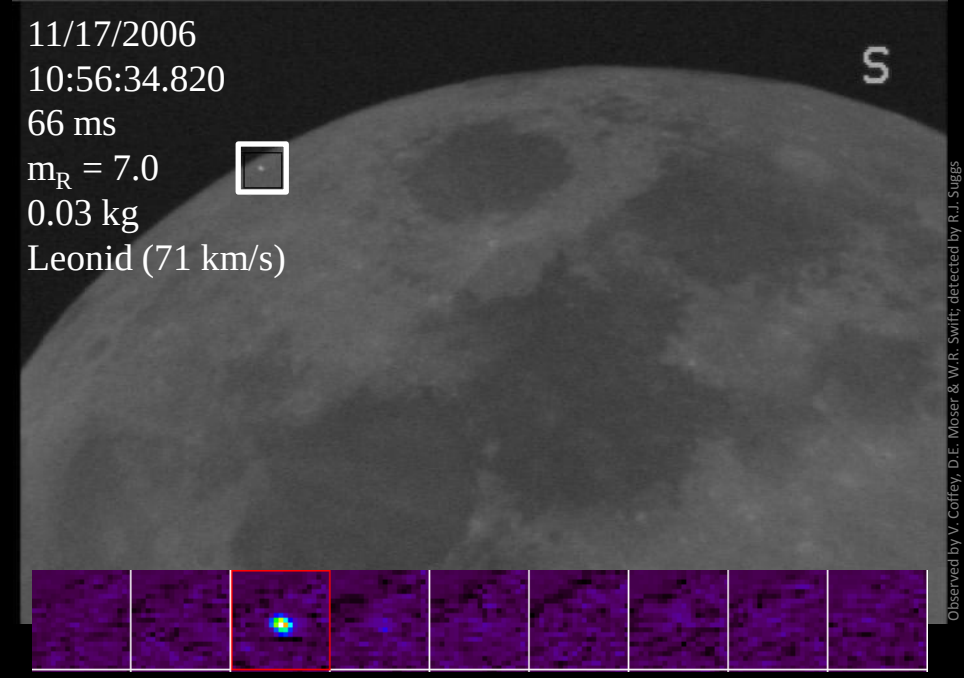
Suggs et al. (2013) to be submitted
Suggs et al. (2011)
Suggs et al. (2007)

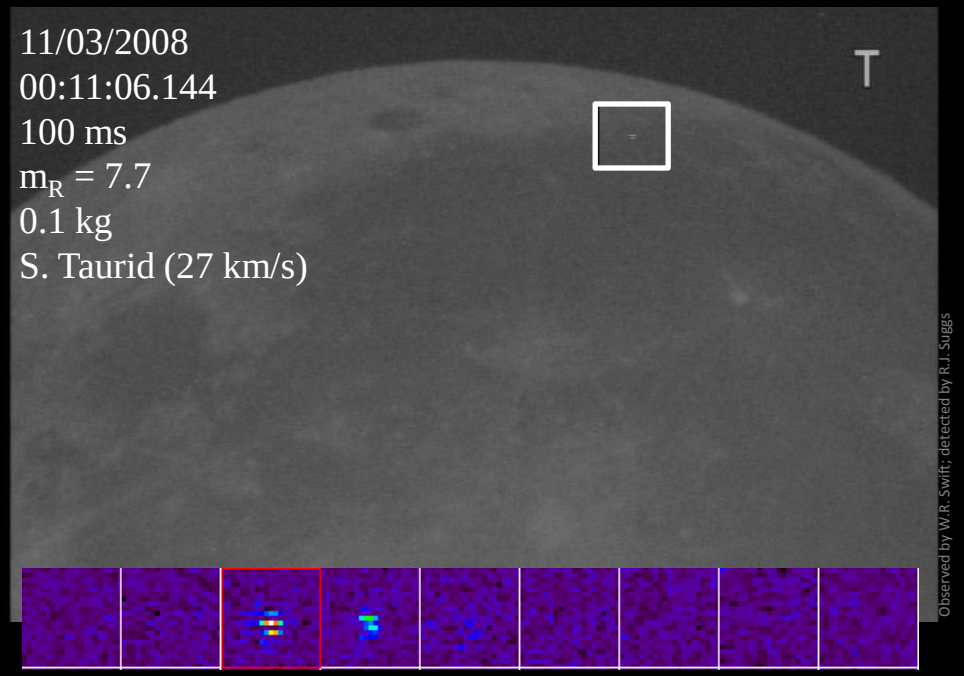
Comparison to meteor shower data

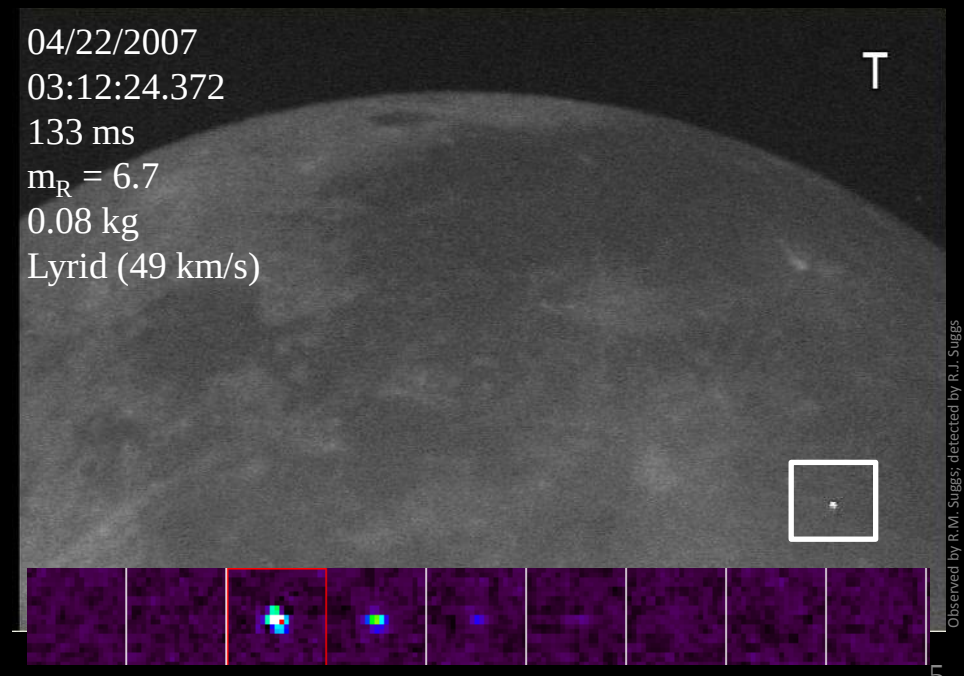


Impact flashes are often associated with meteor showers.

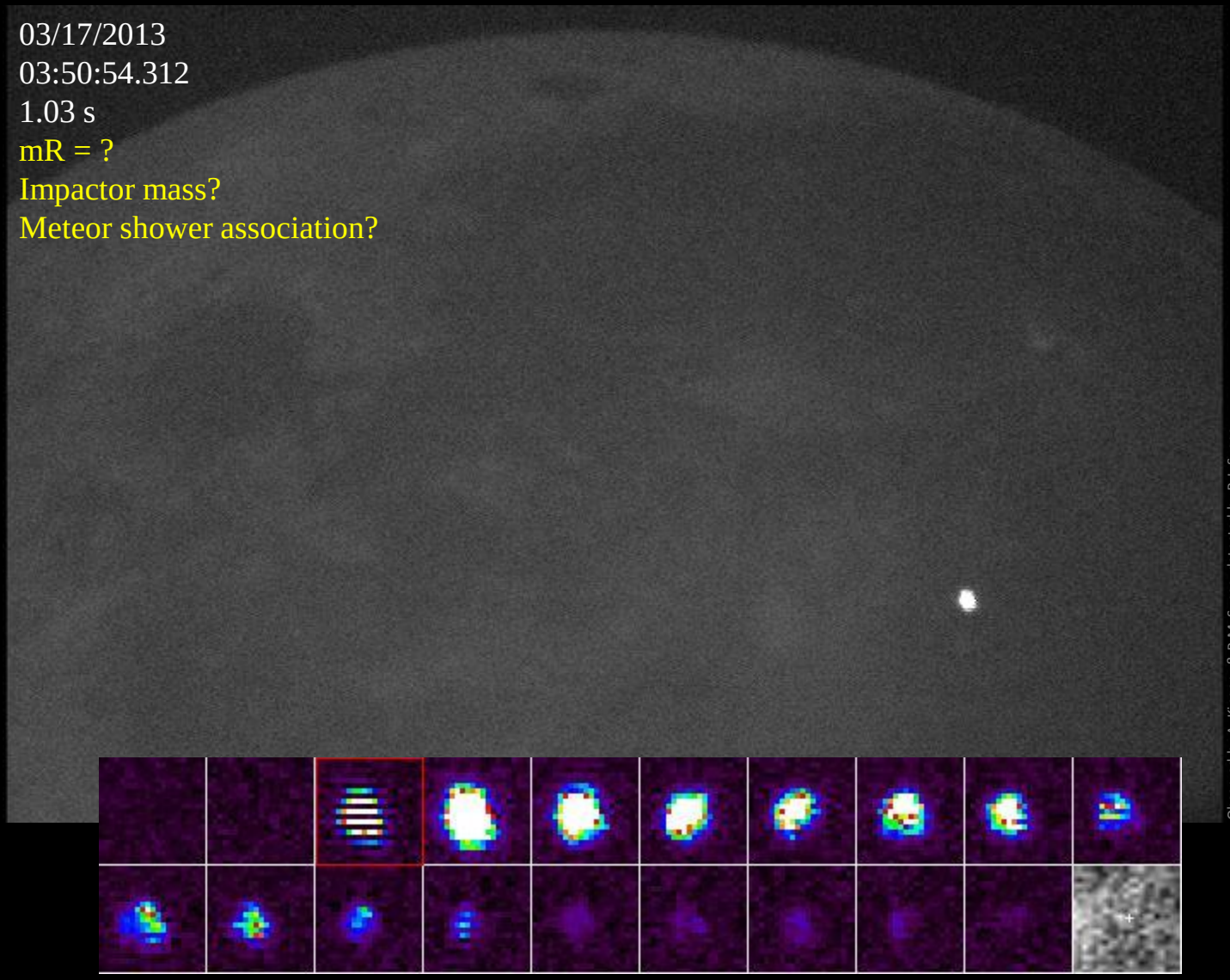

12/15/2006
09:17:39.336
33 ms
m_R = 7.4
0.09 kg
Geminid (35 km/s)
T
Observed by D.E. Moser & W.R. Swift; detected by R.J. Suggs


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

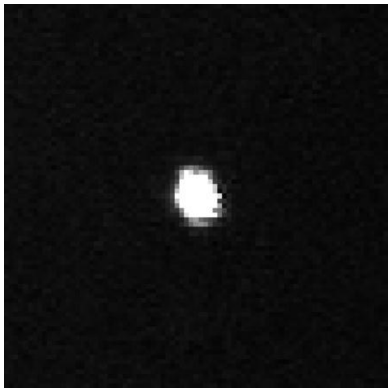

11/03/2008
00:11:06.144
100 ms
m_R = 7.7
0.1 kg
S. Taurid (27 km/s)
T
Observed by W.R. Swift; detected by R.J. Suggs

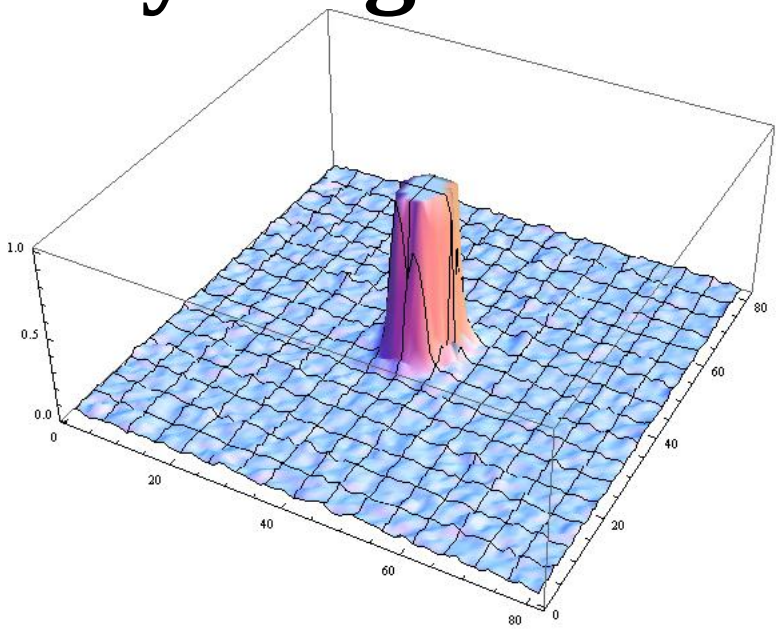

04/22/2007
03:12:24.372
133 ms
m_R = 6.7
0.08 kg
Lyrid (49 km/s)
T
Observed by R.M. Suggs; detected by R.J. Suggs

March 17, 2013 3:50:54 UTC



Preliminary magnitude estimate

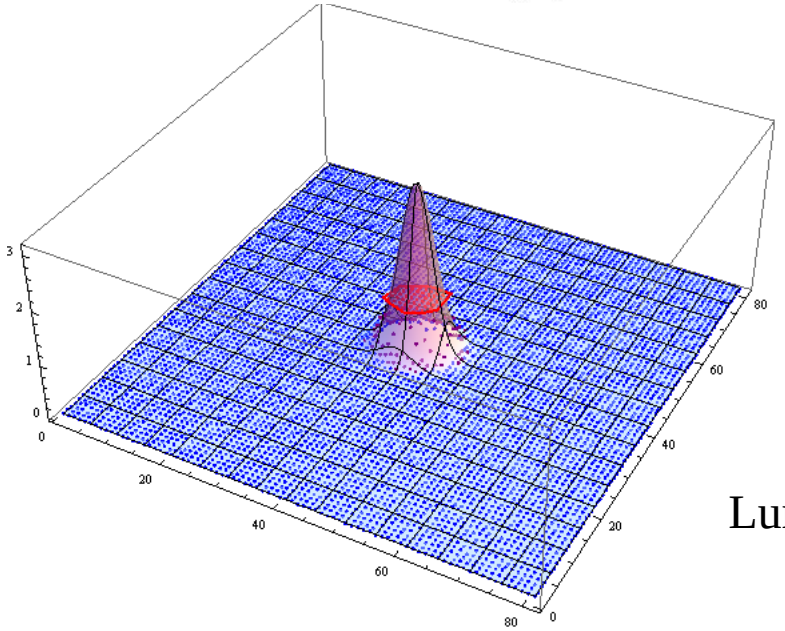




Saturated

Peak $m_R = 4.9$

Photometry performed using comparison stars



2D elliptical Gaussian fit to the unsaturated wings

Peak $m_R = 3.1 \pm 0.4$

Luminous energy = 4.8×10^6 J

Similar results for 2D elliptical Moffat fit

Preliminary energy estimate

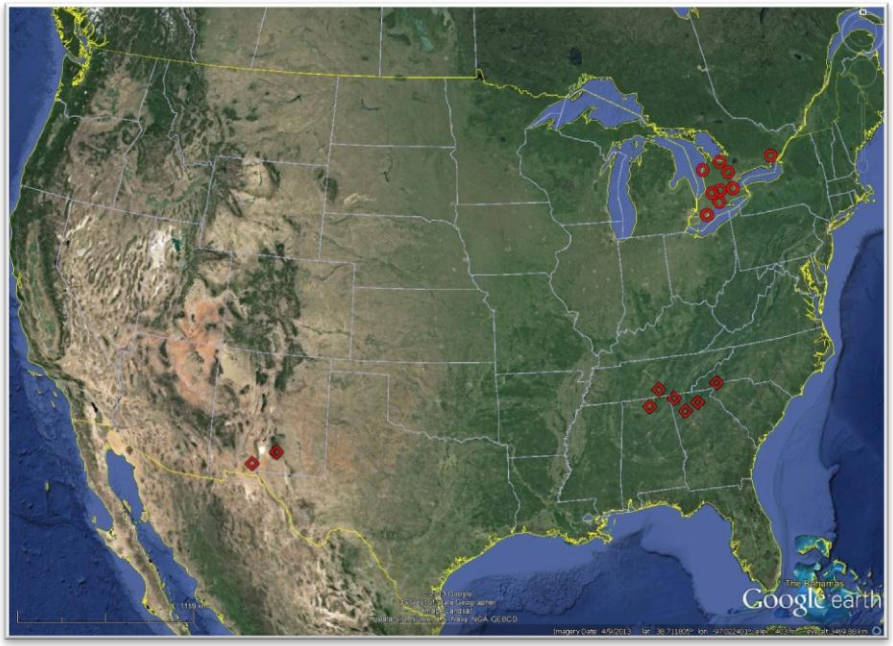
Luminous efficiency (η_λ) relates how much of the impactor's kinetic energy (KE) is converted to luminous energy (LE) in a wavelength range λ

$$LE_\lambda = \eta_\lambda KE_\lambda$$

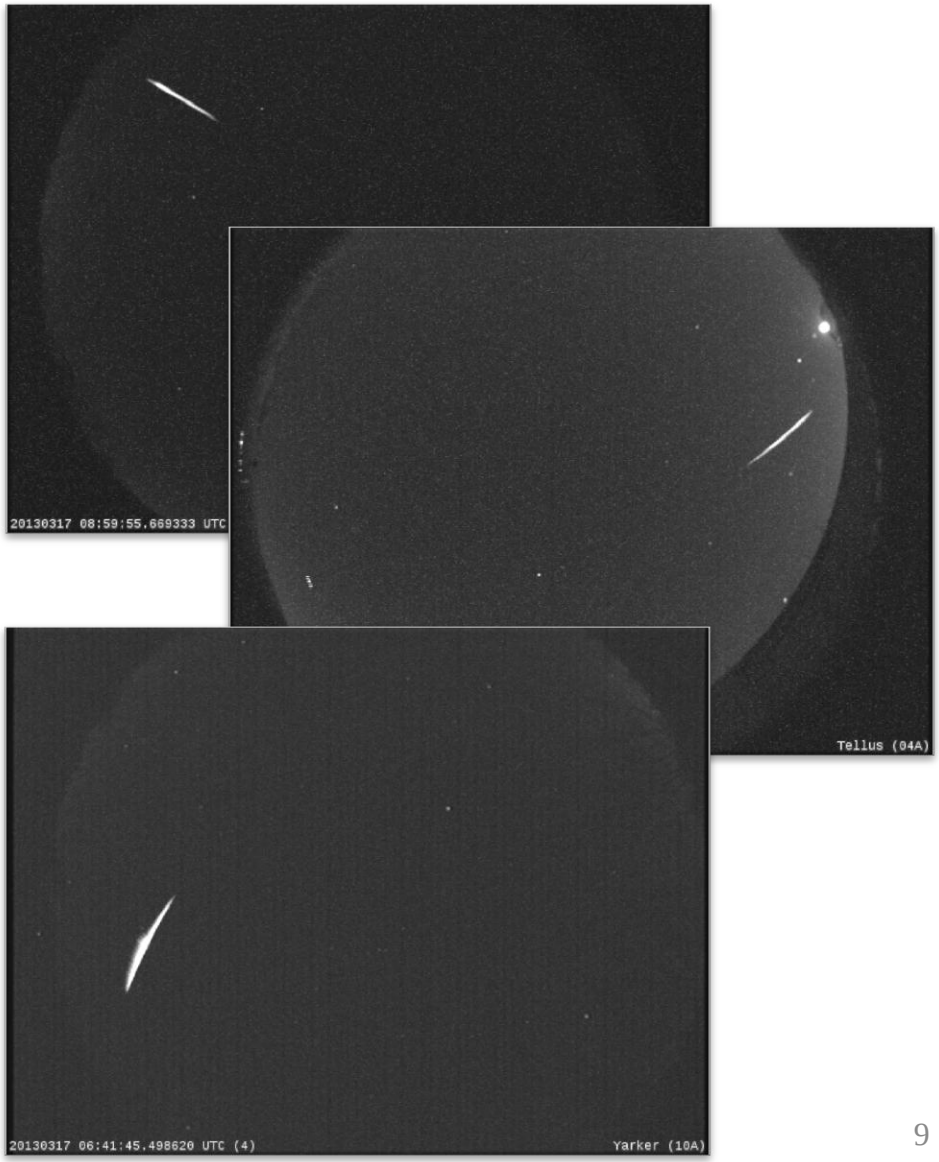
	Const. $\eta = 2 \times 10^{-4}$		**Vel. dep. $\eta = 1.7 \times 10^{-3}$ (Moser et al. 2011)**	
	Average	Range	Average	Range
Luminous energy (J)	4.8×10^6	$3.2 \times 10^6 – 7.1 \times 10^6$	4.8×10^6	$3.2 \times 10^6 – 7.1 \times 10^6$
Kinetic energy of impactor (J)	2.4×10^{10}	$1.6 \times 10^{10} – 3.6 \times 10^{10}$	2.8×10^9	$1.9 \times 10^9 – 4.2 \times 10^9$
Impactor mass (kg) (assuming v_g = 25.6 km/s)	72	48 – 109	8	6 – 13

Why did we assume v_g = 25.6 km/s?

Meteor data on Mar 17

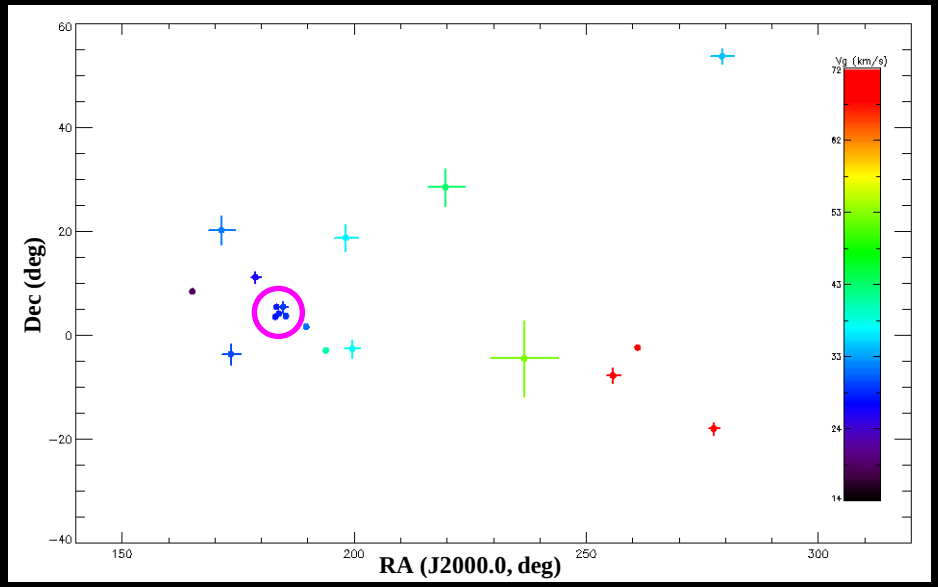


NASA and SOMN all-sky meteor cameras



Meteor shower association

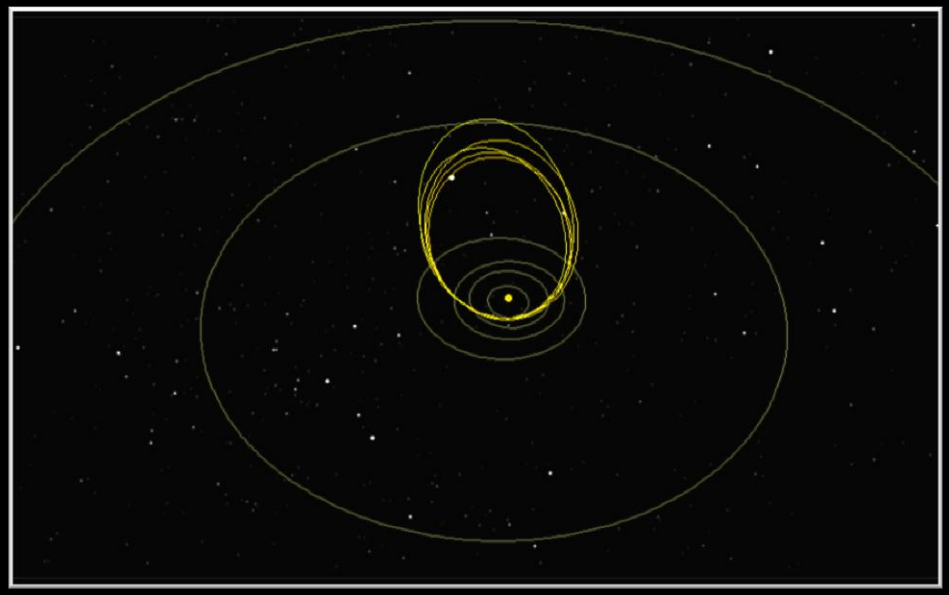
19 fireballs seen on Mar 17, 2013



Geocentric meteor radiants color-coded by speed with a tight cluster of 5 with

	meteors
α_g (°)	184.1 ± 1.0
δ_g (°)	4.4 ± 0.9
v_g (km/s)	25.6 ± 0.8
λ_{sun} (°)	356.6

Cluster of 5 seen on Mar 17, 2013

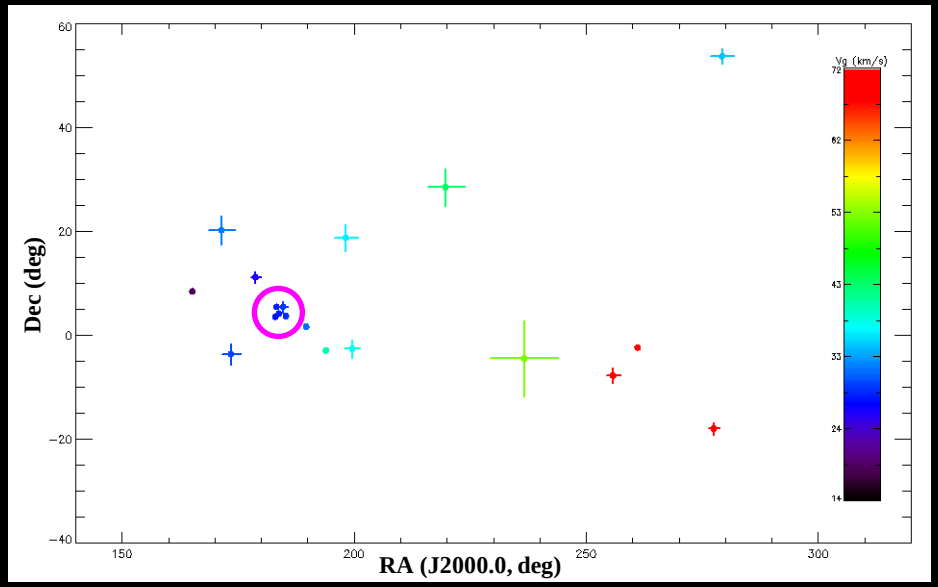


Orbits of the cluster of 5 were very similar with the following average orbital elements

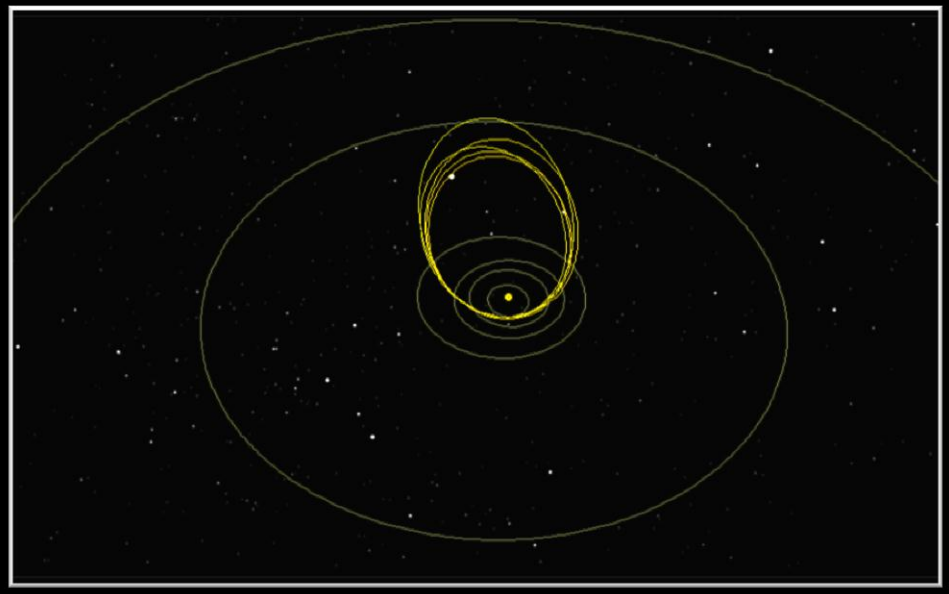
	meteoroids
a (AU)	2.25 ± 0.17
e	0.79 ± 0.02
i (°)	5.26 ± 1.02
ω (°)	280.32 ± 2.11
Ω (°)	356.65 ± 0.07
q (AU)	0.48 ± 0.02
Q (AU)	4.0 ± 0.3
Tj	3.1 ± 0.2

Meteor shower association

19 fireballs seen on Mar 17, 2013



Cluster of 5 seen on Mar 17, 2013



Geocentric meteor radiants color-coded by speed with a tight cluster of 5 with

Virginid Complex

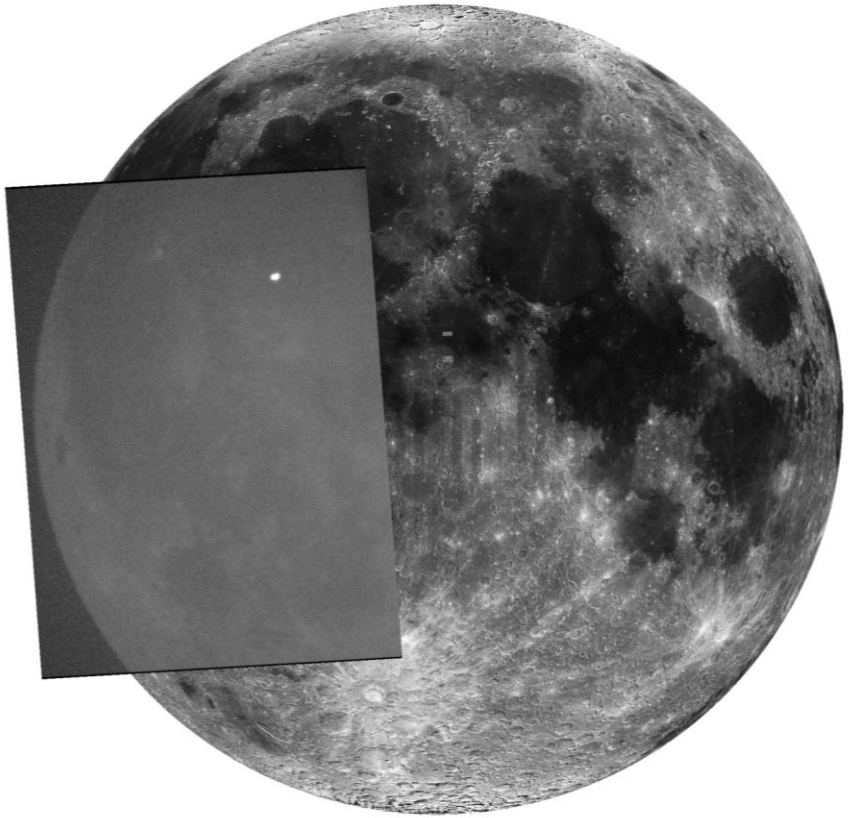
	meteors	NVI[1]	EVI[2]
α_g (°)	184.1 ± 1.0	185.7	183.6
δ_g (°)	4.4 ± 0.9	2.3	3.7
v_g (km/s)	25.6 ± 0.8	23.0	28.9
λ_{sun} (°)	356.6	354	354

Orbits of the cluster of 5 were very similar with the following average orbital elements

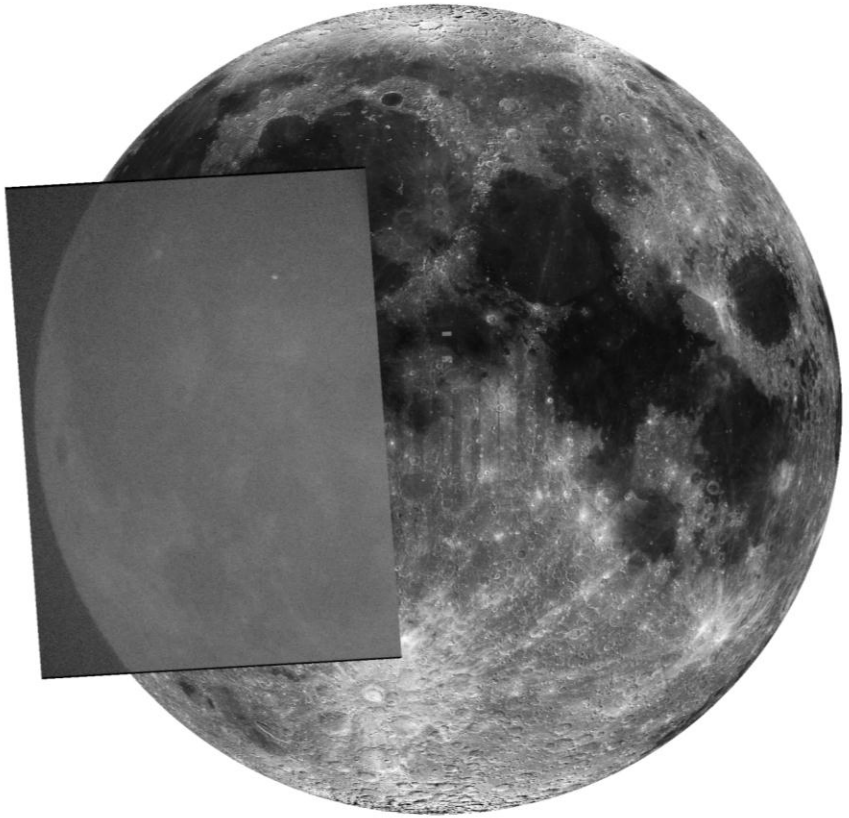
	meteoroids	NVI	EVI
a (AU)	2.25 ± 0.17	1.69	2.82
e	0.79 ± 0.02	0.71	0.86
i (°)	5.26 ± 1.02	3.7	5.2
ω (°)	280.32 ± 2.11	282.4	285.8
Ω (°)	356.65 ± 0.07	358.0	355.1
q (AU)	0.48 ± 0.02	0.496	0.40
Q (AU)	4.0 ± 0.3	2.89	5.25
Tj	3.1 ± 0.2	→	Indicates asteroidal body

[1](Sekanina, 1973), [2](Whipple, 1957)

Mapping the impact location



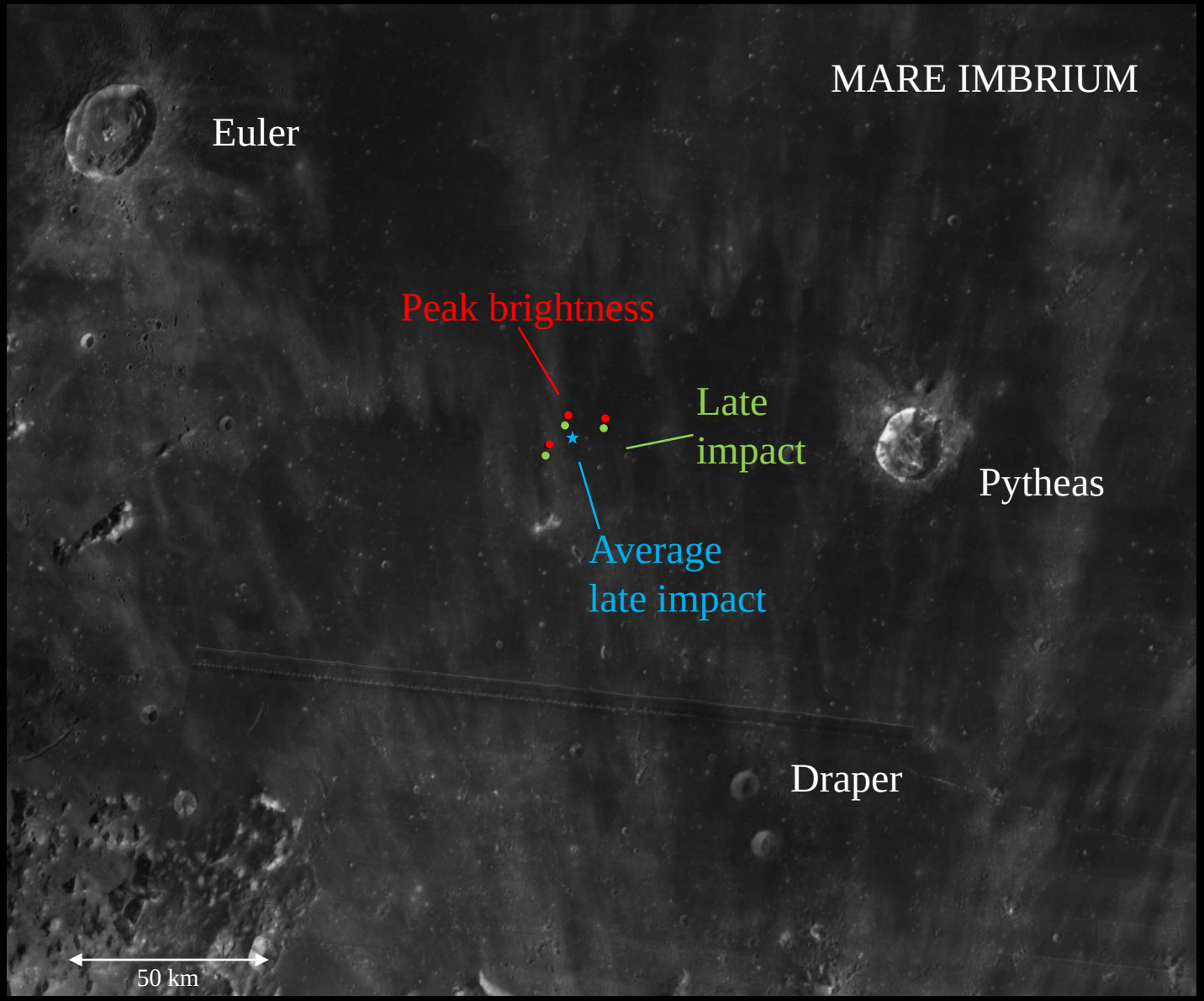
Flash at peak brightness



Flash 10 frames (333 ms) after the peak

ArcMap (ArcGIS 10) was used to georeference the lunar impact video

Impact location



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

Impact geometry

Pink indicates the portion of the moon visible to the radiant.
Impact angle approx 34° from normal.

Crater Estimates

Assumptions

ρ_p = 1.8 g/cm^3 – 3 g/cm^3
(C-type asteroid) (rocky)

ρ_t = 1.5 g/cm^3 – 2.1 g/cm^3
(regolith) (hard soil/soft rock)

g = 1.67 m/s^2

θ_h = 56°

Crater diameter from Gault's scaling law (Bouley 2012)

$D = 0.25\rho_p^{0.167}\,\rho_t^{-0.5}\,g^{-0.165}\,E^{0.29}\,\sin^{1/3}\theta_h$

D (m)	**Const. $\eta = 2 \times 10^{-4}$ E = 2.4 × 10^{10} J**		**Vel. dep. $\eta = 1.7 \times 10^{-3}$ E = 2.8 × 10^{9} J**	
	ρ_t = 1.5 g/cm^3	ρ_t = 2.1 g/cm^3	ρ_t = 1.5 g/cm^3	ρ_t = 2.1 g/cm^3
ρ_p = 1.8 g/cm^3	19.9	16.8	10.7	9.0
ρ_p = 3 g/cm^3	21.6	18.3	11.6	9.8

Rim crater diameter from Holsapple's online calculator

http://keith.aa.washington.edu/craterdata/scaling/index.htm

D_{rim} (m)	**Const. $\eta = 2 \times 10^{-4}$ E = 2.4 × 10^{10} J**		**Vel. dep. $\eta = 1.7 \times 10^{-3}$ E = 2.8 × 10^{9} J**	
	ρ_t = 1.5 g/cm^3	ρ_t = 2.1 g/cm^3	ρ_t = 1.5 g/cm^3	ρ_t = 2.1 g/cm^3
ρ_p = 1.8 g/cm^3	18.4	22.8	10.0	11.3
ρ_p = 3 g/cm^3	18.9	22.9	10.2	11.3

Summary

Date of flash:	17 March 2013 3:50:54 UTC
Duration of flash:	1.03 s
Estimated peak R magnitude:	3.1 ± 0.4
Luminous energy generated by impact:	4.8×10^6 J
Estimated kinetic energy of impactor:	2.8×10^9 J = 0.7 tons of TNT (assuming $\eta = 1.7 \times 10^{-3}$)
Estimated mass of impactor:	8 kg (assuming v = 25.6 km/s)
Estimated diameter of impactor:	18 cm (assuming $\rho_p = 3$ g/cm^3)
Estimated crater diameter:	10.2 – 11.6 m (assuming $\rho_p = 3$ g/cm^3, $\rho_t = 1.5$ g/cm^3, $\theta = 34°$)
Estimated crater location:	20.599±0.172° N, 23.922±0.304° W
Possible meteor shower association:	Virginid Meteor Complex

The brightest meteoroid impact flash of a 7 year lunar observing program was seen on March 17. This meteoroid may have been part of a stream of large particles encountered by the Earth/Moon associated with the Virginid Meteor Complex, as evidenced by a cluster of fireballs in the Earth's atmosphere.

Backup Slides

References

Bouley et al. “Power and duration of impact flashes on the moon: implication for the cause of radiation.” Icarus 218, 115-124 (2012).

Holsapple, K.A. “Crater sizes from explosions or impacts.” http://keith.aa.washington.edu/craterdata/scaling/index.htm. Accessed 2013.

Moser, D.E. et al. “Luminous efficiency of hypervelocity meteoroid impacts on the moon derived from the 2006 Geminids, 2007 Lyrids, and 2008 Taurids.” NASA/CP-2011-216469, 142-154 (2011).

Sekanina, Z. “Statistical model of meteor streams III. Stream search among 19303 radio meteors.” *Icarus* **18**, 253-284 (1973).

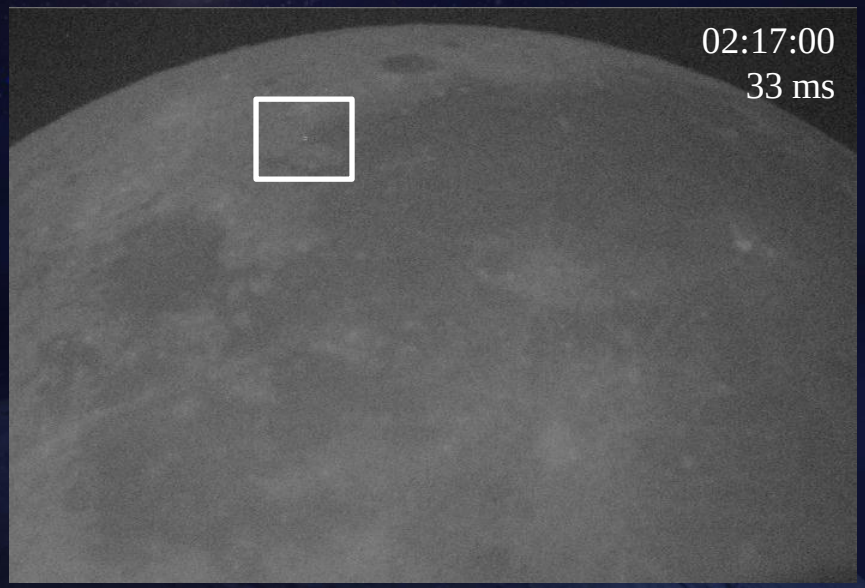
Suggs, R.M. et al. “The NASA lunar impact monitoring program.” *EMP* **102**, 293-298 (2007).

Suggs, R.M. et al. “Lunar meteoroid impact observations and the flux of kilogram-sized meteoroids.” NASA/CP-2011-216469, 116-124 (2011).

Whipple, F.L. “Some problems of meteor astronomy.” In *Radio Astronomy*, Proc. IAU Symp. No. 4, ed. H.C. van de Hulst (1957).

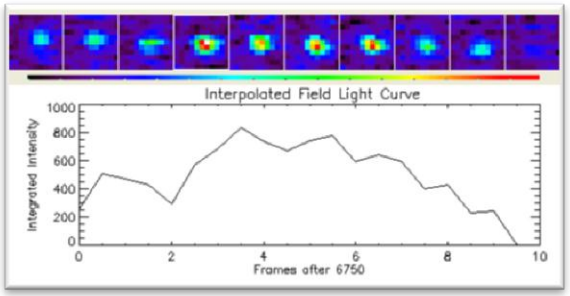
Mar 17 flash detected in 2 telescopes

4 Lunar impacts on Mar 17

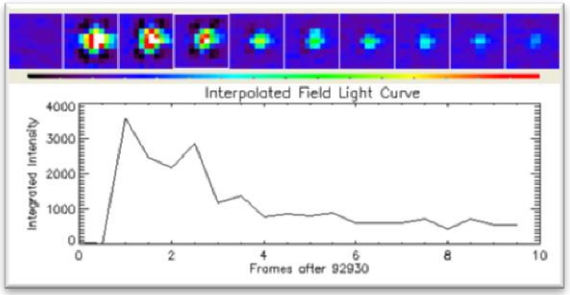


Impact flash candidate requirements

- Multiple pixels
- Simultaneous detection by 2+ telescopes
  - If only 1 telescope, flash longer than 1/30s duration
- No motion field to field
- Characteristic light curve shape



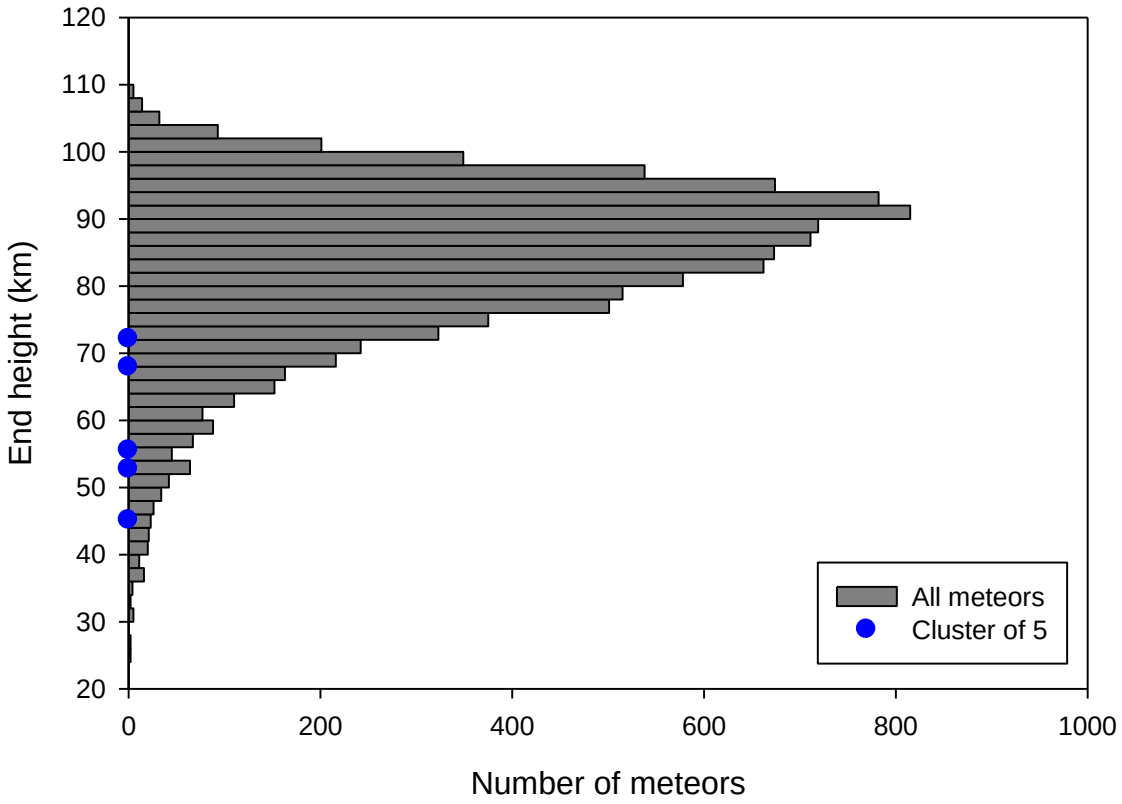
satellite glint



impact flash

These criteria rule out cosmic rays, electronic noise, and sun glints from orbiting satellites.

Fireball heights & masses



Cluster of 5 penetrated fairly deeply into the atmosphere.
Moderately large, 0.003 kg to 0.1 kg masses

Circumstantial evidence

- Timing and intensity on March 17-18
  - 5 fireballs in all sky data with tight radiant cluster & comparable orbital elements
  - Significant rates in Canadian Meteor Orbit Radar
  - 4 lunar impact flashes in 3.5 hours (1 imp/0.86 hr vs normal 1 imp/2 hrs)
- Shower virtually non-existent in previous years

Northern March Virginid (NVI) / Eta Virginid (EVI) outburst March 17-18