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

1. Comet background
   - C/2013 A1 (Siding Spring)
   - Mars encounter
   - Mars spacecraft

2. Coma model
   - Analytic model
   - Validation and simulations
   - Effects at Mars

3. Recent observations
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   - Observational constraints
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## Comet types: classed by orbit

![Comet orbit diagram](image)

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

- 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

- **Hale-Bopp:**
  - Discovered at 7.2 AU
  - Coma was 1 million km in August 1995

- **Siding Spring:**
  - Imaged at 10 AU
  - Already active

Comet Hale-Bopp, NASA
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
NEAR MISS!

Comet Siding Spring (C/2013 A1) is racing toward Mars for a close encounter in October, 2014.

Closest approach to Mars: 
~86,000 miles (138,000 km) 
OCT 19 2014

[Planetary orbits drawn to scale; object icons not to scale]
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
Comet background
Coma model
Recent observations

C/2013 A1 (Siding Spring)
Mars encounter
Mars spacecraft

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

Impact  Plasma formation  Initial electron motion  Plasma expansion
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.
Our analytic model can be used to quickly calculate new fluence estimates as comet properties are measured/constrained.

100 micron particles are capable of cutting exposed spacecraft wires. Mass limit is $4 \times 10^{-6}$ g, actual size limit depends on density.
Analytic model

\[ \sigma_* = \frac{gh^{-\beta}}{a} \left( \frac{2}{\pi} \right)^{\frac{1}{3}} \left( \frac{\rho}{3} \right)^{\frac{2}{3}} 10^{-0.4(M1-m_{\odot,1\text{au}})} \text{ au}^2 \]

\[ \times \left( \frac{3 - k}{1 - k} \right) \left( \frac{m_{\text{max}}^{(1-k)/3} - m_*^{(1-k)/3}}{m_{\text{max}}^{(3-k)/3} - m_{\text{min}}^{(3-k)/3}} \right) \]

\[ \times \cos^{-1}(b/r_c) \]

\[ \frac{b}{r_c} \]
Analytic model

Dependence on comet/meteoroid properties

- Fluence ($m^{-2}$) vs. comet magnitude
- Fluence ($m^{-2}$) vs. albedo
- Fluence ($m^{-2}$) vs. bulk density (g/cc)
- Fluence ($m^{-2}$) vs. size index
Comet background
Coma model
Recent observations
Analytic model
Validation and simulations
Effects at Mars

Analytic model
Fluence depends strongly on close approach distance

![Graph showing the relationship between close approach distance and total fluence. The graph indicates that there is a significant decrease in fluence as the close approach distance increases, with a sharp drop near 138,000 km. The graph also highlights different coma radii (300,000 km, 250,000 km, 200,000 km, 150,000 km, 100,000 km, 50,000 km) and shows that the fluence at close approach of 138,000 km is 0.011 m\(^{-2}\).]
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

![Graph showing flux vs. distance](image)

*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

![Diagram of Stardust spacecraft](image)

*Tuzzolino et al. (2004)* data, our model
Validation #3: comparison with simulations

$4 \times 10^{-6}$ 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

$4 \times 10^{-6}$g particles

- Small scale simulations do not predict number of particles; fluence on right is multiplied by $N_{\text{theory}}/N_{\text{sim}}$.
- Simulations do illustrate (modest) deviance from spherical model due to coma asymmetry and tail.
Validation #3: comparison with simulations

$4 \times 10^{-6}$ 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

$4 \times 10^{-3}$ 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

- Average flux of 100 micron or larger meteoroids in low Earth orbit is $5 \times 10^{-6} \text{ m}^{-2} \text{ per hour}$
- 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.

1966 Leonids by A. Scott Murrell
Effects on the Martian atmosphere

- Atmospheric effects
  - Energy deposition:

\[
KE = \int \frac{d\sigma}{dm} m \, dm \times \frac{v^2}{2} \times \pi r_M^2
\]

- 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)
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

Asami et al., 2013
Cometas_Obs
MEO

Heliocentric distance (au)

Absolute magnitude

S-O-T angle

Heliocentric distance (au)
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

Ye & Hui, 2014
Hubble observations

Comet Siding Spring • March 11, 2014 • Hubble Space Telescope • WFC3/UVIS

Original

Processed

NASA and ESA • STScI-PRC14-19a
The coma does appear to be expanding slowly.
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

Heliocentric distance (au)

Image credit: A. Kammerer
Heliocentric magnitude: Siding Spring

![Graph showing the relationship between heliocentric distance (au) and absolute magnitude for comet observations. The graph includes data from Asami et al., 2013, Cometas_Obs, and MEO.](image)
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 ($4.19 \times 10^{-6}$ 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.