Comet /2013 A1 Siding Spring
Comet Environment Modeling

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Siding Spring Observatory
NEOWISE Image of C/SS
C/SS: Comet /2013 A1 Siding Spring
Comet Siding Spring Modeling Activity

Background:

- Comet C/2013 A1 Siding Spring (C/SS) discovered in January 2013. Long-period comet on first passage from Oort Cloud.
- Predicted closest passage to Mars on **October 19, 2014**.
  - Post April’13 observations rule out possibility of Mars impact;
  - Comet reaches perihelion at 1.399 AU just inside Mars orbit on October 25, 2014.
- Preliminary modeling suggested that the comet fluence (i.e., the number of particles encountered during passage through the cometary debris) could be equivalent to several years of the meteoritic background flux.
- Mars atmosphere will protect surface assets.
- **Fast-moving dust particles (~56km/sec) could harm a Mars orbiter**
- Gas and ions are not of great concern
  - At risk: ODY, MRO, MEX, MAVEN (MOI on Sept. 22) & MOM (arriving Sept. 23)

Current solutions (JPL orbit solution 46; Farnocchia et al., sub. to ApJ):

- Closest passage to Mars occurs on **October 19, 2014 at 18:29 UTC ± 3 min**
- Closest approach distance is **135,200 ± 4500 km (3-sigma)**
Comet Modeling for Risk Mitigation

Model the comet-produced dust distribution as a function of time

- In fall of 2013, two modeling groups were selected through the MEP Critical Data Products program to help with this:
  - Pasquale Tricarico, Nalin H. Samarasinha, Mark Sykes, PSI
  - Tony Farnham, Mike S. P. Kelley, Dennis Bodewits, U. Maryland
- Also participating, providing time-of-arrival of comet nucleus and debris:
  - Davide Farnocchia, Paul Chodas, Steven Chesley, JPL Solar System Dynamics Group
- Beginning in January, several telecons were held over the following weeks, with a face-to-face meeting on March 11, 2014.
- Near-final reports were provided prior to end of April, 2014.
- Comet modeling peer review held on May 6, 2014.
- Reports have been or will soon be submitted for publication
  - Farnocchia et al., submitted to Astrophysical Journal
  - Farnham et al., in preparation

Goals of the modeling activity

- Provide arrival timing and duration of the comet-associated particle flux at Mars
- Characterize the comet-derived particles in terms of size and number density
- Constrain the modeling results using available observations of the comet
Keys to Comet Modeling

- **Gas and Dust production rates as a function of time: How many particles are ejected and when?**
  - The basic activity (volatility) of the comet determines the total number and size variation of the particles that could impact Mars.
  - Transfer of momentum from volatized gas ejects the dust particles and determines their velocities. This changes as a function of heliocentric distance (input energy).
  - Activity of the comet
    - More exposure of ices and/or more volatile ice compositions affect when particles are ejected.
    - Particles with lower speeds can reach the encounter zone even if ejected earlier.

- **Which dust particles will encounter Mars?**
  - Speed of ejected particles
    - Constrained by energy available and so dependent on heliocentric distance;
    - Dependent on particle mass/size (momentum transfer) & nucleus size (comet gravity).
  - Effects of solar radiation pressure
    - Dependent on particle mass and size: More effective on smaller particles.

- **Observational Constraints**
  - Cannot compute from first principles the velocities and sizes of emitted particles;
  - Observations provide estimates of production rates and constraints on ejection speeds
    - Note: Observations tend to be dominated by small (~micron-sized) particles while it is the larger particles that are the greater hazard => weaker observational constraints on the most hazardous particles
  - Models translate these into particle distributions as a function of time.
C/SS Observations

### Table I. Siding Spring Observational Data

<table>
<thead>
<tr>
<th>Date</th>
<th>$r_h$ (^1) (AU)</th>
<th>$\Delta$ (^2) (AU)</th>
<th>$\alpha$ (^3) (deg)</th>
<th>$A(0)f_p$ (^4) (cm)</th>
<th>Comments (^5)</th>
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<td>1460</td>
<td>$Q(CO_2) = 3.5 \times 10^{26}$</td>
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</table>

\(^1\) Heliocentric distance  
\(^2\) Geocentric distance or Spacecraft range  
\(^3\) Solar phase angle  
\(^4\) A measure of dust in the coma  
\(^5\) $Q =$ gas production (molecules/sec)
Comet Modeling Results

➢ Mars will pass near the edge of the comet debris trail
  – Whether it is inside the debris cloud (with particles encountering Mars and Mars orbiters) or outside the edge (with no meteors crossing Mars vicinity) depends critically upon the velocity at which particles are ejected from the nucleus.

  • Observational constraints imply the velocities are relatively low.
    o Reference velocities expressed in terms of a 1 mm-radius particle at a heliocentric distance of 5 AU;
    o Observations ⇒ $V_{ref} < 1 \text{ m/s}$ (relative to comet nucleus moving at ~56 km/s).

  – The time of greatest danger is when Mars comes closest (~27,600 km) to the comet trajectory, not when the comet nucleus comes closest to Mars (~135,000 km).

  • At low ejection velocities, the particles tend to linger near the comet’s path.
  • At these velocities, the particles that could reach Mars had to be ejected more than a year ago.

  – Only larger particles (>0.5 mm in radius) are predicted to reach Mars.
    • Smaller particles have been cleared out by solar radiation pressure.
Comet Modeling: Mars at the Edge

Three groups modeling the distribution of dust particles from comet C/2013 A1 Siding Spring during its close approach to Mars.

Solar System Dynamics Group
Farnocchia et al.

Note: Calculations are for dust particles > 100 µm diameter

Univ. of Maryland
*T. Farnham, M. Kelley, et al.

PSI
*P. Tricarico et al.

*Supported by the MPO Critical Data Products Program (CDP)
Vref: A Key Parameter

\[ V_{\text{eject}} \sim V_{\text{ref}} \cdot \left(\frac{5}{D}\right) \cdot \left(\frac{r}{1000}\right)^{0.5} \]

- \( r = \) particle radius (\( \mu m \))
- \( D = \) heliocentric distance (AU)

**Fig. 2.** Distribution of grain radius and close approach time from \( \text{c/a} \) [hr].

**Fig. 1.** Ejection velocity of dust grains with different density.

\[ \rho_{\text{ref}} = 1.5 \text{ m/s} \quad \rho_{\text{ref}} = 2.0 \text{ m/s} \quad \rho_{\text{ref}} = 2.5 \text{ m/s} \quad \rho_{\text{ref}} = 3.0 \text{ m/s} \]

Comet Siding Spring Dust Analysis

The modeling is done in a stepwise manner, by assigning values to the dust parameters that are needed for our hazard analyses. The results from all of our analyses suggest that comet Siding Spring is fairly typical for a dynamically new comet. For purposes of our hazard analysis, we developed a model that matches the observations and can be used to project the comet’s behavior backward and forward in time to simulate the conditions that will be present during the Mars close approach.

Detailed Modeling Provides Tighter Constraints

- Syndynes: loci of constant size
- Earth crossing C/SS orbital plane
- Synchrones: loci of all sizes emitted at 1 time

Using HST images to constrain Comet Model Parameters

Farnham et al. => Vref ~0.4 m/s

Model Versus Observed Brightness Contours
Specific Modeling Results

- **Best estimate:**
  - $V_{ref} \sim 0.4$ m/s
  - Mars will be just outside the debris trail, encountering no particles.

- **Conservative estimate:**
  - Case 1 (Farnham/Farnocchia): $V_{ref} \sim 0.7$ m/s, particles encounter Mars in a 20 minute window centered at 98 minutes after closest approach of the nucleus;
    - Fluence$^1$ is: $\sim 1-4 \times 10^{-7}$ particles/m$^2$;
  - Case 2 (Tricarico): Assuming a high velocity tail (at a few %) with $V_{ref} \sim 1.5$ m/s, particles encounter Mars in a 30 minute span centered at 95 minutes after closest approach;
    - Fluence$^1$ $\sim 3\% \times 2 \times 10^{-5}$ particles/m$^2$ = $6 \times 10^{-7}$ particles/m$^2$;
  - Summary: Fluence$^1$ is: < $10^{-6}$ particles/m$^2$.

- **Extreme case:** Use unrealistically high velocity component ($V_{ref} = 3$ m/s) assigned to jets/outbursts (a few %) and power law favoring large particles:
  - Fluence$^1$ $\sim 2\% \times 1.3\times 10^{-2}$ particles/m$^2$ $\sim 3 \times 10^{-4}$ particles/m$^2$.

$^1$Fluence = total # of particles encountered per unit area during event
**Figure 3.** Grain count flux normalized to the total fluence and binned over ten-minute periods, to represent the fraction of grains colliding with Mars. The error bars are representative of the counting statistics.

In Figure 4 we have the integrated fluence (count and mass) versus the grain ejection velocity parameter \( v_{\text{ref}} \) and at different SFD index values. The figure provides the fluence value in the case of all ejected grains where at the given \( v_{\text{ref}} \) value, but as we have discussed above, HST observations indicate lower velocities at which no grains intercept Mars, so these suggest that the plots is to assume that while the \( v_{\text{ref}} \) parameter from HST indicates the velocity of the bulk of the grains, it is possible that the velocity distribution of grains contain an high-velocity tail, so that a few percent of the grains will have these high velocities. Processes responsible for this could be the presence of jets, or the shape of the nucleus causing non-uniformities in the gas flow and consequently in the grain acceleration from the surface. In view of this interpretation, the fluence values in Figure 4 should be decreased by approximately two orders of magnitude for \( v_{\text{ref}} \) near 1.5 m/s, with possibly even stronger attenuation at even higher velocities.

The radiant of the dust grains is at R.A. 41° and Dec. −15.5° in the Cetus constellation. In Figure 5 we show the hemisphere of Mars which is exposed to dust grains.

**4. Discussion**

The results presented here can be compared with previous works already in the literature. In Moorhead et al. (2014) the order of magnitude of the dust grains fluence is determined using both analytic and numerical approaches, obtaining a count fluence of \( 0.15 \, \text{m}^{-2} \). In their model, the comet orbit solution was not yet as constrained as it is in our work, the grain densities used are relatively low, and the ejection velocities appear significantly higher than what we used. Additionally, their analytical approach does not include radiation pressure. We find that the modeling details and parameters in Moorhead et al. (2014) are supported by observations such as 2014 P. Tricarico et al., ApJL, 787, L35, 2014.
Comet Encounter Target File (CETF)

CETF generated on 4/25/14 by Rob Lock (Mars Program Office).
Next update expected late June 2014; subsequent updates as needed.

Comet Encounter Target File (CETF)
Generated April 25, 2014 by R. Lock

********************************************************************************
Hiding Zone center location (Mars Mean Equator of J2000 reference frame)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tr>
<td>Right Ascension</td>
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<tr>
<td>Declination</td>
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<tr>
<td>Time of particle fluence center</td>
<td>2014 Oct 19 20:07 (UTC-SCET)</td>
</tr>
<tr>
<td>Tolerance of time estimate</td>
<td>plus/minus 2 minutes</td>
</tr>
</tbody>
</table>

********************************************************************************

Note: the time of particle fluence center is the time specified by the Mars program as 98 minutes after the closest approach.

Sources:
Comet C/2013 A1 Siding Spring
Solution #46
SPK: ftp://ssd.jpl.nasa.gov/pub/xfr/c2013a1_s46_merged_DE431.bsp (Binary SPK format)
C2013A1_delivery_memorandum_2014-3-31.doc
CSS_project_brief_2014_04_14c.ppt
How Many?

Fluence: Number of particles per m² encountered during passage through comet debris

- Vaubaillon et al., *MNRAS*, 2014
- Moorhead et al.
- Farnham et al.
- Li et al.
- Tricarico et al.

**Emission Reference Velocity (Vref)**

*Constraints on Vref from HST Analysis*

*5-Yr b/g meteors*

*Upper Limit: Farnham et al.*

*A high velocity tail (e.g., due to jets or outbursts) is still constrained by the observations to be only a few % of the total particles*

*Ye & Hui 2014*

LMSSC table (for 2.5 g/cc particles ≥ .5 mm @ 20 km/s)
Comparison of Flux & Fluences

• Plot on right below compares the total fluence estimated for C/SS with the Mars & Earth MM background and various meteor streams at Earth.
  – Even conservative fluences derived from modeling C/SS are much lower than those being faced by spacecraft orbiting either Mars or Earth—but the particles all come in a short period of time

• Plot on left shows the short-term flux experienced during the events
  – Short-term flux from CSS is higher than the background MMOD and annual meteor shower threat but about an order of magnitude lower than the flux from the Leonid 1999-2002 meteor storms

Provided by Glenn Peterson, Aerospace Corporation
Comet Modeling Peer Reviewers

A peer review of the comet modeling results was held via a telecon on May 6, 2014. The reviewers were:

- Michael Combi, U. Michigan
- Mihaly Horanyi, LASP, U. Colorado
- Carey (Casey) Lisse, JHUAPL
- Althea Moorhead, NASA MSFC
- Glenn Peterson, Aerospace Corp.
- David Schleicher, Lowell Observatory

____________________________________

Kelly Fast (NASA), Rich Zurek & Serina Diniega (MPO/JPL)
Peer Review Charter Questions

1) Have all processes that could make a significant difference to the results been considered?  
   Yes

2) Has the key information that is available been used to properly constrain the modeling results?  
   Yes¹

3) Are there any deficiencies in the modeling that significantly affect the conclusions and that could reasonably be corrected?  
   No²

4) Are the conclusions consistent with models, between models, and with the key observations?  
   Yes

5) What confidence should the Program and Mars Projects place on these results; i.e., are uncertainties being properly communicated?  
   Yes

Footnotes:

¹Reviewers noted the advisability of continuing to monitor the comet’s activity; observations are starting again in June following the comet’s solar conjunction. Best viewing is later this summer (August-September).

²With caveats discussed on next slide.
Caveats

Could a *late* outburst of particles within weeks of the October 2014 encounter present a danger to the orbiters?

- To reach Mars at this time the particles would have to have very high velocities.
  - The particles would form a more circular coma and would encounter Mars at closest approach of the nucleus;
  - Only the smallest particles could reach the necessary speeds;
  - Solar radiation pressure is more effective on these particles and would move all but the faster particles away from Mars;
  - The required velocities (for impact) would have to be a large fraction of the gas velocities, which is judged to be not realistic.

Could an *early* outburst of particles prior to the comet modeling initial condition (at ~13 A.U.) present a danger to the orbiters?

- Activity of comet when observed has not been extraordinary;
  - The PanSTARRS NEO data base was searched and showed no detections at ~10.3 AU in December 2011, suggesting the comet was not active until it reached a heliocentric distance between 8 and 10 AU;
- There is not much energy available at those great distances to drive activity;
  - The largest particles lifted off the comet would be quite small (< 10 µm).
Summary

Comet modeling constrained by observations of C/SS has significantly changed our perception of the hazards posed by the close encounter of the comet with Mars next October.

- Early estimates made before observations were available typically assumed very high speed particles producing an immense coma.
- The relatively low particle velocities derived from analysis mean:
  - The larger particles are concentrated along the comet trajectory;
    - If the particles do reach Mars, they do so in a relatively brief period more than an hour after closest approach of the C/SS nucleus;
  - Solar radiation pressure has much more time to remove the smaller particles from the encounter zone;
- **End result**: Meteors associated with C/SS may not reach Mars (best estimate) or (conservative estimate) particles larger than 0.5 mm in radius can reach Mars 80 to 110 minutes after closest approach of the comet nucleus.

**Implications of the model/observation results for mitigation activities:**

- Orbit phasing can avoid most, if not all, of the particles reaching Mars;
- Due to their large size and high velocity relative to Mars, damage from particle impacts is less easily mitigated by spacecraft re-orientation.

**Warning**: Comets are famously variable and modeling their activity remains somewhat uncertain. Further observation of Comet Siding Spring is prudent.
View from Approaching Particle Direction
At Comet Closest Approach plus 95 minutes (20:04 UTC)


Same view as Tricario, above, with Mars Odyssey, MRO and MAVEN orbits shown
Acknowledgement: Material reported here is based on model calculations contracted through the JPL Mars Program Office Critical Data Products (CDP) program and on comet trajectory solutions developed by the JPL Solar System Dynamics Group. The following groups contributed:

Tony Farnham, Mike S. P. Kelley, Dennis Bodewits
University of Maryland

Pasquale Tricarico, Nalin H. Samarasinha, Mark Sykes
Planetary Sciences, Inc.

Davide Farnocchia, Paul Chodas, Steven Chesley
JPL Solar System Dynamics Group

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