The meteoroid fluence at Mars due to Comet C/2013 A1 (Siding Spring)

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On October 19, 2014, Comet C/2013 A1 (Siding Spring) will pass within 150,000 km of Mars.

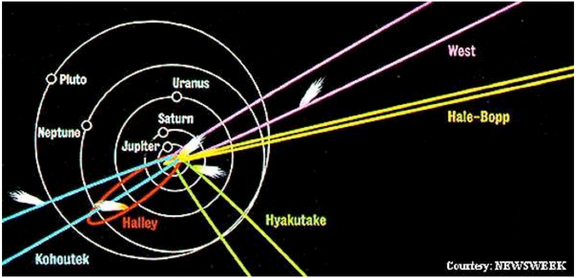
This is closer than all known Earth-comet encounters.

A collision has been ruled out, but Mars and its manmade satellites will pass through the coma and tail.

Mars will be showered with meteors and satellites will have an increased risk of meteoroid impacts.

Outline

Comet types: classed by orbit



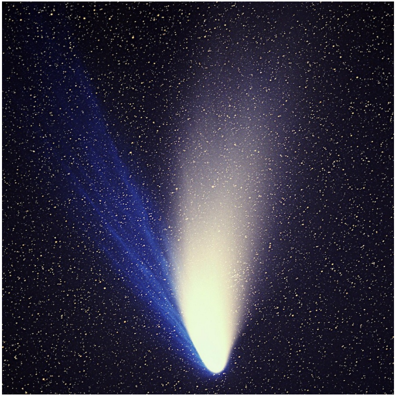
Type	Orbit	Origin	Examples
Short period	$P < 200$ yrs	Kuiper Belt	Halley
Long period (Oort cloud)	$P \sim 1000$s yrs	Oort cloud	Hale-Bopp, C/2013 A1
Sungrazers	Pass near or plunge into the Sun		C/2012 S1 (ISON)

Comet properties

Comet Hartley 2

- Comets are the least reflective objects in the Solar System:
  - Halley has an albedo of about 4%.
  - Asphalt has a albedo of 7%.
- Long period comets contain more volatiles, as short period comets lose much of these in frequent passages around the Sun.

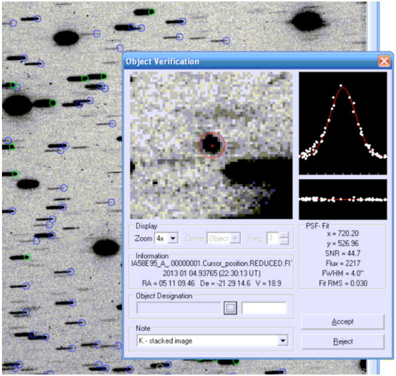
Cometary comae



Comet Hale-Bopp, NASA

- Hale-Bopp:
  - Discovered at 7.2 AU
  - Coma was 1 million km in August 1995
- Siding Spring:
  - Imaged at 10 AU
  - Already active

C/2013 A1 (Siding Spring)



- Discovery:
  - January 3, 2013
  - Rob McNaught
  - 0.5 meter telescope
  - Siding Spring, Australia
- Pre-discovery images located in Catalina Sky Survey
  - Active in earliest images (Dec. 8, 2012)
- Hyperbolic orbit

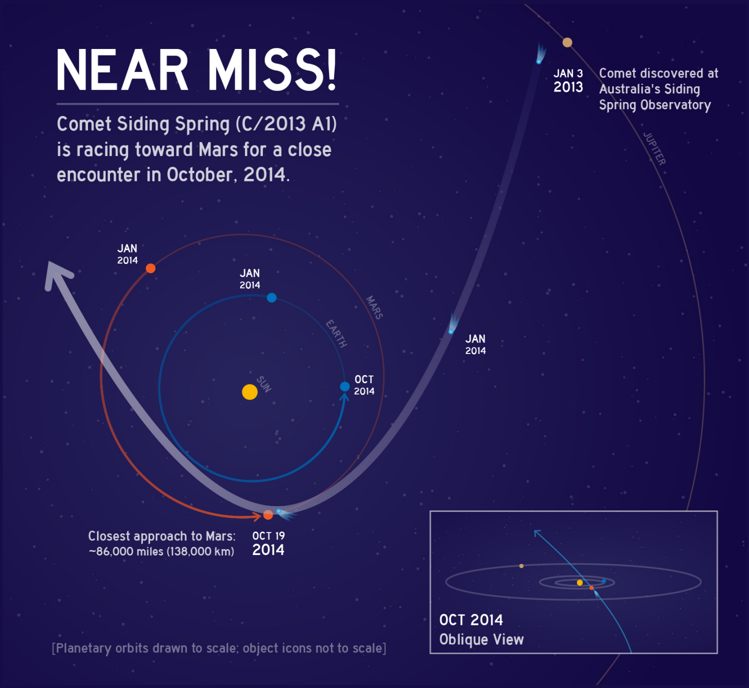
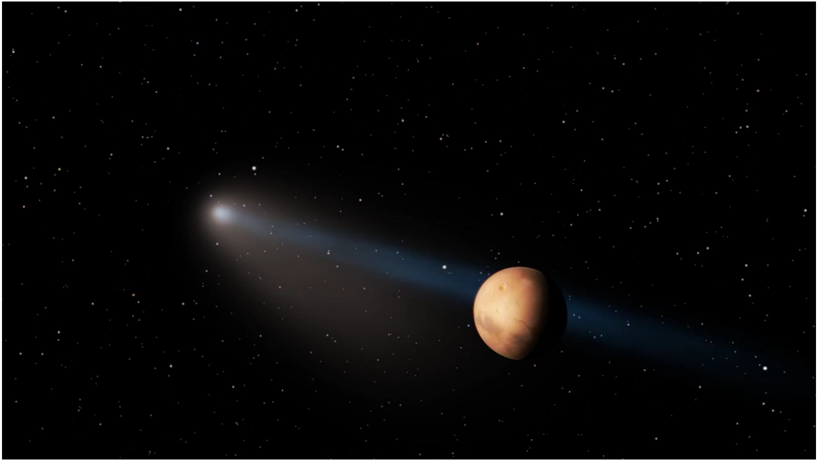


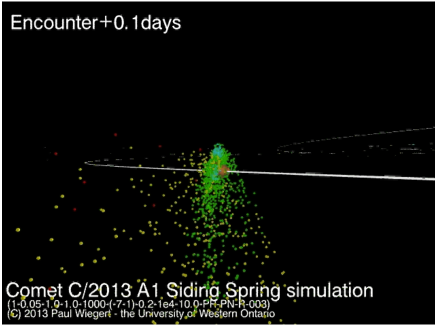
Image credit: NASA/JPL

Close encounter with mars



Movie credit: Leonid Elenin using SpaceEngine software

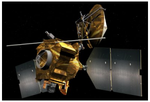
Close encounter with mars



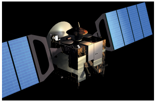
- Comet is north of Mars's orbital plane at closest approach
- Close approach: 131,000 - 145,000 km
- Approach distance nominal value: 138,000 km
- Coma/tail may envelop Mars

Mars satellites

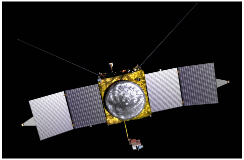
Odyssey (NASA)
400 km, 2 hr orbit



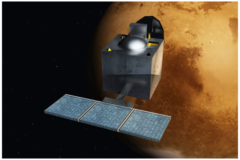
MRO (NASA)
300 km, 2 hr orbit



Mars Express (ESA)
300 - 10,000 km
7.5 hr orbit



MAVEN (NASA)
150 - 6,200 km, 4.5 hr orbit
Arrives September 2014



MOM (ISRO)
365 - 80,000 km, 76.7 hr orbit
Arrives September 2014

Meteoroid impact risks

- Impacts to critical components
- Sudden attitude changes
- Electrostatic/EMP effects may occur, depending on environment and spacecraft charging state

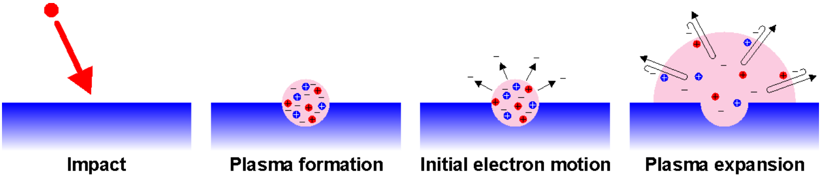


Image courtesy of MEDUSSA

Meteoroid impact risks

- Encounter speed similar to Perseids at Earth
- Two spacecraft anomalies attributed to Perseids:
  - Landsat 5 lost attitude control during 2009 Perseids
  - OLYMPUS satellite [lost during 1993 Perseids]

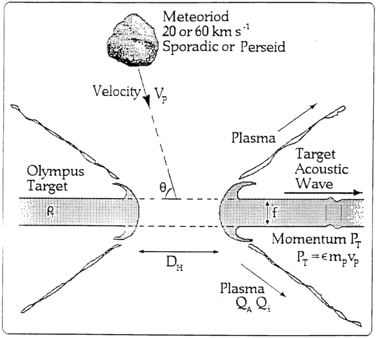


Image from McDonnell et al., 1993

Possible mitigation strategies

- Align solar arrays sunward, edge-on to meteor shower
  - Sun-Mars-comet angle is 90.2°
- Present hard side to radiant
- Phase orbit to use Mars as a partial shield:
  - Depends on orbit geometry
  - Shower will last a few hours, dependent on coma size (30 min per 100,000 km of coma/tail)
  - Odyssey and MRO have 2 hour orbits

Particles in the coma and tail of Siding Spring

- Coma and tail contains both gas and particles
- Both grow as heliocentric distance decreases
- Fluence – flux integrated over Mars/spacecraft trajectory
  - Direct measure of spacecraft risk
- We compute the particle fluence at Mars using properties of Siding Spring (magnitude, orbit), supplementing with Halley data (particle albedo, size distribution) where necessary.

The *Giotto* flyby of 1P/Halley

- We have detailed coma data for one comet: Halley.
- Giotto recorded 12,000 impacts.
- Model fits to these data yield:
  - Particle density and albedo
  - Particle size distribution
  - Particle spatial distribution
- Total number of particles derived from Siding Spring magnitude, not Halley.

Analytic model

Quantifying the number of ∼100 micron[1] or larger particles in the coma/tail:

1. Determine the brightness at the time of the encounter.
2. Use particle albedo to compute the total particle surface area.
3. Combine with Halley-like particle size distribution and material density to compute number of particles.
4. Use r^{-2} spatial distribution to compute the number density.
5. Integrate along the trajectory to get fluence.

Our analytic model can be used to quickly calculate new fluence estimates as comet properties are measured/constrained.

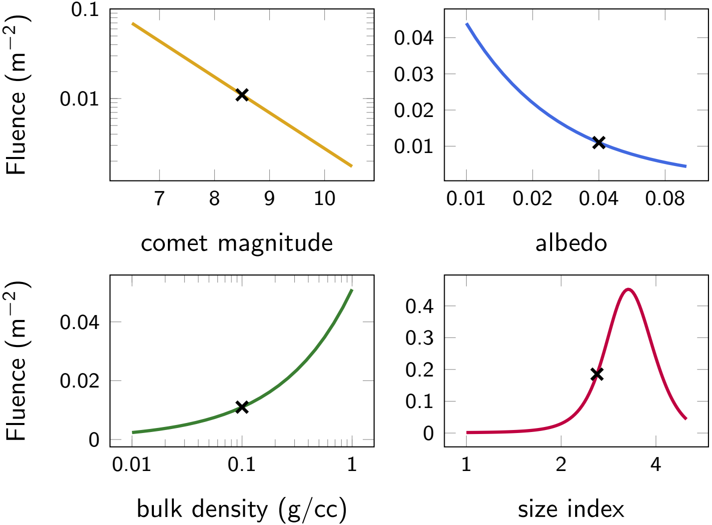
[1] 100 micron particles are capable of cutting exposed spacecraft wires. Mass limit is 4×10^{-6} g, actual size limit depends on density

Analytic model

$$\sigma_* = \frac{gh^{-\beta}}{a}\left(\frac{2}{\pi}\right)^{\frac{1}{3}}\left(\frac{\rho}{3}\right)^{\frac{2}{3}} 10^{-0.4(M1-m_{\odot,1\mathrm{au}})}\ \mathrm{au}^2$$
$$\times\left(\frac{3-k}{1-k}\right)\left(\frac{m_{\mathrm{max}}^{(1-k)/3}-m_*^{(1-k)/3}}{m_{\mathrm{max}}^{(3-k)/3}-m_{\mathrm{min}}^{(3-k)/3}}\right)$$
$$\times\frac{\cos^{-1}(b/r_c)}{b\ r_c}$$

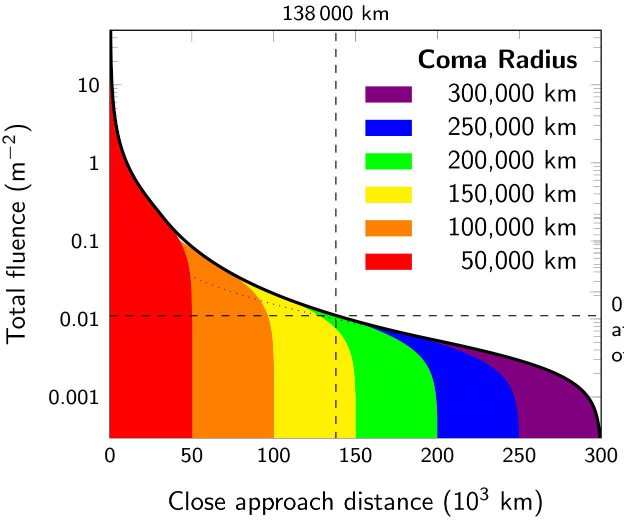
Analytic model

Dependence on comet/meteoroid properties



Analytic model

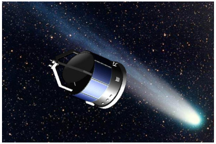
Fluence depends strongly on close approach distance

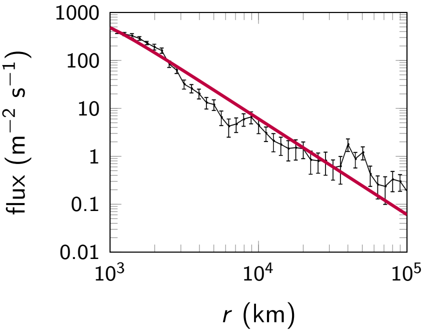


0.011 m^{-2} fluence at close approach of 138 000 km

Validation #1: reproducing *Giotto* results

- We test our model by applying it to 1P/Halley
- Using a coma radius of 200,000 km, we can reproduce the flux Giotto recorded

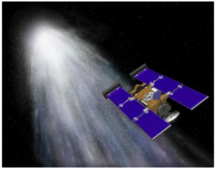


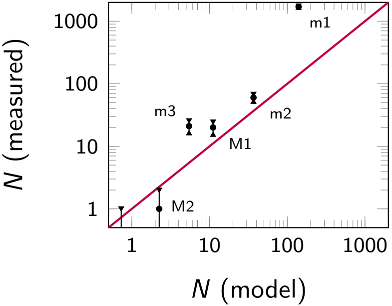


Fulle et al. (2000) data, our model

Validation #2: reproducing *Stardust* results

- *Stardust* flew 300 km from 81P/Wild 2
- Coma radius was 24,000 km at 1.7 au
- We model impacts per mass channel

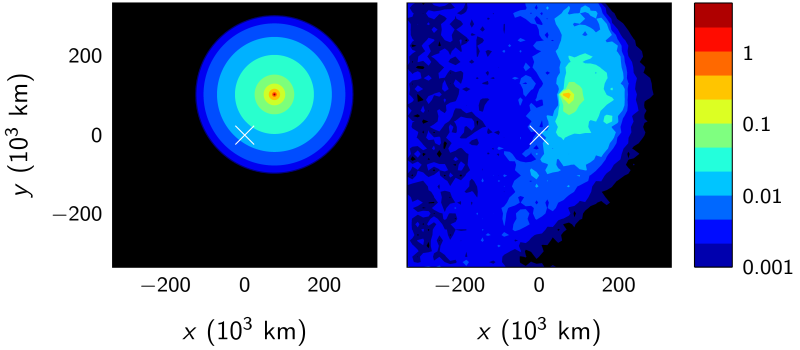




Tuzzolino et al. (2004) data, our model

Validation #3: comparison with simulations

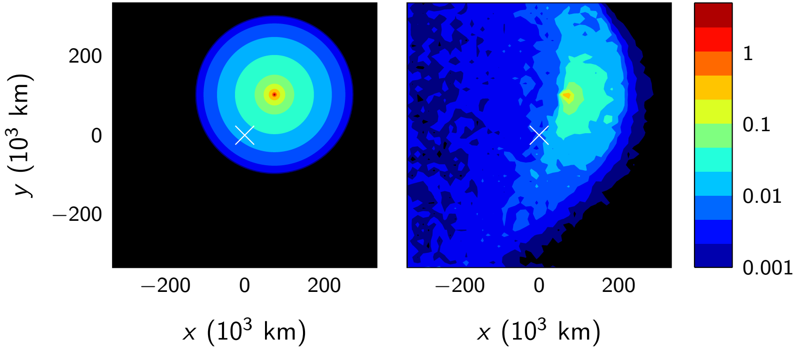
4×10^{-6}g particles



- Analytical model (left) and normalized simulations (right) in plane containing Mars (at origin), perpendicular to trajectory.
- Simulations performed by Paul Wiegert, UWO.

Validation #3: comparison with simulations

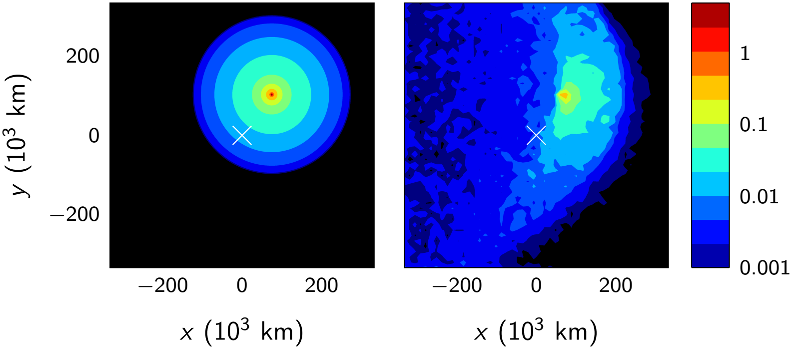
4×10^{-6}g particles



- Small scale simulations do not predict number of particles; fluence on right is multiplied by N_{theory}/N_{sim}.
- Simulations *do* illustrate (modest) deviance from spherical model due to coma asymmetry and tail.

Validation #3: comparison with simulations

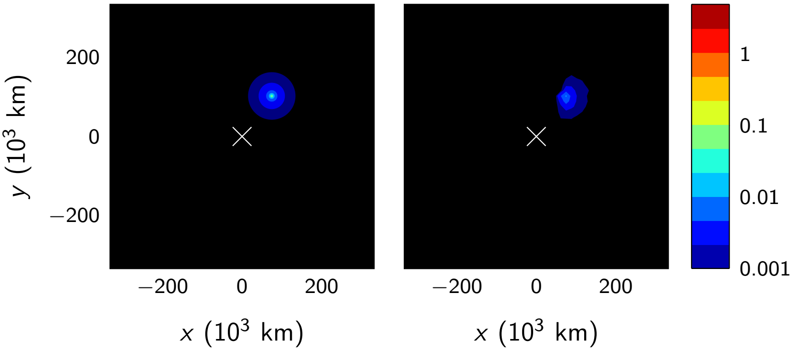
4×10^{-6}g particles



- Simulated coma has large radius (200,000 km) due to early assumed start of activity (10 AU)
- Effective radius may be smaller – needs further study

Validation #3: comparison with simulations

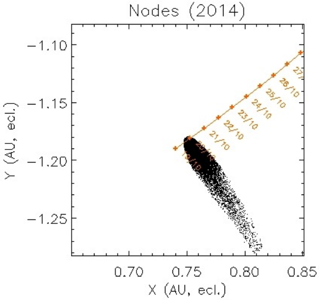
4×10^{-3}g particles



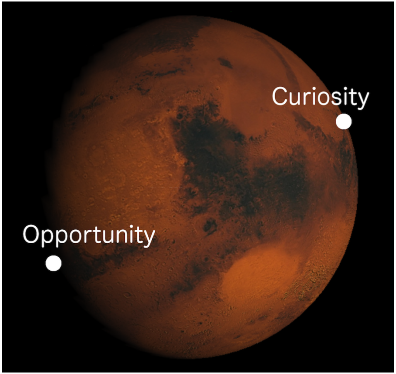
- Larger particles:
  - Have lower ejection velocity
  - Are less subject to radiative forces

Validation #4: comparison with independent studies

- Parallel effort to model coma particle dynamics: Vaubaillon et al., 2014
- Uses $Af\rho$ rather than magnitude to scale dust production.
- Results agree to within an order of magnitude ... with the same input parameters



Martian meteor shower



- Meteor shower will accompany Siding Spring
- ZHR for 10^{-6} g particles $\sim$ 30,000,000 at Mars
- Subradiant near Opportunity at dawn
- MarsExpress may see up to 1000 meteors per minute
    - 10,704 km^2 FOV
    - $m \gtrsim 3$ g
    - Numbers from Anastasios Margonis

Meteoroid impact risks

1966 Leonids by A. Scott Murrell

- Average flux of 100 micron or larger meteoroids in low Earth orbit is 5×10^{-6} m^{-2} per hour
- Fluence due to Siding Spring is 500 times higher (5 years of LEO exposure)
- There has never been an event like this near Earth in recent memory, with the possible exception of the 1966 Leonids.

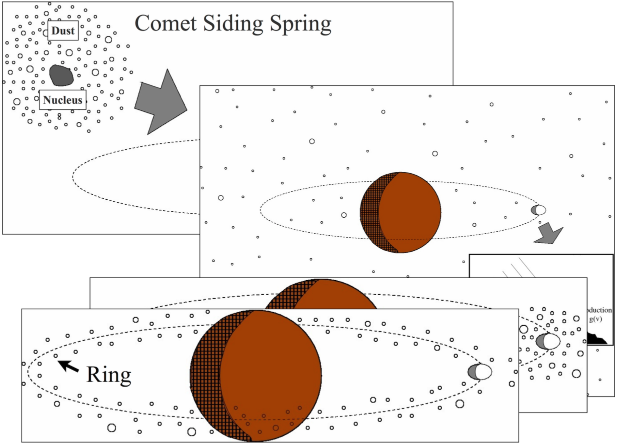
Effects on the Martian atmosphere

- Atmospheric effects
  - Energy deposition:

$$\mathrm{KE} = \int \frac{d\sigma}{dm} m \; dm \times \frac{v^2}{2} \times \pi r_M^2$$

  - 1.14 megatons of TNT equivalent
  - 0.006% of solar irradiance: insignificant
- Metal deposition probably more important (John Plane, Leeds)

Effects on the Martian system



Impact ejecta from the moons could last months or years (Apostolos Christou, Armagh)

Brightness monitoring

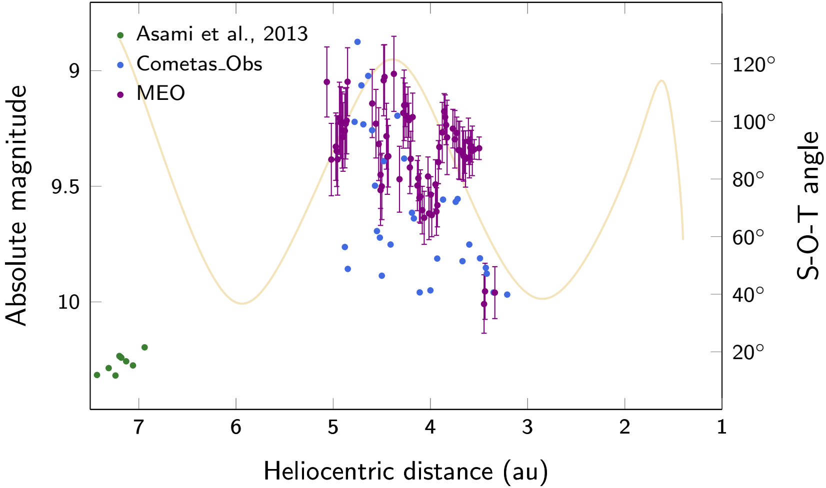
1 m at Siding Spring

Hubble

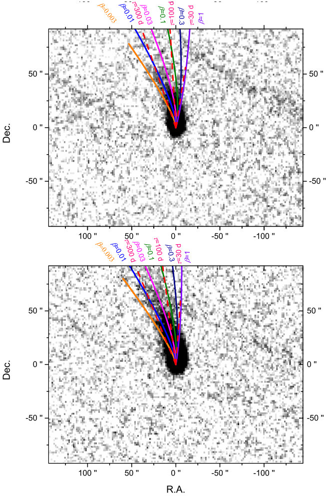
Multiple efforts to monitor Siding Spring:

- NMSkies, 0.5m (MEO)
- Siding Spring, 1m (MEO)
- Siding Spring, 2m (Christou, Armagh)
- NEOWISE
- Hubble (PI: Jian-Yang Li)

Brightness monitoring



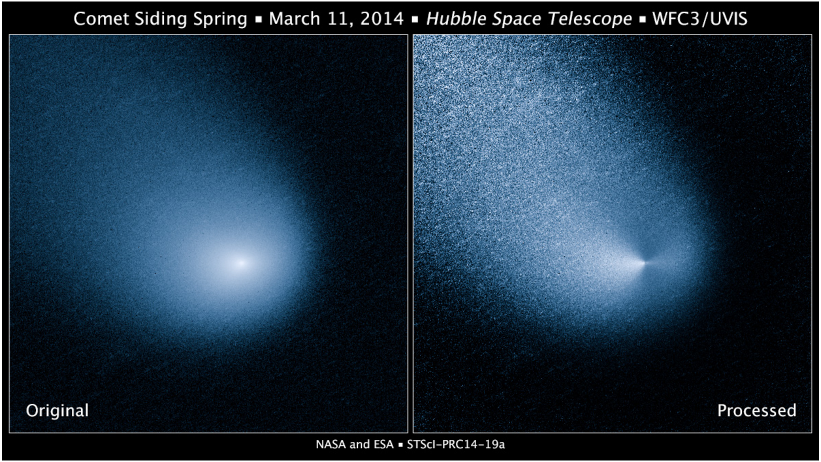
Syndyne calculations



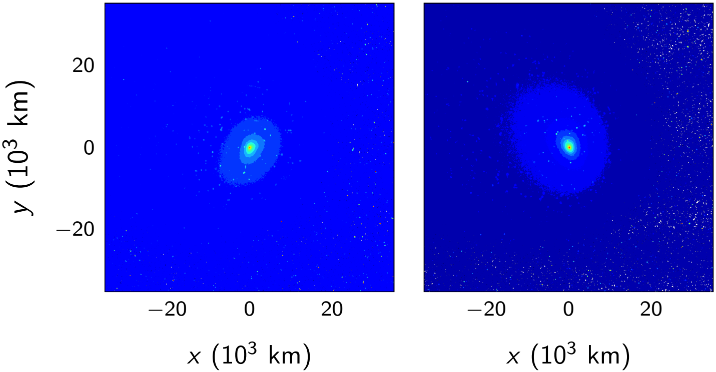
Ye & Hui, 2014

- Ye & Hui, 2014:
  - Shape of cometary tail is influenced by gravity and radiation pressure
  - "Mostly large particles" based on curvature of tail
  - Low ejection velocity based on compactness of the coma
- Low ejection velocity
  = compact coma
  = much lower fluence at Mars

Hubble observations



Hubble observations



The coma does appear to be expanding slowly

Heliocentric magnitude: Hale-Bopp

Hale-Bopp had three phases of activity pre-perihelion (Kidger, 1997)

- $\propto r^{-5}$ at large distances
- $\propto r^{-1}$ around 4 au (a "standstill")
- $\propto r^{-3.5}$ at smaller heliocentric distances

Kidger notes that ice sublimation begins around 4 au

Heliocentric magnitude: Hale-Bopp

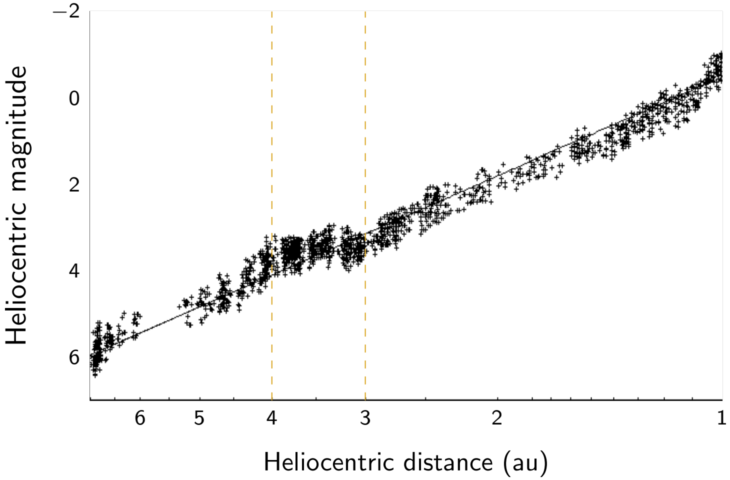
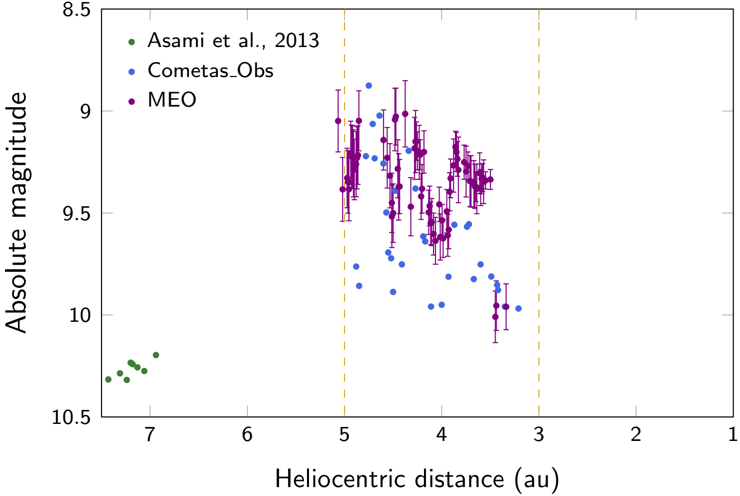


Image credit: A. Kammerer

Heliocentric magnitude: Siding Spring



Summary

- Comet C/2013 A1 (Siding Spring) will have close encounter with Mars on October 19, 2014
- Mars and spacecraft will pass through coma and tail containing meteoroids
- Meteoroids (4.19×10^{-6} g or larger): $\sim$ 1% chance of impact per square meter due to coma and tail
- Continued monitoring is needed to better predict future behavior