AN EARLY LOOK OF COMET C/2013 A1 (SIDING SPRING): BREATHTAKER OR NIGHTMARE?

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ABSTRACT

The dynamically new comet, C/2013 A1 (Siding Spring), is to make a close approach to Mars on 2014 October 19 at 18:30 UT at a distance of 40 ± 1 Martian radii. Such an extremely rare event offers a precious opportunity for the spacecrafts on Mars to closely study a dynamically new comet itself as well as the planet–comet interaction. Meanwhile, the high-speed meteoroids released from C/Siding Spring also pose a threat to physically damage the spacecrafts. Here we present our observations and modeling results of C/Siding Spring to characterize the comet and assess the risk posed to the spacecrafts on Mars. We find that the optical tail of C/Siding Spring is dominated by larger particles at the time of the observation. Synchrone simulation suggests that the comet was already active in late 2012 when it was more than 7 AU from the Sun. By parameterizing the dust activity with a semi-analytic model, we find that the ejection speed of C/Siding Spring is comparable to comets such as the target of the Rosetta mission, 67P/Churyumov–Gerasimenko. Under a nominal situation, the simulated dust cone will miss the planet by about 20 Martian radii. At the extreme ends of uncertainties, the simulated dust cone will engulf Mars, but the meteoric influx at Mars is still comparable to the nominal sporadic influx, seemingly indicating that an intense and enduring meteoroid bombardment due to C/Siding Spring is unlikely. Further simulation also suggests that gravitational disruption of the dust tail may be significant enough to be observable at Earth.

Key words: comets: individual (C/2013 A1) – meteorites, meteors, meteoroids – planets and satellites: individual (Mars)

Online-only material: color figures

1. INTRODUCTION

Near-Earth Objects (NEOs) play an important role in shaping the geological histories of terrestrial planets. Recent studies have shown that NEO impacts are common in the inner solar system (see, e.g., Strom et al. 2005). For other terrestrial planets, it has been suggested that the impact flux is comparable to the near-Earth environment (Le Feuvre & Wieczorek 2011). Although over 99% of the impactors are asteroids (Yeomans & Chamberlin 2013), comets are generally of special interest, as they carry a significant amount of volatile and organic material, which is essential for life. On Earth, kilometer-sized cometary impacts occur every ∼10⁶ yr (Stokes et al. 2003).

On the other hand, the close comet-planet approach is also significant in terms of the accretion of water and organic materials on the planet: comets eject a large amount of material into the vicinity of their nuclei, and they may still influence the planet without a direct impact. Although approaches are more common than impacts, they are still too rare for us to observe and study a real case: the closest cometary approach to the Earth since the establishment of modern science was D/1770 L1 (Lexell), which missed the Earth by ∼356 Earth radii. From the impact rates, we estimate that a close approach within 25 Earth radii with kilometer-sized comets occurs once every ∼10⁷ yr. This is equivalent to the frequency of cometary approach within 50 Martian radii to Mars assuming that the cometary impact flux (like the total impact flux) is comparable between Earth and Mars.

Yet this is what will happen later this year: a dynamically new (dynamically new) comet, C/2013 A1 (Siding Spring), is to miss Mars by ∼40 Martian radii on 2014 October 19.8 (UT) (Figures 1 and 2). C/Siding Spring was discovered on 2013 January 3 at a heliocentric distance of 7.2 AU; subsequent follow-up observations revealed a 10″ coma, which indicated distinct cometary activity at such a large heliocentric distance (McNaught et al. 2013). As of 2014 February 1, the comet is determined to be in a hyperbolic orbit, with $e = 1.0006$; C/Siding Spring is currently estimated to miss Mars by about 40 ± 1 Martian radii or 135,600 ± 6000 km.³ Dynamically new comets are constrained on loosely bounded or unbounded orbits, and are thought to originate from the outer region of the solar system, namely the Oort cloud. Due to the fact that they have had no access to the inner solar system, they preserve valuable and unique information about the pre-solar nebula. However, comparing with the periodical comets, which usually return to the inner solar system on a frequent and predictable basis, the dynamically new comets are difficult to investigate due to their small number and limited opportunity to study individual objects (generally only once). The most productive method to study comets—in-situ exploration—is currently very difficult to use on dynamically new comets, due to very short lead-times available for preparing and operating such missions.

As such, the close approach offers an unprecedented and extremely rare opportunity to directly study how material may be transferred from comets to terrestrial planets as well as the dynamically new comet itself. Currently there are three operational orbiters (the Mars Reconnaissance Orbiter, Mars Odyssey, and Mars Express) and two operational rovers (Opportunity and Curiosity) on Mars; in addition, two orbiters (the Mars Atmosphere and Volatile Evolution or MAVEN, and the Mars Orbiter Mission or MOM) will arrive ∼1 month before C/Siding Spring’s closest approach. The fleet will have front row seats for this

³ Update numbers can be found at http://ssd.jpl.nasa.gov/sbdb.cgi?ssstr=2013A1.
event; however, the small distance by which the comet will miss the planet also means that they may pass inside the dust coma/tail of C/Siding Spring. While the Martian atmosphere will shield incoming dust particles (meteoroids) for the two rovers, the five orbiters will be at risk for the bombardment of dust particles originating from the comet. Cometary dust poses a significant threat of causing physical damage to the spacecrafts (see, e.g., A’Hearn et al. 2008). Additionally, meteoroids originating from C/Siding Spring have higher kinetic energy than nominal sporadic (background) meteoroids, as the relative speed of the comet is twice as high as that of Mars. Early studies of C/Siding Spring before its close visit to Mars will be essential to monitor the evolution of the comet and help assess the risk posed to the spacecrafts.

Here we present our observations and modeling effort of C/Siding Spring in the hope of characterizing the physical properties of the comet. We will first discuss our observations and their significance for constraining the particle size distribution (PSD) of the comet. Then we will present the semi-analytic model that will be used to match the observation and parameterize the cometary dust activity. Eventually, we will use the best-matched parameters to investigate the fluency of cometary dust particles experienced by Mars (and anything in the proximity) during the close encounter.

2. OBSERVATIONS AND INITIAL INTERPRETATION

2.1. Planning and Conducting the Observations

After being released by the parent body, different sizes of dust particles follow different Keplerian trajectories due to different amounts of radiation pressure and gravity from the Sun. The ratio of the later two quantities is defined as $\beta$, of which $\beta \propto (\rho r)^{-1}$, where $\rho$ is the particle density and $r$ is the size. If we ignore the initial velocity of the particles with respect to the nucleus and compute a large number of particles with different $\beta$ released at different times, we can produce the so-called synodyne–synchrone diagram as defined by Finson & Probstein (1968).

Occasionally, the Earth–comet geometry is favorable so that different synodyne curves (i.e., equal-$\beta$ curves) are well separated from each other as seen by the observer, which allows us to qualitatively constrain the PSD of the comet. The occurrence of such geometry depends on the orientation of the orbital plane of the comet. We discover that for C/Siding Spring, such geometry would have occurred in 2013 September to November, while the solar elongation of the comet is adequate for optical observations (Figures 3 and 4). The next “slots” will occur in 2014 June and September, but they either suffer from small solar elongation or from being too close to the encounter event.

We conduct broadband observations with a 0.18 m f/7 refraction telescope and 4k × 3k CCD camera (pixel size 1.5′′) at the Jade Scope Observatory near Siding Spring, Australia (149°12′ E, 31°17′ S), on 2013 November 12, 20, and 23 (details summarized in Table 1). Observations are unfiltered and the CCD sensor is most sensitive at ~500 nm. The raw frames...
are then subtracted by dark and bias fields and divided by flat fields. After the initial reduction, the frames are registered with the NOMAD catalog (Zacharias et al. 2004) so that they can be combined and stacked following the motion of C/Siding Spring. Eventually, we end up with three “master” images from each night (Figure 5).

2.2. Is C/Siding Spring Rich in Big Particles?

We compute the syndyne–synchrone curves for the three master frames (Figure 6) and immediately notice that C/Siding Spring’s tail is skewed to smaller $\beta$ values (i.e., larger particles), dominantly of the order of 0.01. If we use $\beta = 5.74 \times 10^{-4}/(\rho r)$ (Williams & Fox 1983) and assume $\rho = 300 \text{ kg m}^{-3}$, $\beta = 0.01$ is equivalent to $r = 200 \mu\text{m}$ or $10^{-9}\text{ kg}$ for a spherical particle. This number is significant because $10^{-9}\text{ kg}$ is considered to be the lower end of the threat regime by spacecraft designers (McNamara et al. 2004). Since optical observation strongly favors micron-sized particles due to their higher scattering efficiency, the absence of a tail structure at larger $\beta$ suggests that the cometary tail is dominated by larger, spacecraft-threatening particles.

3. THE DUST TAIL MODEL

3.1. Philosophy of the Model

We develop a semi-analytic dust tail model (DTM) to parameterize the cometary dust tail. The key of parameterization involves the initial velocity, i.e., the velocity vector of the particles at the time of its ejection from the cometary nucleus. We start from the revised Whipple’s (1951) model by Brown.

Table 1

| Date           | Exposure | Total Frames | Airmass $r_h$ (AU) | $\Delta$ (AU) |
|----------------|----------|--------------|--------------------|---------------|
| 2013 Nov 12.63 | 90 s     | 34           | 1.010              | 4.450         |
| 2013 Nov 20.56 | 90 s     | 60           | 1.019              | 4.374         |
| 2013 Nov 23.59 | 90 s     | 63           | 1.012              | 4.345         |

Figure 3. Observation circumstances of C/Siding Spring from 2013 September to 2014 August.

(A color version of this figure is available in the online journal.)

Figure 4. Syndyne simulations of C/Siding Spring from 2013 September to 2014 August. $\beta$ ranges from 0.01 (light gray) to 1 (black). Each diagram is 10’ × 10’ in size, north is up and east is left.
Brown & Jones (1998), which was used to study the Perseid meteor stream formed by 109P/Swift–Tuttle:

\[ V = (10.2 \text{ m s}^{-1}) \left( \frac{r_h}{1 \text{ AU}} \right)^{-\frac{1}{2}} \left( \frac{\rho}{1 \text{ g cm}^{-3}} \right)^{-\frac{1}{2}} \times \left( \frac{r_C}{1 \text{ km}} \right)^{\frac{1}{2}} \left( \frac{m}{1 \text{ g}} \right)^{-\frac{1}{2}}, \]  

(1)

where \( V \) is the ejection velocity relative to the nucleus in m s\(^{-1}\), \( r_h \) is heliocentric distance of 1 AU, \( u \) is ejected by a cometary body of a diameter of 1 km at a heliocentric distance; the introduction of \( u \) will be elaborated upon in the next section. The \( V_0 \) corresponds to the constant of 10.2 in Brown & Jones’ model would be \( V_0 = 8.0 \text{ m s}^{-1} \). We assume that the particles are symmetrically released at the comet’s sub-solar point at a direction of \( w < 45^\circ \) from the sunward direction. This \( w \) limit is chosen following the results of Ishiguro et al. (2007) and Ishiguro (2008).

The initial velocity model is fed by a Monte–Carlo subroutine that generates random particle with sizes following a power law: \( N(a) = (a/a_0)^q \), where \( N(a) \) is the accumulative particle number, and \( q \) is the size distribution index. We then solve Kepler’s equation rigorously from the start time to the time of the observation to determine the position of the particle. These steps are repeated until we have a sufficient number of particles to simulate the morphology of the cometary tail.

At the end, we compute the spatial intensity on a sky plane coordinate \( (\alpha, \delta) \). We consider a simple model without secondary effects such as the response efficiency of the CCD sensor to different wavelength and the scattering efficiency due to particle shape. We consider the light contribution from each particle:

\[ I'(\alpha, r_h) = \left( \frac{r_h}{1 \text{ AU}} \right)^{-2} a^2 A_p, \]  

(3)

where \( A_p \) is the modified geometric albedo. The intensity at \( (\alpha, \delta) \) will be just the sum of intensities from all particles within the region \( (d\alpha \, d\delta) \):

\[ I(\alpha, \delta) = \int \int I'(\alpha, r_h) \, d\alpha \, d\delta. \]  

(4)

Finally, a two-dimensional intensity map is created by looping around all possible \( (\alpha, \delta) \) and computing the value of \( I(\alpha, \delta) \) at each position.

### 3.2. Determining the \( u \) Constant

The treatment of \( u \) is somewhat tricky, as a number of \( u \) values have been suggested by previous workers. For example, some studies from both cometary and meteor communities suggested \( u = 0.5 \) (e.g., Crifo 1995; Brown & Jones 1998; Ishiguro et al. 2007; Ishiguro 2008), Whipple’s (1951) original model suggested \( u = 1.125 \), while \( u = 1 \) (Brown & Jones 1998; Reach et al. 2000; Ma et al. 2002) and \( u = 3 \) (Agarwal et al. 2010) were also used. We note that most studies that adopted \( u = 0.5 \) do not have data that cover a broad range of \( r_h \); our initial test with \( u = 0.5 \) also shows a noticeable mismatch at large \( r_h \). This may be due to the fact that the range of \( r_h \) is not broad enough to constrain \( u \) more effectively, but could also be due to, for example, the onset of water–ice sublimation at \( \sim 2.3 \text{ AU} \) which dramatically enhances the ejection regime and hence no unique \( u \) can be defined.

To investigate this matter, we use the observations of C/2012 S1 (ISON), which are available for a broad range of \( r_h \). The unfiltered observations were taken at the Xingming Observatory, China, from a few days after the discovery \( (r_h = 6.2 \text{ AU}) \) to a few weeks before the perihelion \( (r_h \lesssim 1 \text{ AU}) \); see Table 2. The DTM model is run at grids with \( u \in [0.5, 4.0] \) and \( V_0 \in [1.0, 8.4] \text{ m s}^{-1} \), with orbital elements from JPL 54 (Table 3). A few parameters at the far ends are not tested as initial trials indicate that they are unlikely to contain the best fits.

### Table 2

| Date        | Instrument | Pixel Size (pixel\(^{-1}\)) | Exposure | Total Frames | \( r_h \) (AU) | \( \Delta \) (AU) |
|-------------|------------|-----------------------------|----------|--------------|----------------|-----------------|
| 2012 Oct 19 | 0.35 m SASP | 0.9                         | 90 s     | 50           | 6.029          | 6.051           |
| 2013 Feb 2  | 0.35 m SASP | 0.9                         | 90 s     | 60           | 4.916          | 4.026           |
| 2013 May 16 | 0.35 m SASP | 0.9                         | 60 s     | 34           | 3.710          | 4.342           |
| 2013 Aug 31 | 0.11 m XP1  | 3.5                         | 60 s     | 10           | 2.179          | 2.973           |
| 2013 Sep 26 | 0.11 m CSP  | 3.5                         | 120 s    | 30           | 1.726          | 2.667           |
| 2013 Oct 26 | 0.35 m SASP | 0.9                         | 20 s     | 20           | 1.116          | 1.374           |

### Figure 5

Master frames of the observations on 2013 November 12, 20, and 23. Each image is \( 6' \times 4' \).
Figure 6. Syndyne–synchrone computation for the master frames. North is up and east is left. (A color version of this figure is available in the online journal.)

Except for the nucleus size of C/ISON, which has been reported to be of the order of 1 km (Knight & Walsh 2013; Li et al. 2013), we must make some assumptions, such as the albedo and particle density. Although the nucleus size will not effectively affect our final result (since its contribution is modest in most cases and can be balanced by a slightly larger or smaller $V_0$ term), we still keep it in the simulation as we hope that $V_0$ can be comparable to C/Siding Spring and other comets. The set of parameters are summarized in Table 4. The simulation results and the observations are then compared and graded separately by both authors on a Boolean basis (i.e., as “possible fit” or “definitely not a possible fit”). Finally, the grades are summed and it is rated on a scale from 0 to 100.

The final score chart (Figure 7) indicates that with $V_0 = 2.1$ (m s$^{-1}$), $u = 1.0$ is the best fit. It is encouraging that no dramatic morphological change is presented near the water–ice sublimation line ($\sim 2.3$ AU), which means that the $u$ we found is a unique approximation to the entire $r_h$ range. The change in the $r_h = 1.1$ AU case is most likely due to the contamination from cometary gas emission, as no filters were used to block the primary emission lines (e.g., C$_2$ and C$_3$ which falls in the $\lambda = 500$ nm range where the imaging CCD is sensitive); we may remove the $r_h = 1.1$ AU case and it does not alter our result.

### 3.3. Simulation Result

After pinned down the $u$ constant, we run the DTM model for the case of C/Siding Spring with $V_0$ ranging from 1.0 to 4.2 m s$^{-1}$ to determine $V_0$. The input parameters and orbital elements are summarized in Tables 3 and 5. Since the epochs of our observations are fairly close, we only simulate the November 23 case, as the master frames were stacked from more frames and had a slightly better airmass. We estimate $d_C = 5$ km considering two comparable comets in which the nucleus diameters are constrained at a higher level of confidence: 19P/Borrelly ($M_1 = 8.9$, $M_2 = 13.8$, $d_C = 4.8$ km)$^4$ and 19P/Borrelly ($M_1 = 8.9$, $M_2 = 13.8$, $d_C = 4.8$ km)$^4$ and

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Table 3

| Element | C/ISON | C/Siding Spring |
|---------|--------|-----------------|
| $q$ (AU) | 0.01245259 | 1.3991521 |
| $e$ | 1.000201 | 1.00057866 |
| $i$ | 62.697775 | 129.025859 |
| $\Omega$ | 295.6520316 | 300.972350 |
| $\omega$ | 345.5312406 | 2.432872 |
| $t_p$ (UT) | 2013 Nov 28.77866 | 2014 Oct 25.40490 |

Table 4

| Parameter | Symbol | Value |
|-----------|--------|-------|
| Maximum $\tau$ (days) | $\tau_{\text{max}}$ | 365 |
| Particle size (m) | $a$ | $[10^{-5}, 10^{-2}]$ |
| Size distribution index | $s$ | $-2.6$ |
| Modified geometric albedo | $A_p$ | 0.04 |
| Number-distance constant | $k$ | $-3.0$ |
| Bulk density of particle (kg m$^{-3}$) | $\rho$ | 300 |
| Size of cometary nucleus (km) | $d_C$ | 1 |
| Dependence constant on heliocentric distance | $u$ | $0.5, 1.0, 1.5, 2.0, 3.0, 4.0$ |

Table 5

| Parameter | Symbol | Value |
|-----------|--------|-------|
| Maximum $\tau$ (days) | $\tau_{\text{max}}$ | 1000 |
| Particle size (m) | $a$ | $[10^{-4}, 10^{-2}]$ |
| Size distribution index | $s$ | $-2.6$ |
| Modified geometric albedo | $A_p$ | 0.04 |
| Number-distance constant | $k$ | $-3.0$ |
| Bulk density of particle (kg m$^{-3}$) | $\rho$ | 300 |
| Size of cometary nucleus (km) | $d_C$ | 5 |
| Dependence constant on heliocentric distance | $u$ | 1.0 |

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4 http://ssd.jpl.nasa.gov/sbdb.cgi?str=19P, retrieved 2014 March 2.
C/1996 B2 (Hyakutake) (M1 = 7.3, M2 = 11.1, dC = 4.2 km),\(^5\) in contrast, C/Siding Spring has M1 = 8.6, M2 = 10.4.

The simulation result is shown in Figure 8. Comparing the simulation to the observation (Figure 5), we see \(V_0 = 1.0\) m s\(^{-1}\) as the optimal match. We note that the strong size gradient indicated in the syndyne diagram (Figure 6) actually forged the result: since optical observation strongly favors smaller particles that dominate the west-end sector of the tail (i.e., toward the clockwise direction), the west-end boundary (about P.A. \(\sim 345^{\circ}\)) marks the true boundary of the tail. As we only simulate particles with \(\beta < 0.01\), the simulated particles should mostly be distributed within the anticlockwise direction of P.A. \(\sim 345^{\circ}\), which is only satisfied by the \(V_0 = 1.0\) m s\(^{-1}\) case. Such converge allows us to make a stronger conclusion on the optimal \(V_0\).

The \(V_0 = 1.0\) m s\(^{-1}\) value is comparable to some comets that were previously studied, including 4P/Faye, 22P/Kopff, and the Rosetta mission target, 67P/Churyumov–Gerasimenko (see, e.g., Ryabova 2013; note that the \(V_0\) value here needs to be \(\times 4\) to make the numbers comparable), although the dynamical origins of these comets seem to be different. It is interesting to note that this similarity comes with the fact that comets with similar dynamical origins can great deviations in \(V_0\); for example, \(V_0\) for 2P/Encke is about a magnitude larger. This may be purely by coincidence, but further studies with larger sample sizes may determine if there are any physical causes.

4. ENCOUNTER

Eventually, we run the simulation for the encounter with best-fit parameters found in the previous iterations (summarized in Table 5) to study the influence of cometary dust on Mars and its vicinity. Unlike other meteor stream models, our model does not include planetary perturbation; however, we believe that this is acceptable for the case of C/Siding Spring since the comet is far from the ecliptic plane (\(i = 129^{\circ}\)) until the encounter.

The synchronic feature in Figure 6 suggests that C/Siding Spring was active at least a year before our observations; therefore we choose \(\tau_{\text{max}} = 1000\) days (corresponding to 2012 January 23) as the start date of the simulated cometary activity to catch any early activities. State vectors of simulated particles are recorded within \(\pm 1\) day of the closest encounter (2014 October 18, 18:30 UT to 2014 October 20, 18:30 UT) in a time-step of 1 minute. Since simulating the entire set of cometary particles will take quite a bit of time (comets typically release particles at a rate of \(\sim 10^7\)–\(10^{10}\) s\(^{-1}\)), we only simulate a representative number of particles and scale them up afterward.

\(^5\) http://ssd.jpl.nasa.gov/sbdb.cgi?str=1996+B2, retrieved 2014 March 2.
We first need to examine the dust production rate of C/Siding Spring; this can be tied to the so-called $Af\rho$ quantity (A'Hearn et al. 1984). The number of ejected particles in the particle size range $(a_1, a_2)$ can be related to $Af\rho$ by (Vaubillon et al. 2005; Ye & Wiegert 2014)

$$Q_g(a_1, a_2) = \frac{655 A_1(a_1, a_2) Af\rho}{8\pi A_B j(\phi)[A_3(a_1, a_2) + 1000A_3.5(a_1, a_2)]},$$

where $A_x = (a_x^x - a_1^{-1})/(x - s)$ for $x \neq s$ and $A_x = \ln(a_2/a_1)$ for $x = s$, where $s$ is the size population index, $A_B$ is the Bond albedo, and $j(\phi)$ is the normalized phase function.

We obtain the $Af\rho$ measurements conducted by a group of observers and collected by the “Cometas Obs.” (Ye & Wiegert 2014) measurements show a steady $Af\rho$ near 1500 cm from $r_h = 6.76$ AU to $r_h = 3.72$ AU. By assuming $Af\rho \propto (q/r_h)^{13/3}$ when the comet gets into the water–ice sublimation line (to include possible early onsets, we use a loose constraint, $r_h \simeq 3$ AU), we estimate the $Af\rho$ of C/Siding Spring at 1 AU to be 3700 cm, which corresponds to $N_0 = 3 \times 10^{10}$ s$^{-1}$.

The result is shown in Figure 9: Mars will miss the dust cone by some 20 Martian radii or 67,800 km.

What about the extreme cases in the uncertainty ranges? To investigate this, we run further simulations with some educated guesses about the uncertainty ranges: a factor of 10 for the minimum particle size, a factor of 2 for the diameter of the cometary nucleus, and 50% for the reference velocity. Four combinations are tested while the other parameters remain the same as in Table 5. The combinations and results are shown in Table 6 and Figure 10.

For scenario 4, in which the minimum particle size/mass remains unchanged (i.e., particles are confined to within the spacecraft-threatening category), we still find no direct encounter between Mars and the dust cone. For the other three scenarios, the dust cone does reach Mars. The peak times are about 30–60 minutes behind the closest approach. We see some “peak-lets” in the time series plots which should be artifacts due to low statistics rather than any physical explanations. The low statistics also make it difficult to determine the duration of the event, but we can crudely estimate the FWHM to be $\sim 1$ hr or
less. The peak fluxes are on the order of $10^{-7} \text{ m}^{-2} \text{s}^{-1}$ while the accumulative fluxes are on the order of $10^{-5} \text{ m}^{-2}$, appropriate for the meteoroids larger than $10^{-12} \text{ kg}$. The absence of an encounter in scenario 4 suggests that the particles that arrive at Mars in scenarios 1–3 are in the range of $10^{-12}$ to $10^{-9} \text{ kg}$, which are below the spacecraft-threatening regime.

5. DISCUSSION

5.1. Comparison with Moorhead et al. (2014)

Moorhead et al. (2014) also studied the meteoroid influence on Mars during the encounter of C/Siding Spring but with a different approach: they construct a symmetric analytic model of the coma that relates the dust production rate to the total magnitude (M1) of the comet. As a separate check, the meteoroid flux experienced by Giotto and Stardust spacecrafts during their encounter with 1P/Halley and 81P/Wild were reproduced by this model and compared with the actual data, and order-of-magnitude agreements were found. Since more parameters were unconstrained at the time of their study, they parameterized their result and reported an accumulative flux of 0.15 m$^{-2}$ for particles over $4.19 \times 10^{-9} \text{ kg}$ under nominal conditions. They also conducted simulation with a dynamical meteor stream model that uses Brown & Jones’s (1998) ejection model (P. A. Wiepert 2013, private communication) and found that the numbers from the two models agreed within an order of magnitude, although the number from the dynamic model is in fact lower by a factor of two, which they attributed to the difference in modeling assumptions.

Since their study, the M1 of C/Siding Spring has been revised from 5.2 to 8.6; using Equation (18) in their study and $\rho = 300 \text{ kg m}^{-3}$, we find a new value of 0.0135 m$^{-2}$. This is still more than three orders of magnitude higher than our result. To investigate this difference, we test our model with $V_0$ set to the value equivalent to the Brown & Jones’s (1998) model and find a much closer value (~0.001 m$^{-2}$), which would allow an order-of-magnitude agreement to Moorhead et al.’s result from the dynamical model. From here we suggest that the difference between the two results is primarily caused by different input parameters.

5.2. Implications for the Spacecrafts, Rovers, and Martian Moons

The sporadic meteoroid influx on Mars is about half of the influx on Earth (Domokos et al. 2007) or $\sim 1.8 \times 10^{-8} \text{ m}^{-2} \text{s}^{-1}$ for a meteoroid larger than $10^{-9} \text{ kg}$. For comparison, the peak flux of the 2012 Draconid meteor storm is $3.3 \times 10^{-6} \text{ m}^{-2} \text{s}^{-1}$ for a meteoroid larger than $10^{-9} \text{ kg}$, assuming a general power law distribution (Ye et al. 2014). From here, our simulation seems to indicate that the meteoric influx on Mars due to C/Siding Spring is comparable to the sporadic background. For the case of smaller-sized meteoroids, the sporadic influx is about 3 mag higher from $10^{-9} \text{ kg}$ to $10^{-12} \text{ kg}$, which would still put the influx due to C/Siding Spring no higher than the sporadic background. The simulation also suggested that the bulk of the outburst (if any) would not be longer than the orbital period of the orbiters around Mars. For the Opportunity and Curiosity rovers, the potential meteor outburst takes place during the Martian morning and afternoon, respectively, which prevents any meteor observations from reaching the rover.

The impact on the Martian moons is another interesting topic. At the time of the encounter, Deimos will be about 2 Martian radii closer to the cometary nucleus than Mars itself. Depending on its physical properties and impact angle, a 200 μm meteoroid may produce a sub-meter crater on Phobos and Deimos. Unfortunately, such a crater is below the resolution of our current best images (about 5 m pixel$^{-1}$), but it is worth pointing out that the high-speed nature of meteoroids originating from C/Siding Spring should create larger craters more efficiently than nominal sporadic meteoroids.

7 The power law distribution is quoted from Ceplecha et al. (1998, Table XXVI), which suggested a factor of $10^{5.69}$ between the cumulative number of meteoroids larger than $10^{-7}$ and $10^{-9} \text{ kg}$ respectively.

8 Estimate with http://www.lpl.arizona.edu/tekton/crater_c.html.
Figure 11. Evolution of the dust tail after the gravitational perturbation of Mars, from $T + 0$ day (encounter) to $T + 30$ days. The graphs are constructed in ecliptic coordinate system, with the $X$-axis pointing to the vernal point.

Figure 12. Evolution of the dust tail after the encounter as observed from the Earth.
5.3. Possibility of a Gravitational Disrupted Tail

As one of the closest cometary approaches to a major planet among known objects, we expect the dust tail of C/Siding Spring to be disrupted by the gravitational field of Mars to some degree. To investigate this matter, we integrate a snapshot of the locations of some 12,000 dust particles (generated from previous simulations under the nominal condition) from \( T + 0 \) to \( T + 30 \) days (where \( T \) is the time of closest approach). The integration is performed with the HNBODY package (Rauch & Hamilton 2002) using the symplectic integrator, with the barycenter of the Martian system included. The result is shown in Figures 11 and 12. We find that at \( T + 20 \) days, the apparent size of the “clump” reaches of the order of 0.01 or 30' as seen on Earth, which may be detectable by ground-based telescopes.

6. CONCLUSION

We reported on the observations and modeling works of C/Siding Spring, a dynamically new comet that will make a close approach to Mars on 2014 October 19. By fitting the observations with synodyne simulations, we found that the tail of C/Siding Spring was dominated by larger particles at the time of its observation. Synchrone simulation suggested that the particles dominating the optical tail were released by the comet as early as late 2012, when the comet was more than \( \approx 7 \) AU from the Sun. We then developed a semi-analytic model to simulate the cometary dust activity. The modeling result suggested a modest ejection velocity of C/Siding Spring that is comparable to a few other comets, including P/Churyumov–Gerasimenko, the target of the Rosetta mission.

The same model was then used to study the meteoroid influence on Mars during the encounter, fed with the constraints found in the previous steps. We found that the planet will miss the dust cone by some 20 Martian radii (67,800 km) under the nominal situation. Although the planet may be engulfed by the cometary dust tail if we made an educated guess about the uncertainties and pushed the parameters to the most extreme cases, the simulation suggested that the meteoroids that reach the vicinity of Mars are dominated by non-spacecraft-threatening meteoroids, and the meteoric influx is not significantly higher than the sporadic background influx; the duration of the event is of the order of 1 hr. From our simulation, it seems that an intense and enduring meteoroid bombardment of Mars and its vicinity is unlikely during the flyby of C/Siding Spring.

We also study the potential gravitational disruption of the cometary dust tail. A simple numerical integration suggested that the dust “clump” created by the gravitational drag would be of the order of tens of arcsec at \( T + 20 \) days as seen from Earth, which may be detectable by ground-based facilities.

At the time of the writing, C/Siding Spring is about 4 AU from the Sun. As the comet travels into the inner solar system and enters the water–ice sublimation line, its progress could evolve dramatically. We encourage observers to closely monitor C/Siding Spring as it helps on creating a full picture of this unprecedented cosmic event.

Note added: at the reviewing stage of this paper, J. Vaubaillon et al. also reported their modeling result of the same event (see Vaubaillon et al. 2014). Our initial check using their input values suggested an order-of-magnitude agreement between the two results, which indicated that the difference between the two results is primary due to input parameters.

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