Large Meteoroid Impact on the Moon on 17 March 2013

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Overview

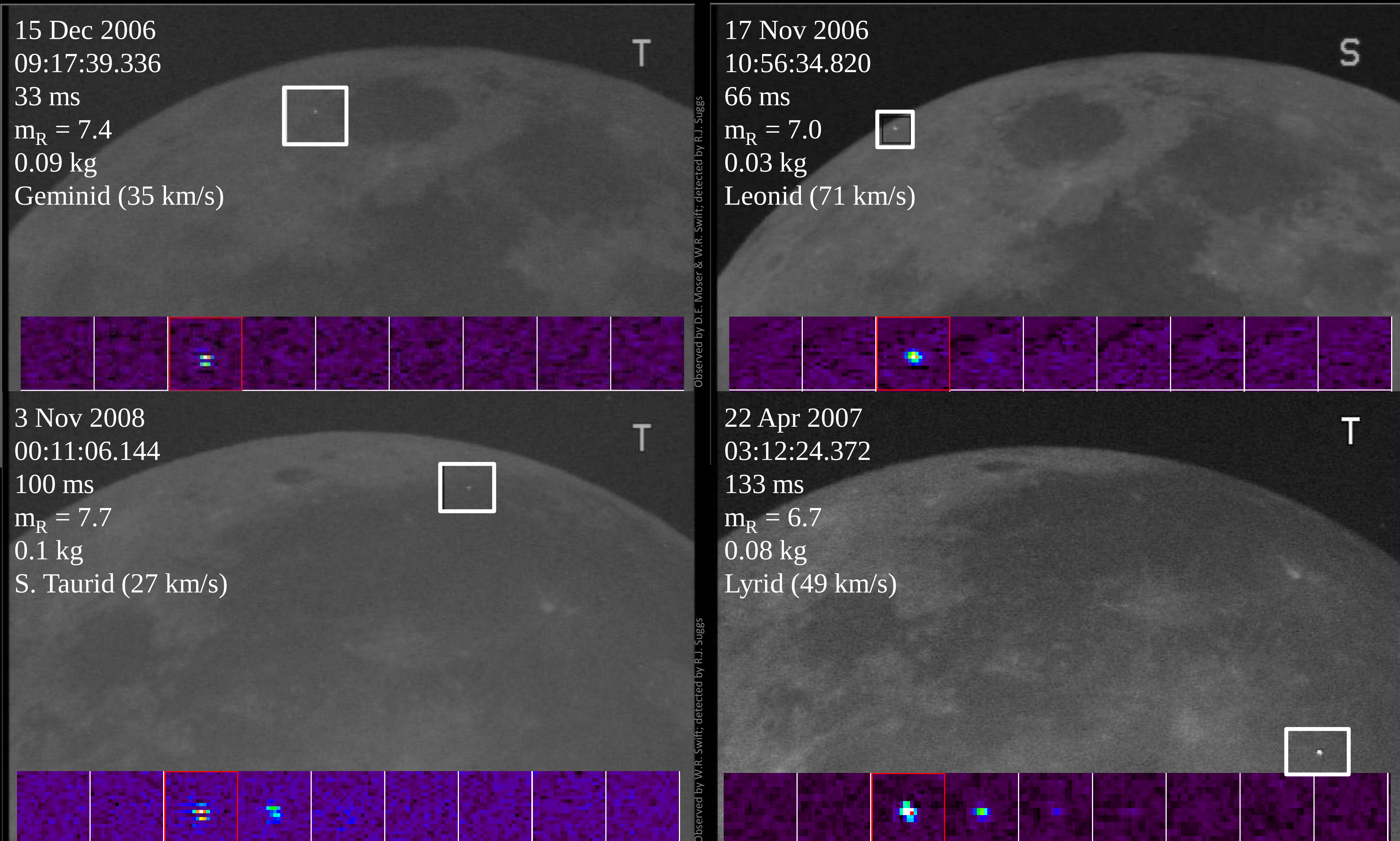
On 17 March 2013 at 03:50:54 UTC, NASA detected a bright impact flash on the Moon caused by a meteoroid impacting the lunar surface.

There was enhanced meteor activity in Earth's atmosphere the same night, and one night following, from the Virginid Meteor Complex.

The impact crater associated with the impact flash was found and imaged by Lunar Reconnaissance Orbiter (LRO).

Luminous efficiency estimates can be made by combining flash and crater measurements. A sanity check of photometric procedures and crater scaling relations is also possible.

Typical impact flashes



Atypical 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

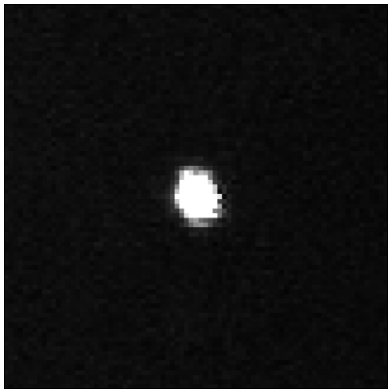
Watec 209H2 Ult monochrome CCD cameras

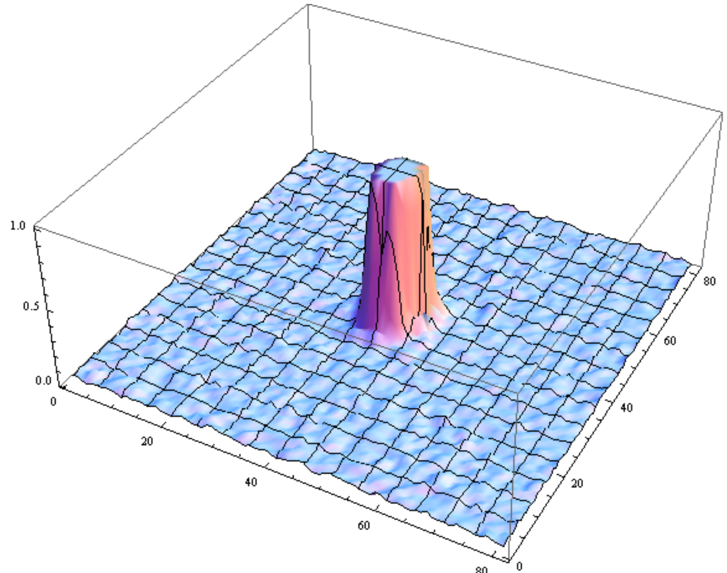
- Manual gain control
- No integration
- $\Gamma = 0.45$

Interlaced 30 fps video

Saturated → needed saturation correction!

Peak R magnitude saturation correction

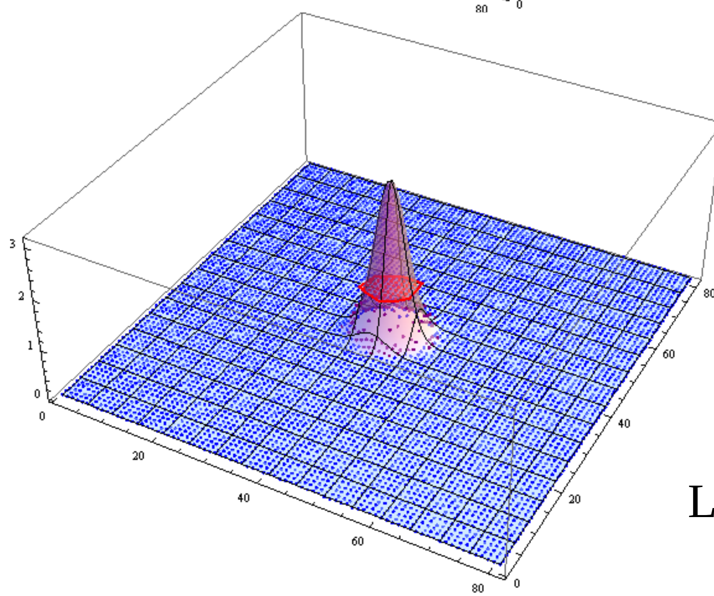




Saturated

Peak $m_R = 4.9$

UNDERESTIMATED!



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

CORRECTION:

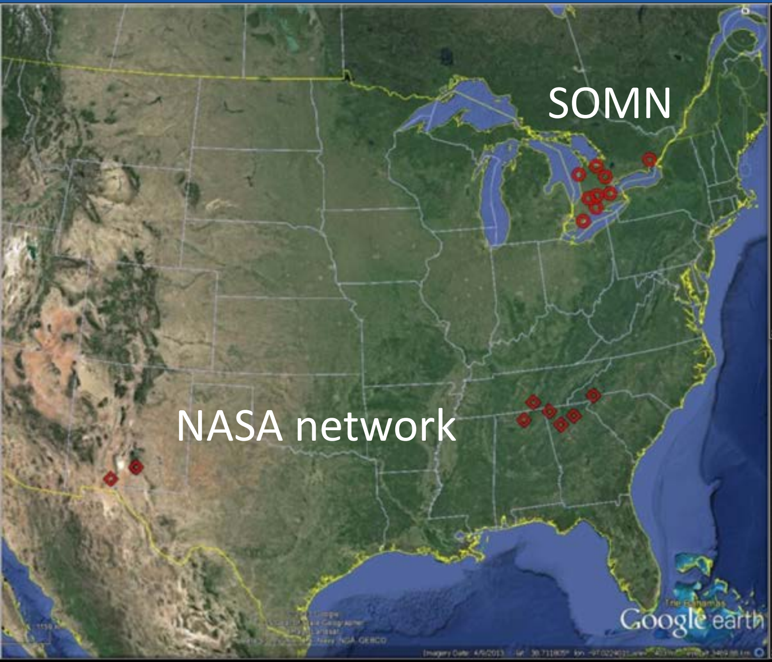
2D elliptical Gaussian fit to the unsaturated wings

Peak $m_R = 3.0 \pm 0.4$

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

(Similar results for 2D elliptical Moffat fit)

Correlated meteor activity on 17 Mar



All-sky meteor cameras detected a deeply penetrating cluster of 5 fireballs on 17 March.

Radiant and orbital elements consistent with the Virginid Meteor Complex (EVI/NVI).

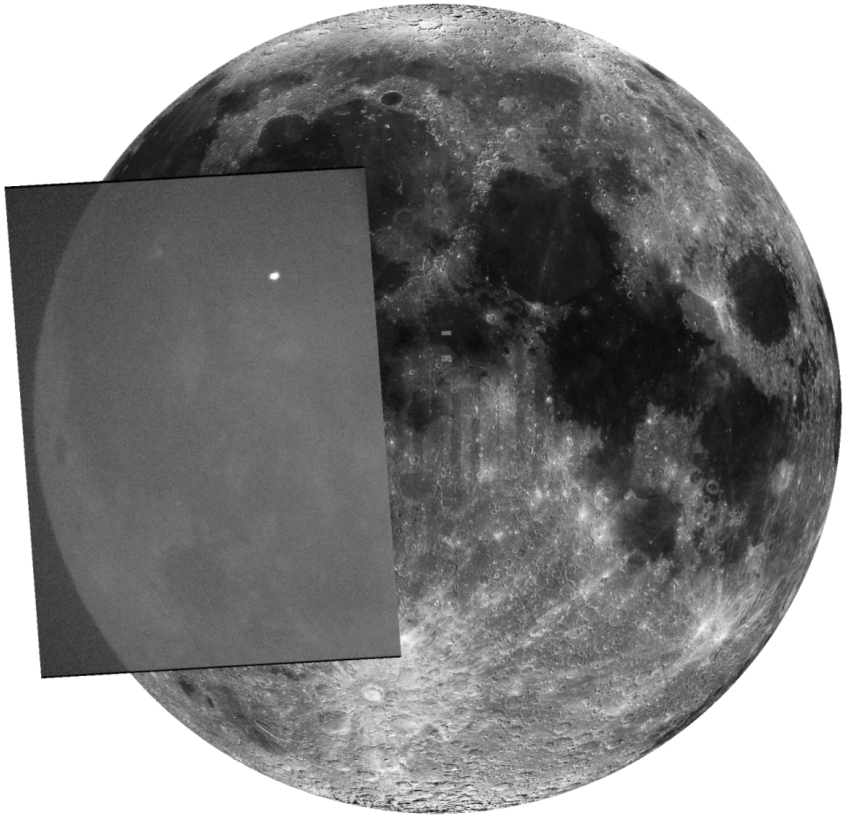
Significant rates in Canadian Meteor Orbit Radar 1 day later indicating possible outburst.

➡ Assume impact flash was part of Virginid Meteor Complex

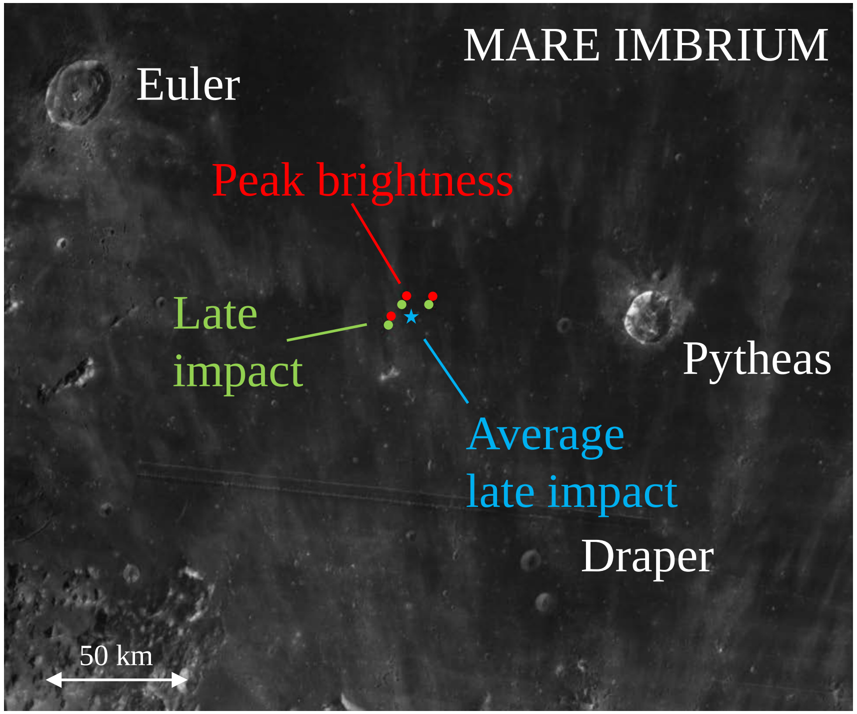
$\therefore\ v_g = 25.6$ km/s

$\theta_h = 56°$

Mapping the impact location

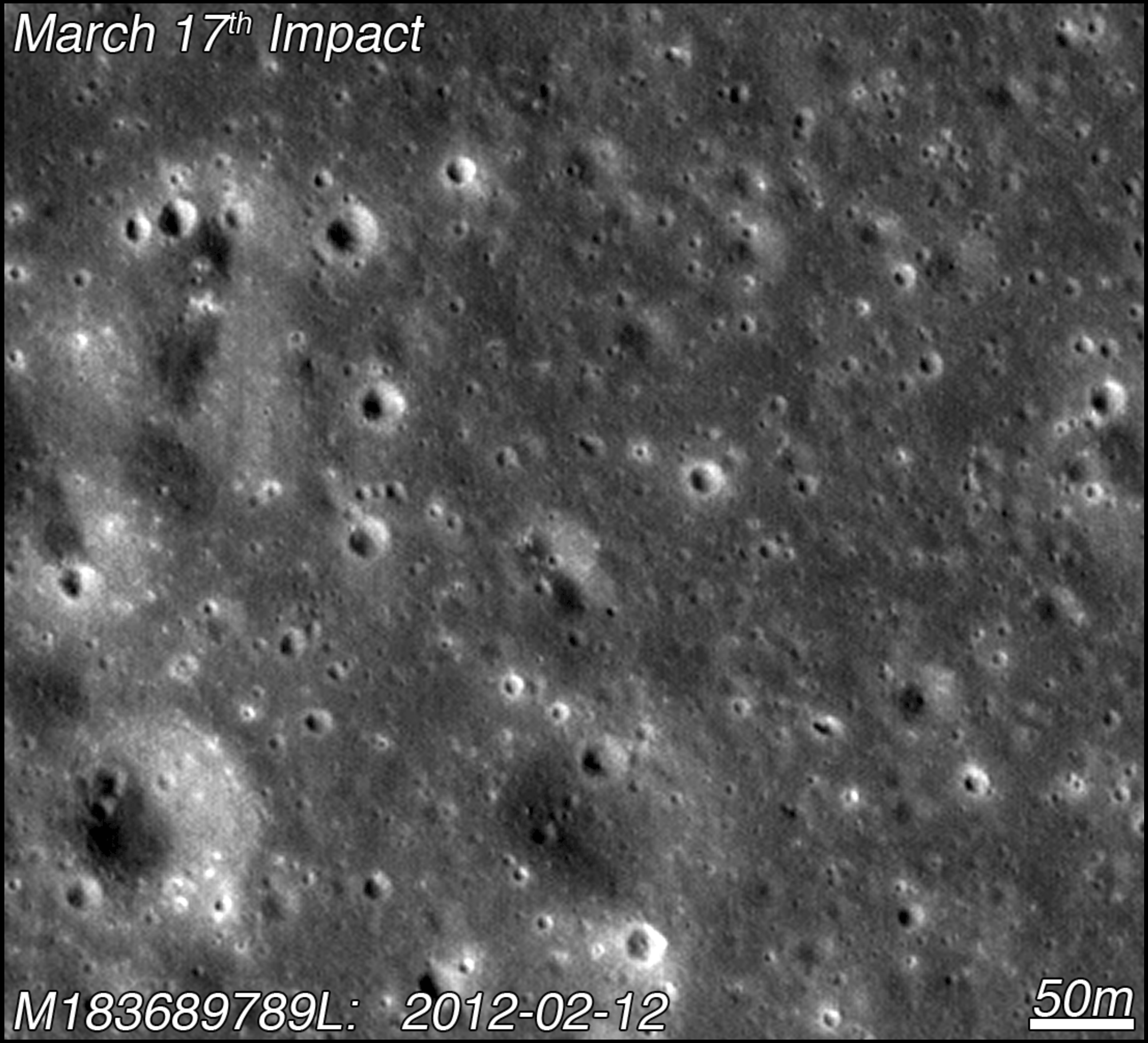


GIS tools were used to "georeference" the lunar impact video 3 times, at peak brightness and late impact.



Average crater position
20.60 ± 0.17° N, 23.92 ± 0.30° W
was sent to LRO.

Impact crater found by LRO!



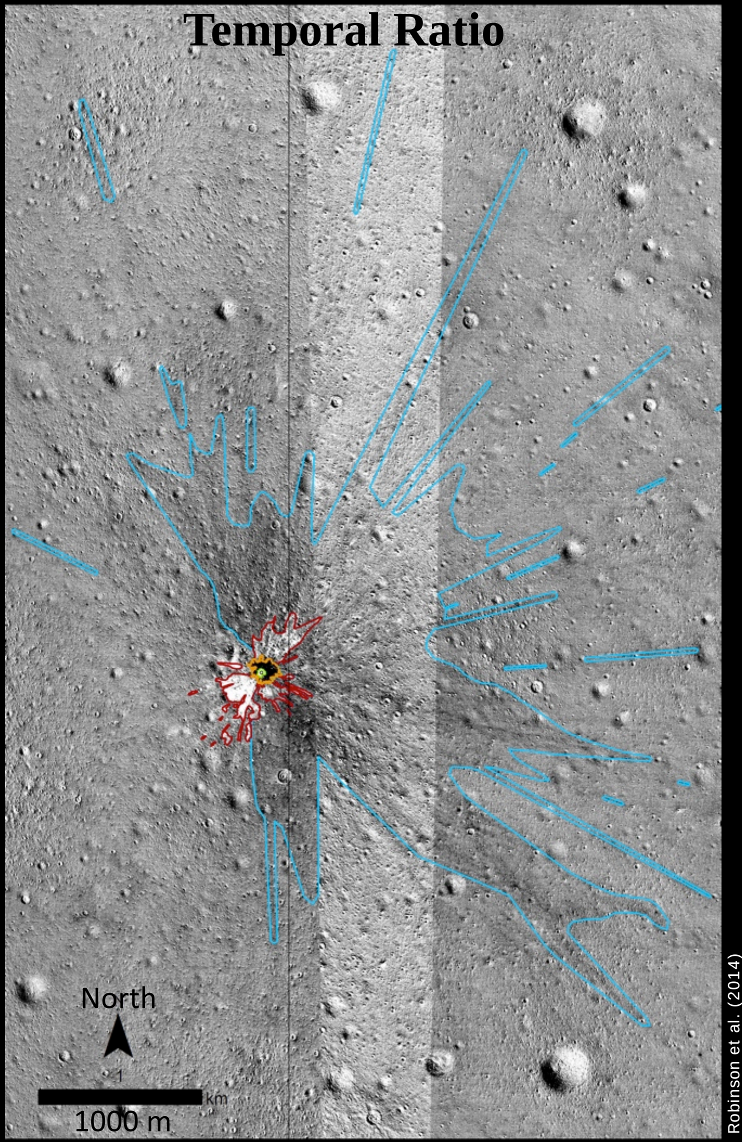
NASA/GSFC/Arizona State University

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
- Δ ≈ 0.399° or 12.1 km

Impact constraints



Ejecta in multiple reflectance "zones"

High/High reflectance

Low/Low reflectance

(Robinson et al. 2014)

Impact Constraints

➡ Circular crater, impact angle constrained >15°

➡ HR zone – impact possible from SE or NW
LR zone – impact possible from SW
∴ no azimuth constraint (Robinson, personal comm.)

An impact from the SW is consistent with an impactor from the Virginid Meteor Complex.

Transient crater diameter estimates

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

Model	η	KE $\times 10^9$ (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 of 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 transient crater
D_{obs} = 18 m rim-to-rim

Impact summary

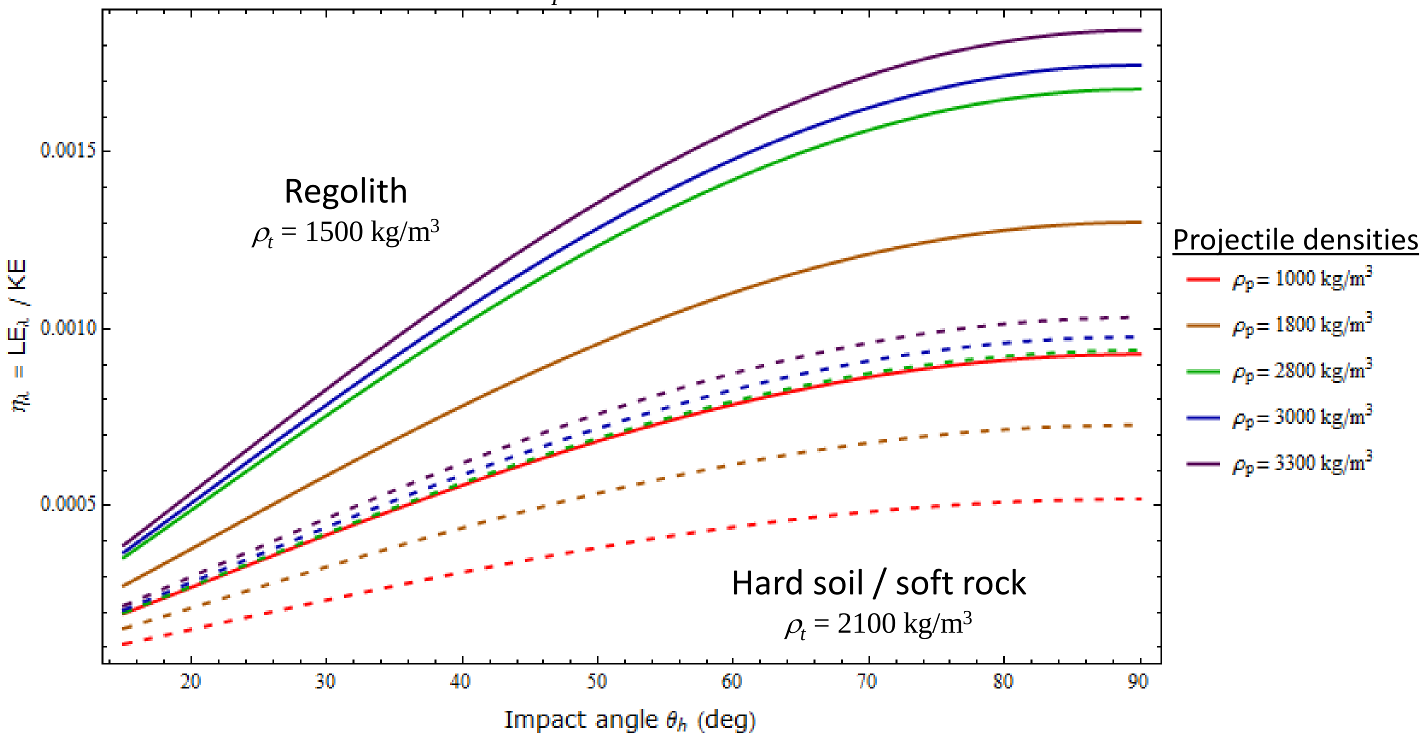
Date of impact:	17 March 2013 3:50:54 UTC
Duration of impact:	1.03 s
Corrected flash peak R magnitude:	3.0 ± 0.4
Luminous energy generated by impact:	$7.1^{+3.9}_{-2.4} \times 10^{6}$ J
Estimated kinetic energy of impactor:	$5.4^{+3.0}_{-1.8} \times 10^{9}$ J = 1.3 tons of TNT (assuming $\eta = 1.3 \times 10^{-3}$)
Estimated mass of impactor:	16^{+10}_{-5} kg (assuming v = 25.6 km/s)
Estimated diameter of impactor:	22 ± 3 cm (assuming $\rho_p = 3$ g/cm^3)
Crater diameter:	18 m rim-to-rim, 15 m inner (‘transient’)
Crater location:	20.7135° N, 24.3302° W
Possible meteor shower association:	Virginid Meteor Complex

Luminous efficiency: $LE_\lambda = \eta_\lambda\, KE$

D_t = 15 m from crater measurements
$LE = 7.1 \times 10^6$ J from flash measurements

Gault's crater scaling law (Gault 1974) rearranges to give η vs θ_h without assuming impact speed.

$$KE = (4.0\, D_t\, \rho_p^{-0.167}\, \rho_t^{0.5} \sin^{-1/3}\theta_h)^{1/0.29}$$



Typical values of η_λ derived from lunar regolith range from $2 \pm 1 \times 10^{-4}$ to $2 \pm 1 \times 10^{-3}$.

Assuming association with the Virginids, $\theta_h = 56°$ and $7.5^{+4.5}_{-2.5} \times 10^{-4} < \eta_\lambda < 1.5^{+0.8}_{-0.5} \times 10^{-3}$.

Backup Slides

References

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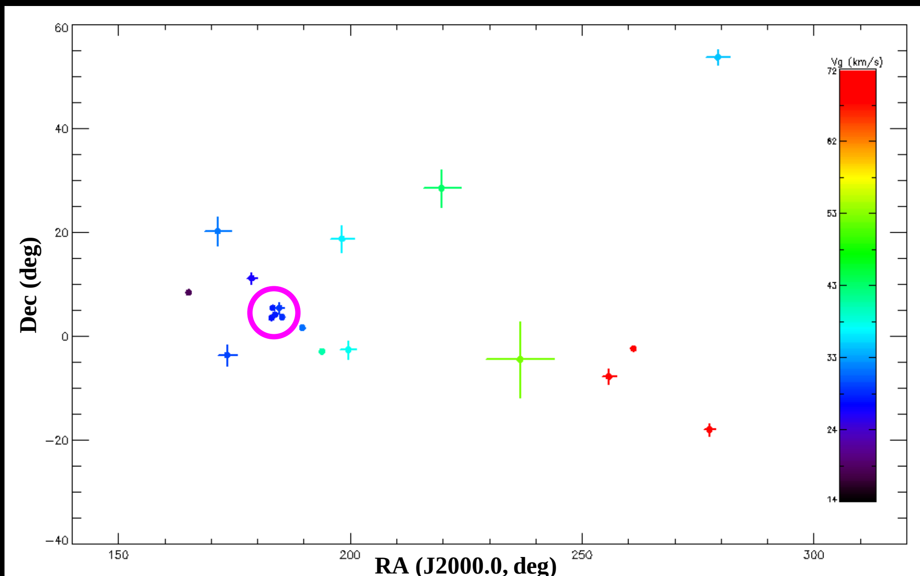
Possible meteor shower association

19 fireballs seen on 17 Mar 2013

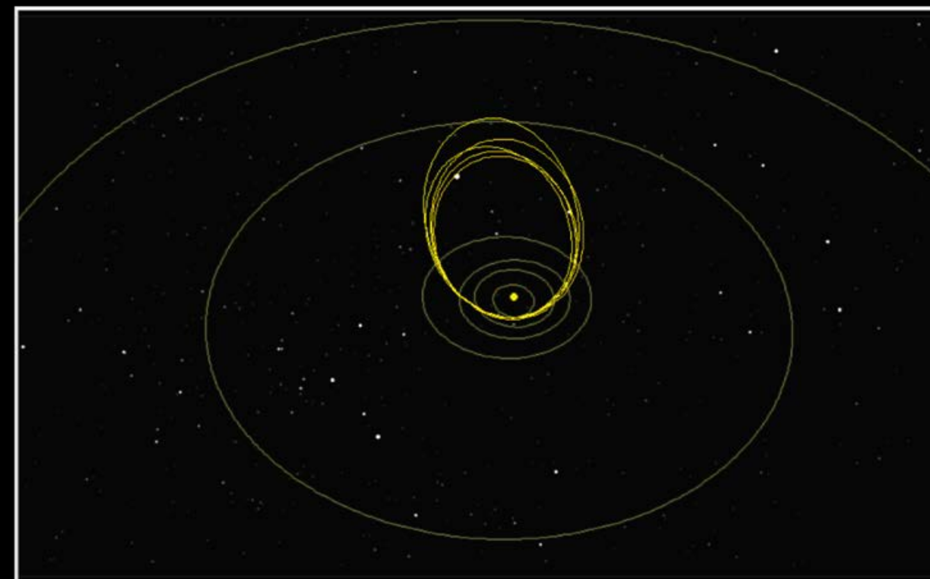


Geocentric meteor radiants color-coded by speed with a tight cluster of 5 with:

	meteors	NVI[1]	EVI[2]
		Virginid Complex at λ=356.6	
α_g (°)	184.1 ± 1.0	183.1	181.0
δ_g (°)	4.4 ± 0.9	2.3	4.7
v_g (km/s)	25.6 ± 0.8	23.0	28.9
λ_{sun} (°)	356.6	356.6	356.6

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

Cluster of 5 seen on 17 Mar 2013

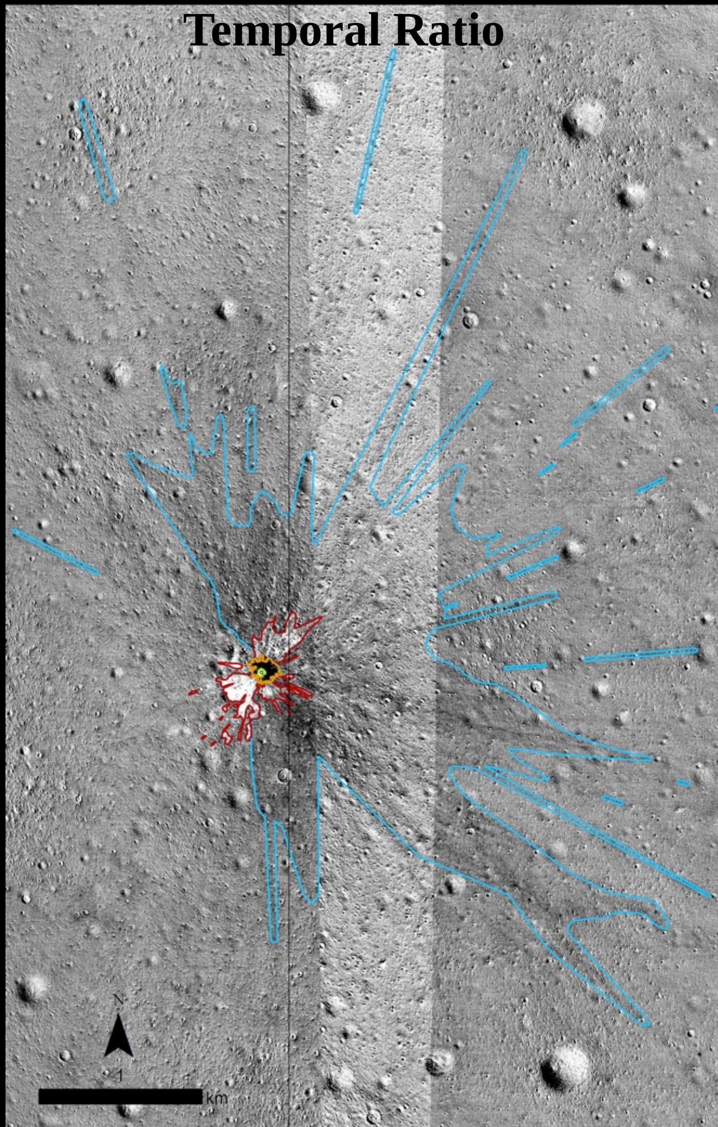


Orbits of the cluster of 5 were very similar with the following average orbital elements:

	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	

Ejecta distribution

after Robinson et al. (2014)



Robinson et al. (2014)

Ejecta in multiple reflectance "zones"

High reflectance zone
10-20 m SW, <10 m NE

Low reflectance zone
50 m WSW, 80 m ENE

High reflectance zone
~300 m rough semicircle

Low reflectance zone
~1 km centered in NE

248 splotches within 30 km
circular/irreg., majority low reflec.

See
Robinson et al. (2014)
for more details

Impact Constraints

➡ Circular crater, impact angle constrained >15°

➡ HR zone – impact possible from SE or NW
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