National Aeronautics and
Space Administration

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

Mars Exploration Program

Comet /2013 A1 Siding Spring

Comet Environment Modeling

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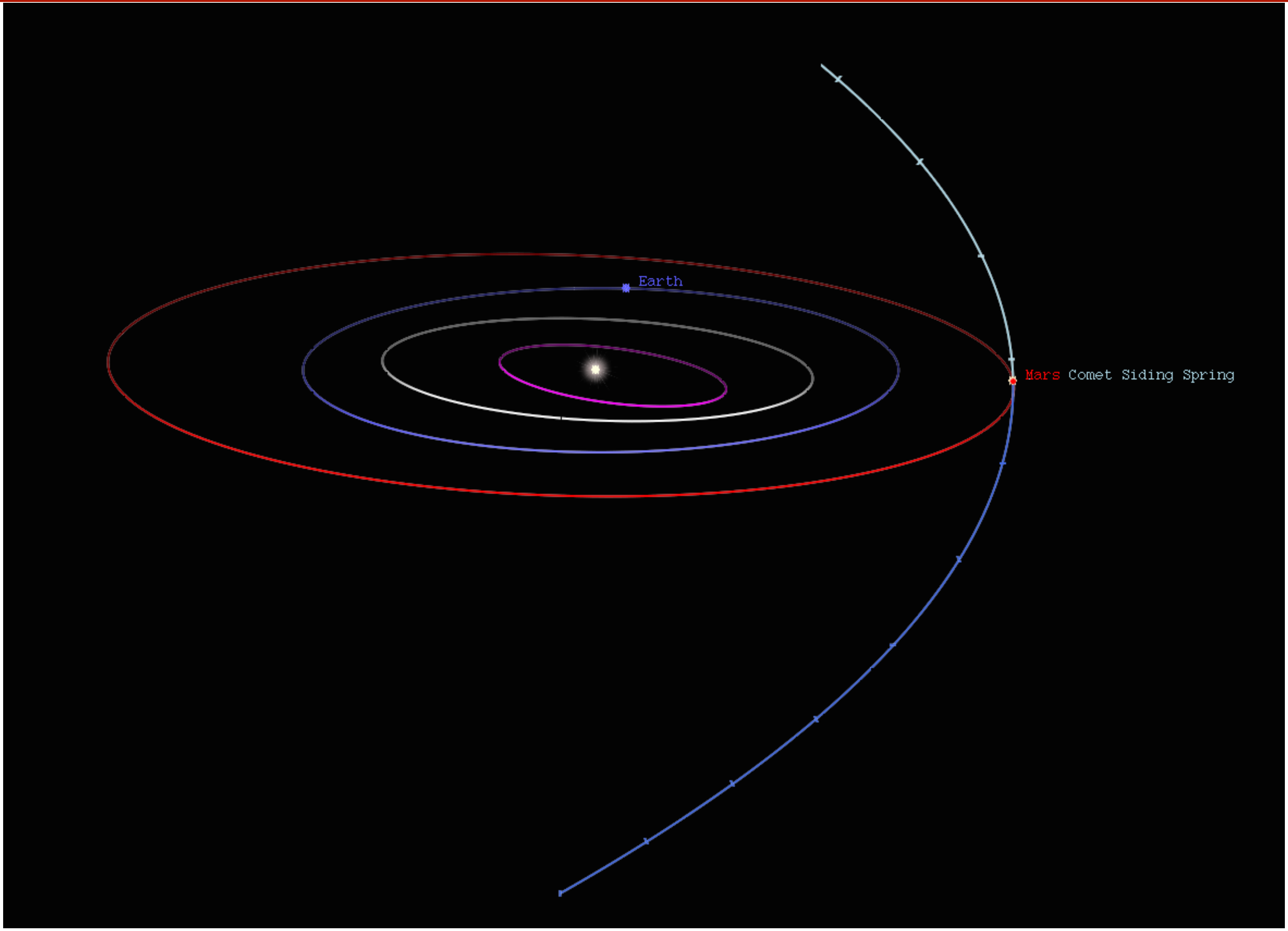
June 6, 2014

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
    - P. Tricarico et al., *Astrophysical Journal Letters*, 787, L35, 2014
    - 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

Date	r_h [1] (AU)	Δ [2] (AU)	α [3] (deg)	A(0)fρ [4] (cm)	Comments [5]
PanSTARRS					
20 Nov 2011	10.3	9.6	4		Undetected
2 Dec 2011	10.2	9.5	4		Undetected
HST/WFC3					
29 Oct 2013	4.6	4.0	11	2705	
21 Jan 2014	3.8	3.7	15	2365	
11 Mar 2014	3.3	3.8	14	1920	
NEOWISE					
16 Jan 2014	3.8	3.7	15	280	$Q(CO_2) = 4\times10^{26}$
Swift/UVOT					
2 Nov 2013	4.5	4.0	11	1740	$Q(H_2O) < 6\times10^{27}$
28 Dec 2013	4.0	3.6	14	1495	$Q(H_2O) < 2\times10^{27}$
18 Feb 2014	3.5	3.8	15	1530	$Q(H_2O) < 3\times10^{27}$
15 Mar 2014	3.2	3.8	14	1100	$Q(H_2O) < 3\times10^{27}$
Spitzer					
26 Mar 2014	3.1	3.1	19	1460	$Q(CO_2) = 3.5\times10^{26}$

[1] Heliocentric distance

[2] Geocentric distance or Spacecraft range

[3] Solar phase angle

[4] A measure of dust in the coma

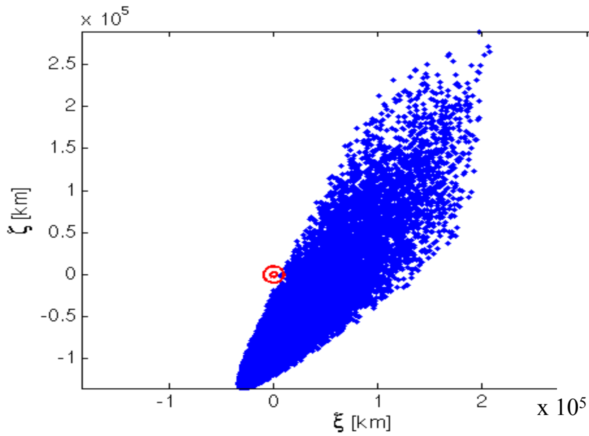
[5] Q = gas production (molecules/sec)

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.
      - Reference velocities expressed in terms of a 1 mm-radius particle at a heliocentric distance of 5 AU;
      - Observations => Vref < 1 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

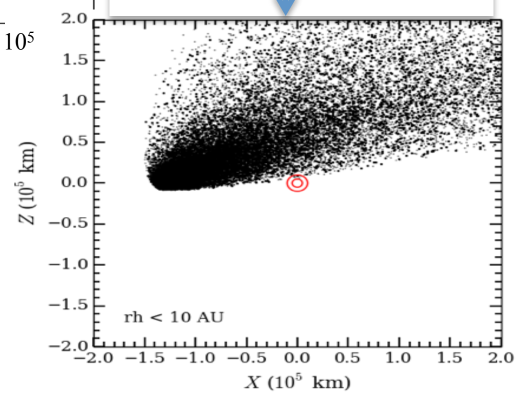
Three groups modeling the distribution of dust particles from comet C/ 2013 A1 Siding Spring during its close approach to Mars.

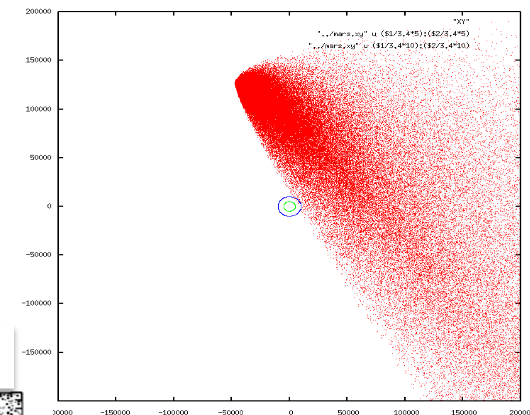


Solar System Dynamics Group
Farnocchia et al.

Note: Calculations are for dust particles > 100 µm diameter

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





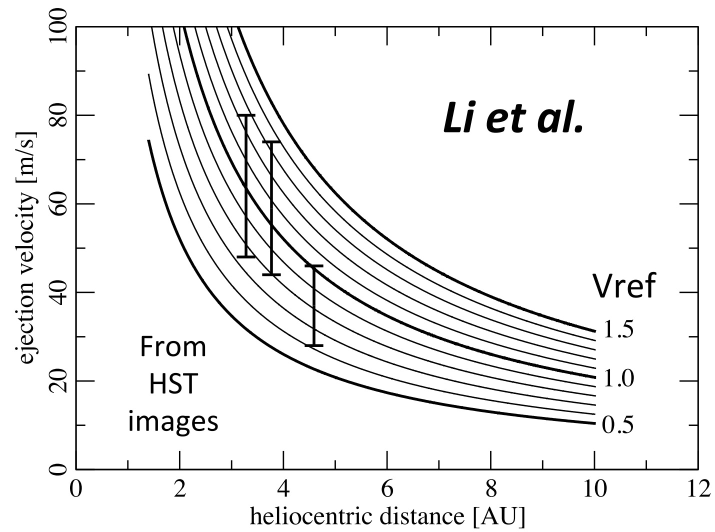
PSI
*P. Tricarico et al.

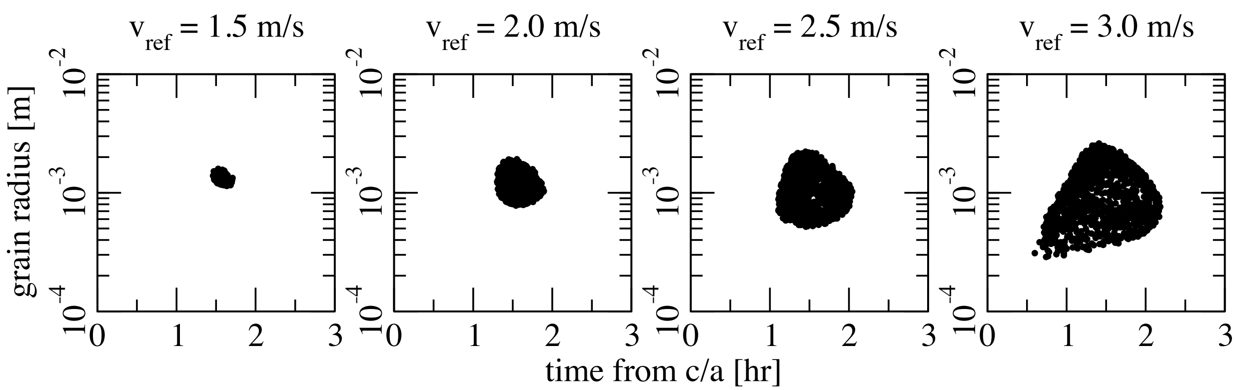
**Supported by the MPO Critical Data Products Program (CDP)*

Vref: A Key Parameter

Veject ~ Vref *(5 /D) / (r/1000)$^{0.5}$

r = particle radius (μm)
D = heliocentric distance (AU)

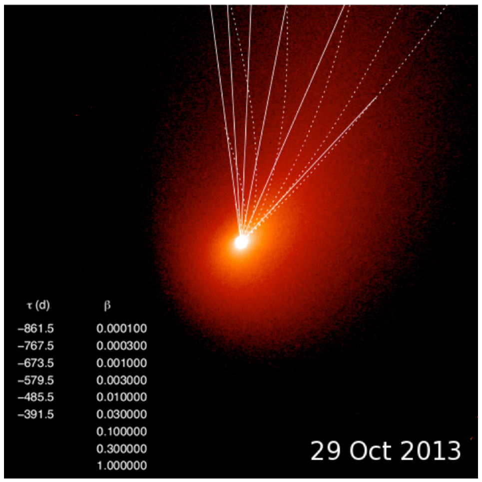




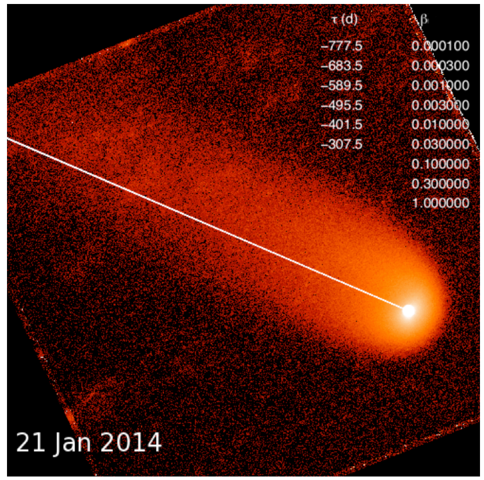
P. Tricarico et al., ApJL, 787, L35, 2014

Detailed Modeling Provides Tighter Constraints

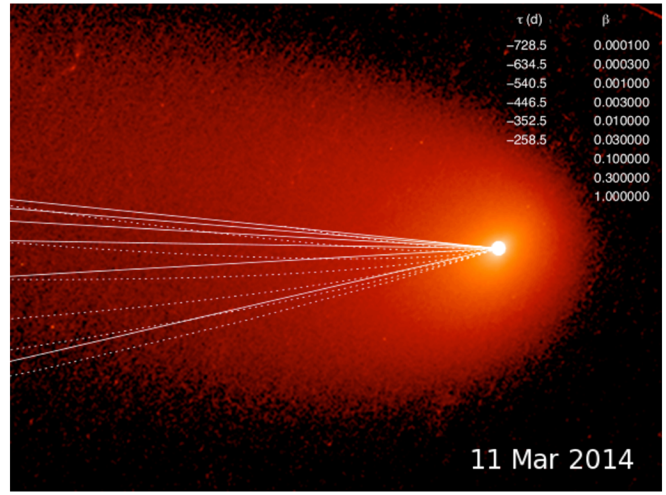
- - Syndynes: loci of constant size



Earth crossing C/SS orbital plane



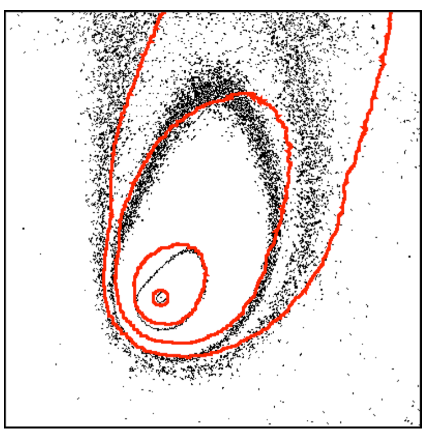
– Synchrones: loci of all sizes emitted at 1 time

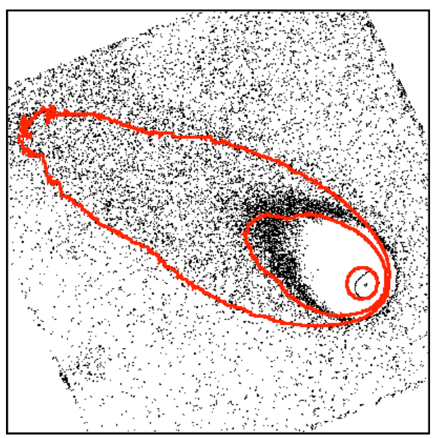


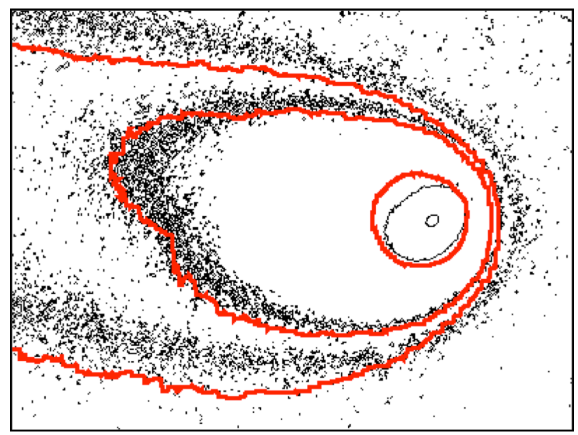
Using HST images to constrain Comet Model Parameters

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

Model Versus Observed Brightness Contours







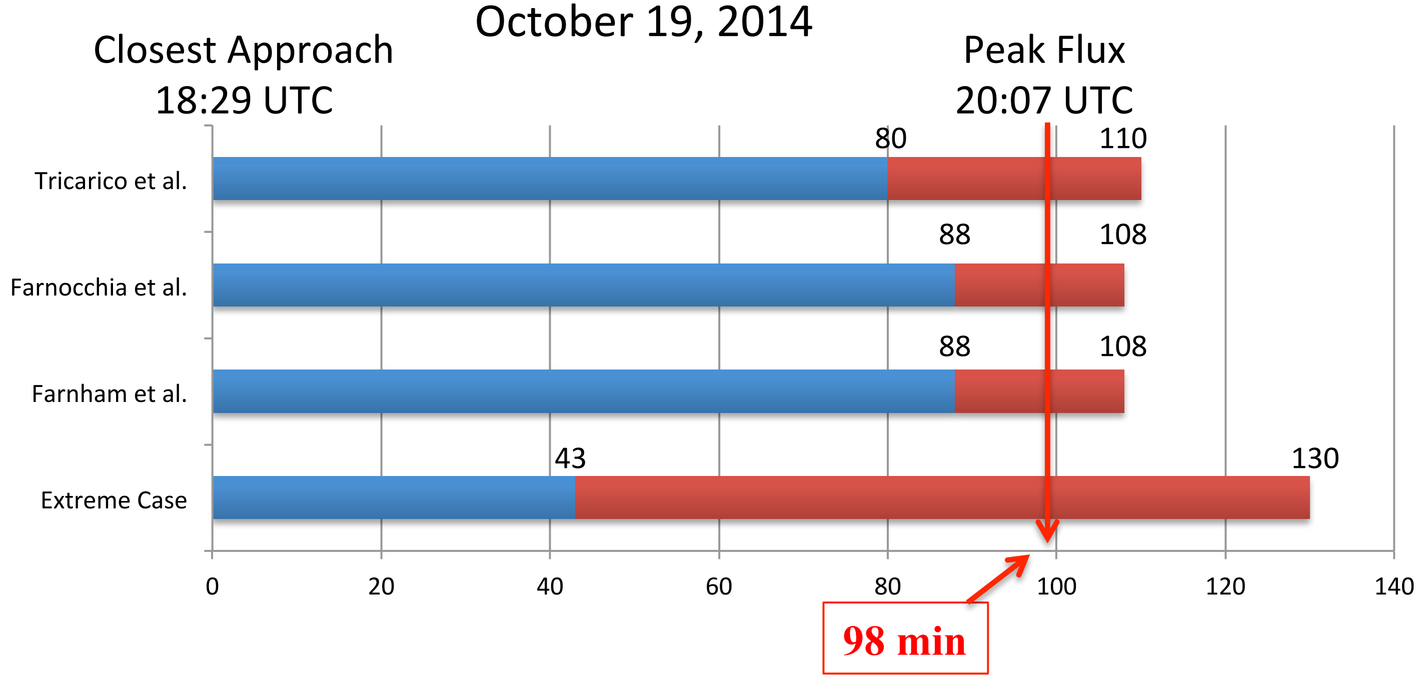
Specific Modeling Results

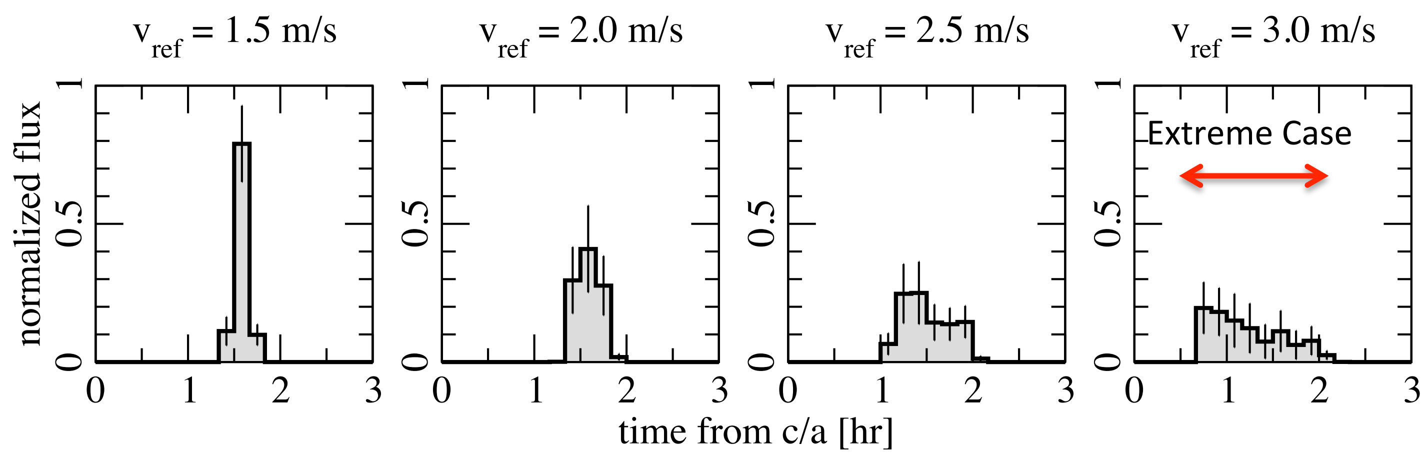
- **Best estimate**:
  - Vref ~0.4 m/s
  - Mars will be just outside the debris trail, encountering no particles.
- **Conservative estimate:**
  - Case 1 (Farnham/Farnocchia): Vref ~ 0.7 m/s, particles encounter Mars in a 20 minute window centered at 98 minutes after closest approach of the nucleus;
    - Fluence[1] is: ~ 1-4 x 10^{-7} particles/m^2 ;
  - Case 2 (Tricarico): Assuming a high velocity tail (at a few %) with Vref ~ 1.5 m/s, particles encounter Mars in a 30 minute span centered at 95 minutes after closest approach;
    - Fluence[1] ~ 3% x 2x10^{-5} particles/m^2 = 6 x 10^{-7} particles/m^2 ;
  - Summary: Fluence[1] is: < 10^{-6} particles/m^2.
- **Extreme case**: Use unrealistically high velocity component (Vref = 3 m/s) assigned to jets/outbursts (a few %) and power law favoring large particles:
    - Fluence[1] ~ 2% x 1.3x10^{-2} particles/m^2 ~ 3 x 10^{-4} particles/m^2.

[1]*Fluence = total # of particles encountered per unit area during event*

Time of Maximum Flux

October 19, 2014





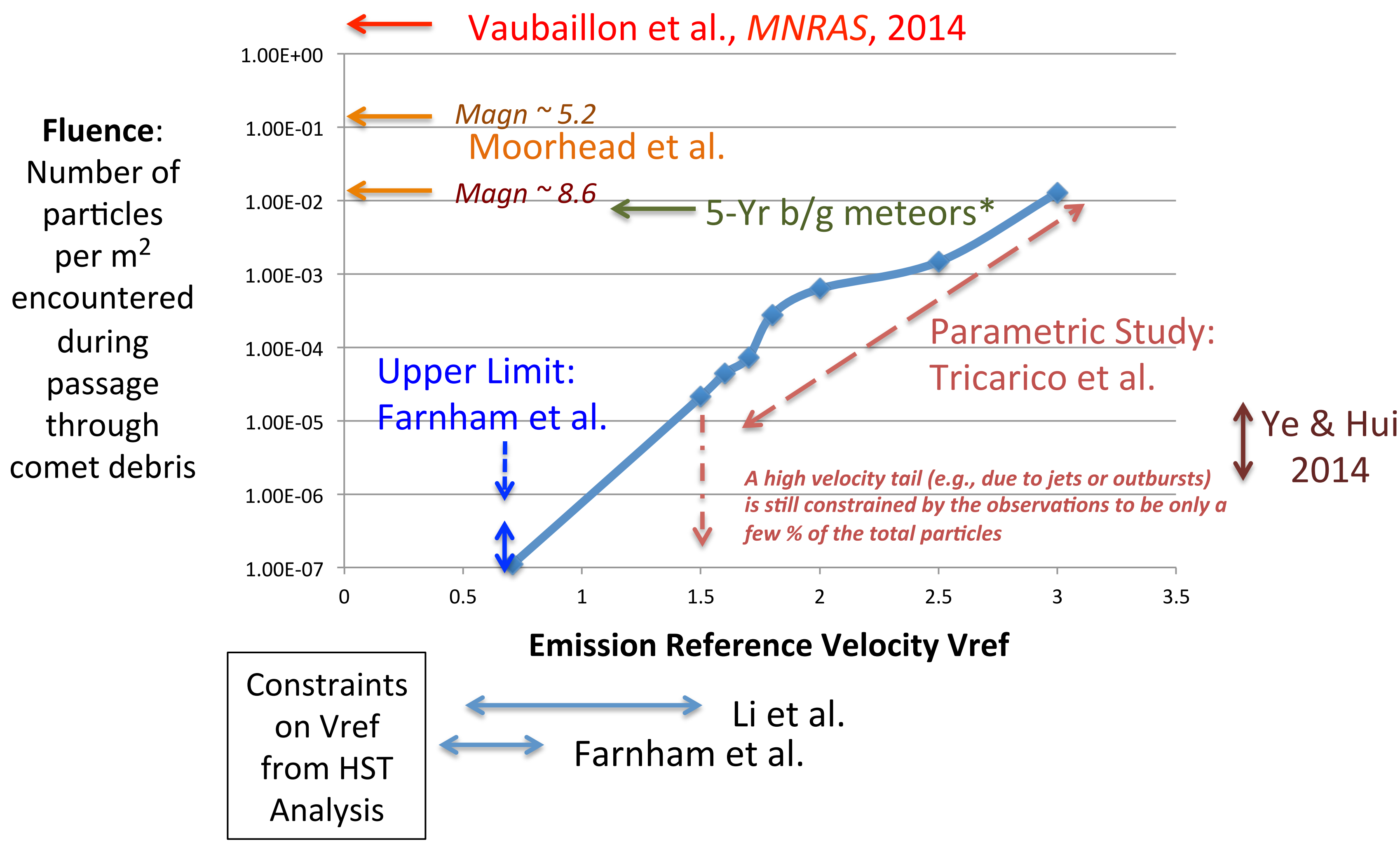
P. Tricarico et al., ApJL, 787, L35, 2014

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)

        Right Ascension:                     165.4 deg
        Declination:                         8.5 deg
        Time of particle fluence center:     2014 Oct 19 20:07 (UTC-SCET)
        Tolerance of time estimate:          plus/minus 2 minutes

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

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?

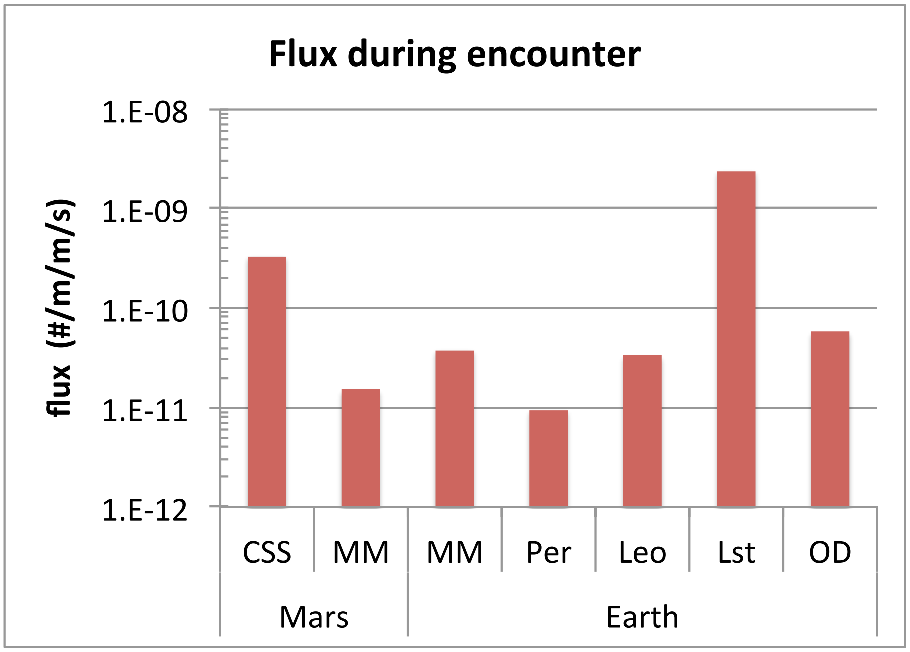


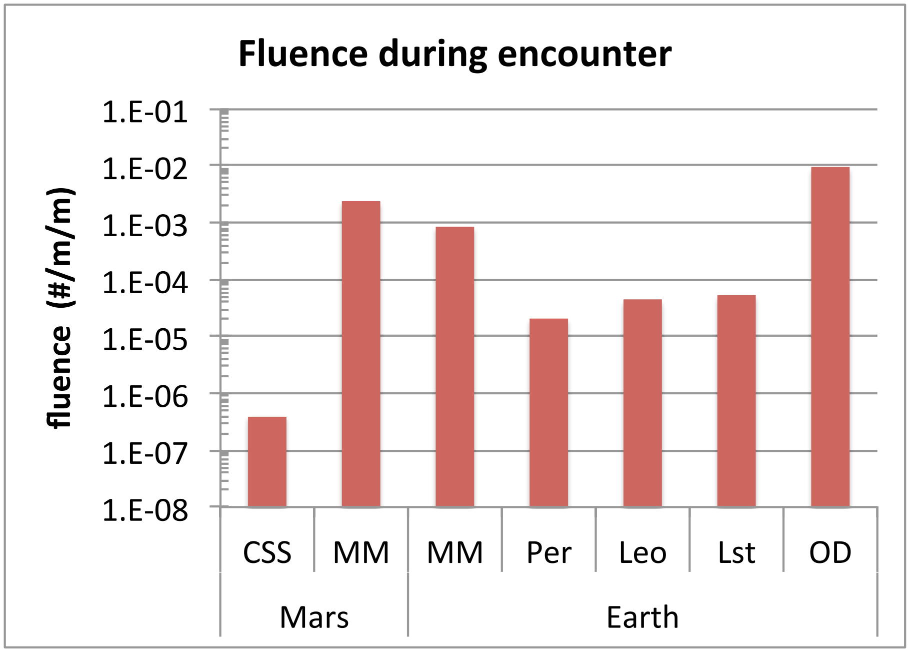
*LMSSC table (for 2.5 g/cc particles ≥ .5 mm @ 20 km/s)

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? **Yes[1]**

3) Are there any deficiencies in the modeling that significantly affect the conclusions and that could reasonably be corrected? **No[2]**

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., <u>are uncertainties being properly communicated</u>? **Yes**

<u>Footnotes</u>:

[1]Reviewers 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).

[2]With 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).

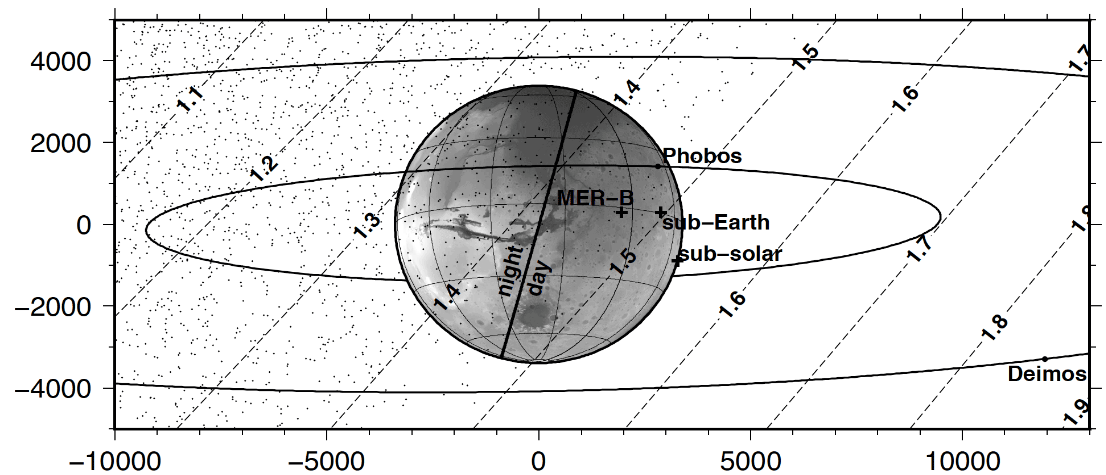
Summary

- **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

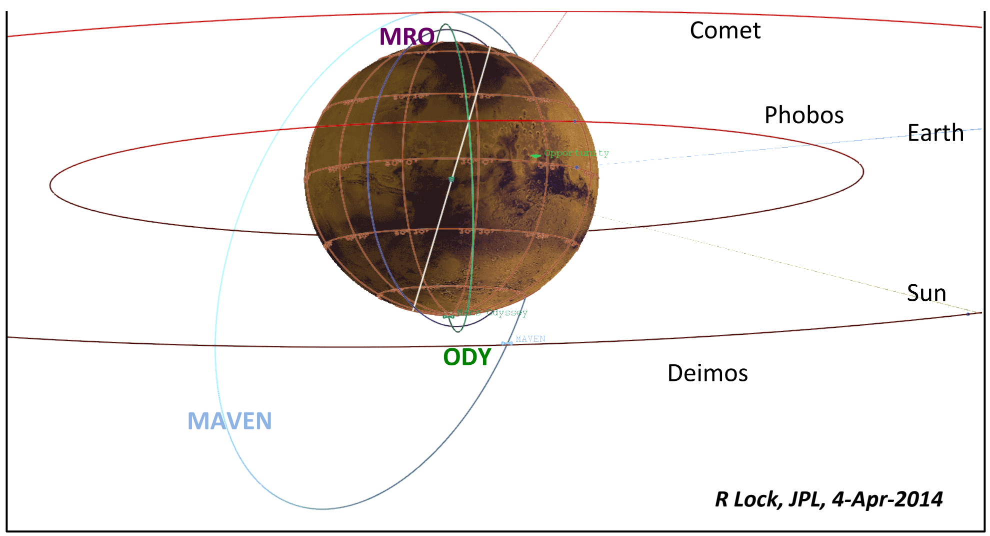
At Comet Closest Approach plus 95 minutes (20:04 UTC)

P. Tricarico et al., ApJL, 787, L35, 2014



Dashed lines show edge of the CSS debris cloud as a function of Vref. Particle density is reflected for

Vref = 1.5 m/s



Same view as Tricarico, above, with Mars Odyssey, MRO and MAVEN orbits shown

Acknowledgement

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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