INTERPRETATION OF (596) SCHEILA’S TRIPLE DUST TAILS

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ABSTRACT

Strange-looking dust cloud around asteroid (596) Scheila was discovered on 2010 December 11.44–11.47. Unlike normal cometary tails, it consisted of three tails and faded within two months. We constructed a model to reproduce the morphology of the dust cloud based on the laboratory measurement of high-velocity impacts and the dust dynamics. As a result, we succeeded in reproducing the peculiar dust cloud by an impact-driven ejecta plume consisting of an impact cone and downrange plume. Assuming an impact angle of 45°, our model suggests that a decameter-sized asteroid collided with (596) Scheila from the direction of (αim, δim) = (60°, −40°) in J2000 coordinates on 2010 December 3. The maximum ejection velocity of the dust particles exceeded 100 m s\(^{-1}\). Our results suggest that the surface of (596) Scheila consists of materials with low tensile strength.

Key words: comets: general – comets: individual ((596) Scheila) – minor planets, asteroids: general

Online-only material: color figures

1. INTRODUCTION

In this Letter, we suggest one plausible explanation for the peculiar dust cloud of (596) Scheila.

(596) Scheila is a large asteroid (113–120 km in diameter) orbiting the Sun in the outer region of the main belt with the orbital period of 5.01 years (Tedesco & Desert2002; Usui et al. 2011). The orbital elements of the object are typical for the outer main belt, that is, the semi-major axis, the eccentricity, and the inclination are 2.93 AU, 0.164, and 14°. A peculiar feature is that the asteroid’s rotational spin-up resulted in a mass loss that formed a comet-like debris tail (Snodgrass et al. 2010). It has been proposed that the dust cloud of (596) Scheila was discovered on 2010 December 11.4 with the 0.68 m f/1.8 Schmidt telescope (Larson2010). The observation with the same instruments on 2010 December 3.4 showed a diffuseness at magnitude 13.2, about 1.3 mag brighter than that of the observation in the previous month (Larson2010).

Ishiguro et al. (2011) found that the dust particles ranging from 0.1–1 μm to 100 μm were ejected impulsively on 2010 December 3.5 ± 1.0 through the synchro analysis of extended dust structure appeared after 2011 February. It is therefore likely that Larson (2010) observed (596) Scheila immediately after the dust ejection. The total mass of the ejecta was estimated to be (2.0–6) × 10\(^{15}\) kg, depending on the assumed particle size and the mass density (Jewitt et al. 2011; Hsieh et al. 2011; Bodewits et al. 2011; Ishiguro et al. 2011). To date, gas emission has never been detected (Jewitt et al. 2011; Hsieh et al. 2011; Bodewits et al. 2011). Accordingly, it is natural to think that the comet-like activity was triggered by an impact. The impactor diameter was estimated to be 20–50 m (Jewitt et al. 2011; Bodewits et al. 2011; Ishiguro et al. 2011).

Similar evidence for asteroid–asteroid impact was reported in another object. The dust cloud of P/2010 A2 (LINEAR) was discovered on 2010 January 6, showing not only a comet-like extended dust cloud but also a mysterious X-shaped debris pattern (Jewitt et al. 2010). It has been proposed that the dust ejection was created by the impact of a small object in 2009 February or March (about 10 months before the discovery), although it cannot be ruled out that the asteroid’s rotational spin-up resulted in a mass loss that formed a comet-like debris tail (Snodgrass et al. 2010; Jewitt et al. 2010).

The morphology of (596) Scheila’s dust cloud was also mysterious, in that it consisted of three prominent structures. Figure 1(a) shows the image taken on 2010 December 12 at the Ishigakijima Astronomical Observatory with a 1 m telescope and a 3ch (the g’, Rc, and Ic bands) simultaneously imaging system. In the image, three components appear: the northern tail, southern tail, and westward tail (Ishiguro et al. 2011). Similar structures were found in Jewitt et al. (2011). To date, no studies have addressed the physical implication of the mysterious morphologies of impact-triggered dust clouds. In this Letter, we attempted to reconstruct the observed morphology of (596) Scheila’s triple dust tails on the basis of the impact hypothesis. The image taken on 2010 December 12 at the Ishigakijima
Astronomical Observatory was compared to the model that considers the laboratory measurement of high-velocity impact and dust dynamics, and derive the best-fit parameters.

2. MODEL DESCRIPTION

To begin, we would like to clarify the difference in shape between normal comets and (596) Scheila. The morphology of (596) Scheila cannot be explained by the sublimation of ice. Figures 1(b) and (c) show the results of model simulations on 2010 December 12 performed under the assumption of comet-like dust ejection. We applied continuous dust-ejection models using the parameters of 238P/Read as an analog of a main-belt comet that was activated by the sublimation of ice (Hsieh et al. 2009; Figure 1(b)), and those of 22P/Kopff as an analog of a Jupiter-family comet (Ishiguro et al. 2007; Figure 1(c)). In these models, it is assumed that dust particles are ejected in cone-shaped jets that are radially symmetric with respect to the Sun–object axis with a half-opening angle of 45° (238P/Read) and 60° (22P/Kopff). We considered continuous dust emission from two months prior to the observation on 2010 December 12. In these model images, the dust cloud smoothly extended in an almost anti-solar direction. There is only one dust tail in these images. The observed image differs from these simulation images in that it consisted of multiple tails.

Second, we show simple impulsive emission models in Figures 1(d)–(i). In these models, we assumed the isotropic dust emission of 1 μm and 10 μm particles with different velocities ejected on 2010 December 3. We adopted the ejection day based on the previous studies; the dust emission should have occurred on 2010 December 3.5 ± 1.0 (Ishiguro et al. 2011) but before 2010 December 3.4 (Larson 2010). It may seem at first glance that there should be dust particles ejected with high terminal velocity ($v_{\text{tml}} \approx 100$ m s$^{-1}$ or higher) because the rim diameters of models with the terminal velocity of $<100$ m s$^{-1}$ look smaller than that of the observed image. In addition, small grains ($\lesssim 1$ μm) should exist because the dust cloud was deflected toward the anti-solar direction by solar radiation pressure. For comparison, assuming the mass density of 1670 kg m$^{-3}$ (equivalent to the mass density of the Tagish Lake meteorite; Hiroi & Hasegawa 2003; Zolensky et al. 2002), the escape velocity from (596) Scheila is 55 m s$^{-1}$. The estimated terminal velocity is two times faster than the escape velocity.

To reconstruct the observed morphology of the (596) Scheila dust cloud, we considered a new dust emission model, described below. We assumed that the dust particles were ejected in two different forms from an impact point, i.e., a conical impact ejecta curtain and a downrange plume, which are commonly observed in oblique impact experiments. Figure 2 shows an example of the laboratory oblique impact experiment. It was conducted with a two-stage light gas gun at the Institute of Space and Astronautical Science (ISAS), Japan Aerospace Exploration Agency (JAXA). A 3.2 mm steel sphere was accelerated with the gun in a sabot (Kawai et al. 2010) to 4.521 km s$^{-1}$, which is the typical impact velocity in outer main belt (O’Brien et al. 2011). Soon after the impact, the dust particles were ejected as the luminous downrange plume with high speed in the horizontal
direction with respect to the local surface. Later, the conical ejecta curtain was grown. We simplified these forms, as shown in Figure 2(e). The conical impact ejecta curtain is symmetrical with respect to a vector normal to the asteroid surface (αcone, δcone) with a half-opening angle of θ. Dust particles are assumed to be ejected between θ−Δθ/2 and θ+Δθ/2 (see the shadowed area in Figure 2(e)). We modeled the downrange plume as a stretched cone with a central axis ranging from (α1dwn, δ1dwn) to (α2dwn, δ2dwn).

The dust particles ejected with the ejection velocity of \( v_{ej} \) would be decelerated by the asteroid’s gravity and reach the terminal velocity \( v_{tml} \). We applied the power-law function of the ejection velocity of dust particles:

\[
\begin{align*}
    v_{ej} &= V_0 a^\alpha \\
    v_{tml} &= \sqrt{\frac{2GM_{596}}{R_{596}} \left( v_{ej} > \sqrt{\frac{2GM_{596}}{R_{596}}} \right)},
\end{align*}
\]

where \( V_0 \) is the reference ejection velocity (m s\(^{-1}\)) of the particles of radius \( a = 1 \times 10^{-6} \) (m), \( k \) is the power index of size dependence of the ejection velocity, and \( M_{596} \) and \( R_{596} \) are the mass and radius of (596) Scheila. We considered the energy conservation for the terminal velocity \( v_{tml} \) in the second condition of Equation (1).

A power-law size distribution with index \( q \) was used. The number of dust particles within a size range of \( a \) and \( a+da \) is given by

\[
N(a)da = \begin{cases} 
N_0a^qda & \text{for } a_{min} \leq a \leq a_{max} \\
0 & \text{for } a < a_{min}, a > a_{max},
\end{cases}
\]

where \( a_{max} \) and \( a_{min} \) are the maximum and minimum particle sizes, respectively, and \( N_0 \) represents the reference dust production rate. We fixed \( a_{min} = 0.1 \) \( \mu \)m and \( q = -3.5 \) (discuss later) because particles much smaller than the wavelength are inefficient scatterers in the optical wavelength. The size distribution exponent was also fixed to \( q = -3.5 \) (Dohnany 1969). The maximum size \( a_{max} \) can be derived when the size-dependent velocity \( v_{ej} \) becomes equal to the escape velocity from (596) Scheila.

The trajectories of the particles were computed from the terminal velocity and the ratio of the force exerted by the solar radiation pressure and the solar gravity (\( \beta \)). It can be expressed as \( \beta = K Q_{pr}/\rho a \), where \( K = 5.7 \times 10^{-3} \) kg m\(^{-2}\) and \( Q_{pr} \) is the radiation pressure coefficient averaged over the solar spectrum (Burns et al. 1979). We assumed \( Q_{pr} = 1 \). \( \rho \) denotes the mass density of dust particles. We supposed that the mass densities of the dust particles were 1670 kg m\(^{-3}\). The model images were reconstructed using the Monte Carlo approach for the parameters above (Ishiguro et al. 2007; Ishiguro 2008; Sarugaku et al. 2007; Hsieh et al. 2009). We calculated the positions of the dust particles at a given time by solving the Keplerian equation.

We considered the impulsive dust emission on 2010 December 3 as stated above. The free parameters of our model are listed in Table 1.

3. RESULTS AND DISCUSSION

Multiple simulations are carried out using various parameter sets, and the resulting model images are then visually compared to the data to find plausible model parameters. As a result, we obtained the best-fit values. Figure 3 shows some example results for the conical ejecta curtain. First, we noticed that the southern tail and westward tail (see Figure 1) could be reproduced by a conical ejecta curtain given a half-opening angle of 50°. Our observations were consistent with the case in which the central axis at (αcone, δcone) of the downrange was (90°, −15°) in the J2000 coordinate system. Similarly, we examined the dependence of the downrange plume (αdwn, δdwn) on the central axis. We notice that the integral along the great circle joining from (α1dwn, δ1dwn) = (150°, +40°) to (α2dwn, δ2dwn) = (180°, +50°) matches the observed image. As θ increased, the opening angle of the ejecta became broader; as \( V_0 \) increased, the dust cloud extended more widely. Accordingly, these two variables, \( \theta \) and \( V_0 \), were well determined by comparison to the observed images. We estimated \( \theta = 15° \) (the downrange plume as a stretched cone with a central axis ranging from the shadowed area in Figure 2(e)). We modeled the downrange energy conservation for the terminal velocity \( v_{tml} \). The conical impact ejecta curtain is symmetrical with respect to a vector normal to the asteroid surface (αcone, δcone) with a half-opening angle of θ. Dust particles are assumed to be ejected between θ−Δθ/2 and θ+Δθ/2 (see the shadowed area in Figure 2(e)). We modeled the downrange plume as a stretched cone with a central axis ranging from (α1dwn, δ1dwn) to (α2dwn, δ2dwn).

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\[
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    v_{ej} &= V_0 a^\alpha \\
    v_{tml} &= \sqrt{\frac{2GM_{596}}{R_{596}} \left( v_{ej} > \sqrt{\frac{2GM_{596}}{R_{596}}} \right)},
\end{align*}
\]

where \( V_0 \) is the reference ejection velocity (m s\(^{-1}\)) of the particles of radius \( a = 1 \times 10^{-6} \) (m), \( k \) is the power index of size dependence of the ejection velocity, and \( M_{596} \) and \( R_{596} \) are the mass and radius of (596) Scheila. We considered the energy conservation for the terminal velocity \( v_{tml} \) in the second condition of Equation (1).

A power-law size distribution with index \( q \) was used. The number of dust particles within a size range of \( a \) and \( a+da \) is given by

\[
N(a)da = \begin{cases} 
N_0a^qda & \text{for } a_{min} \leq a \leq a_{max} \\
0 & \text{for } a < a_{min}, a > a_{max},
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The power index of size dependence of the ejecta velocity is typical to impact fragment (Dohnanyi 1969). We performed the fitting with $q = -3.5$ and $a_{\text{min}} = 0.1 \mu m$ seems to be reasonable.

In laboratory experiments, the central axis of the conical curtain is usually perpendicular to the local surface. The downrange plume appears along the trajectory axis of the impactor. Therefore, we can derive the impactor’s trajectory if the impact angle with respect to the local surface is known. The most probable impact angle on an arbitrary planetary body is 45° (Gault & Wedekind 1978). If an impact angle of 45° is assumed, it is likely that a small asteroid collided with (596) Scheila. This result suggests that the impactor collided with (596) Scheila from behind. The angle between the central axis of the conical curtain and that of the downrange plume is 85°, which is a potential value based on the impact experiments (see Figure 2(b) in this Letter and Figure 19 of Schultz et al. 2007). The derived half-opening angle of 50° is consistent with the results obtained for the rocky ejecta with velocity from hundreds to thousands m s$^{-1}$ through the laboratory measurement (Gault & Heitowitz 1963). The power index of size dependence of the ejecta velocity ($k \sim -1/4$) is smaller than that of comets (i.e., $k \sim 1/2$, typical of hydrodynamical gas drag) but within the range of the laboratory impact experiments (Giblin 1998). Our model predicts that

$$v_{\text{ej}}(\theta) = \frac{10}{\alpha_{\text{cone}}(\theta)} \times 10^{-3} \text{ (fixed)}$$

Table 1

| Parameter          | Conical curtain | Best-fit Values |
|--------------------|-----------------|-----------------|
| $\theta$ (deg)     | 10–90 with 5 interval | 50              |
| $\Delta \theta$ (deg) | 3, 5, 10, 15, 20, 30, 40 | 10              |
| $\alpha_{\text{cone}}$ (deg) | 0–360 with 15 interval | 90              |
| $\delta_{\text{cone}}$ (deg) | −90 to +90 with 10 interval | −15             |
| $V_0$ (m s$^{-1}$) | 60–300 with 10 m s$^{-1}$ interval | 80              |
| $k$                | −1/6, −1/5, −1/4, −1/3, −1/2 | −1/4           |
| $q$                | −3.5 (fixed)     | ...             |
| $a_{\text{min}}$ (m) | 1.0 $\times$ 10$^{-7}$ (fixed) | ...             |
| $a_{\text{max}}$ (m) | Defined as $v_{\text{ej}}(a_{\text{max}}) = 55$ m s$^{-1}$ | $4 \times 10^{-6}$ |

Downrange plume

| Parameter          | Best-fit Values |
|--------------------|-----------------|
| $\theta$ (deg)     | 10–90 with 5 interval | 15              |
| $\alpha_{1\text{dwn}}$ (deg) | 0–350 with 15 interval | 150             |
| $\delta_{1\text{dwn}}$ (deg) | −90–90 with 10 interval | 40              |
| $\alpha_{2\text{dwn}}$ (deg) | 10–360 with 15 interval, $\alpha_{2\text{dwn}} > \alpha_{1\text{dwn}}$ | 180             |
| $\delta_{2\text{dwn}}$ (deg) | −90–90 with 10 interval | 50              |
| $V_0$ (m s$^{-1}$) | 60–300 with 10 m s$^{-1}$ interval | 190             |
| $k$                | −1/6, −1/5, −1/4, −1/3, −1/2 | −1/4           |
| $q$                | −3.5 (fixed)     | ...             |
| $a_{\text{min}}$ (m) | 1.0 $\times$ 10$^{-7}$ (fixed) | ...             |
| $a_{\text{max}}$ (m) | Defined as $v_{\text{ej}}(a_{\text{max}}) = 55$ m s$^{-1}$ | $1.4 \times 10^{-4}$ |

If there are a large amount of small particles in the dust cloud, it should look bluer because of Rayleigh scattering. As we noticed in Ishiguro et al. (2011), no significant difference appears in the morphology observed in the three different optical channels. The observational evidence implies that the diffuse cloud consisted of dust particles large enough to scatter optical light (i.e., $2\pi a/\lambda > 1$, where $\lambda$ denotes the optical wavelength). The size distribution exponent $q = −3.5$ was applied because it is typical to impact fragment (Dohnanyi 1969). We performed the fitting with $q = −4$ and $q = −3$, but could not obtain a plausible result. Therefore, the initial assumptions of $q = −3.5$ and $a_{\text{min}} = 0.1 \mu m$ seems to be reasonable.

Figure 3. Images of conical curtain ejection models for 2010 December 12 for $\theta = 50^\circ$, $\Delta \theta = 10^\circ$, $V_0 = 80$ m s$^{-1}$, and different jet directions as labeled, where $\alpha_{\text{cone}}$ is constant for each row of models and $\delta_{\text{cone}}$ is constant for each column of models. In all panels, the emission source, (596) Scheila, is at the center of each image. (A color version of this figure is available in the online journal.)
up to 140 μm particles could escape from (596) Scheila. In fact, 100 μm particles were found in the observed images after 2011 February (Ishiguro et al. 2011). The velocity of dust particles depends on the tensile strength of the surface materials when the impact process is dominated by the material strength rather than gravity. The maximum ejecta velocity for solid and porous targets measured in the laboratory exceeds $10 \times (Y_t/\rho_t)^{0.5}$, where $Y_t$ is the tensile strength and $\rho_t$ is the target density (see Figure 18 of Housen & Holsapple 2011 and references therein), i.e., $v_{\text{max}} > 10 \times (Y_t/\rho_t)^{0.5}$. Since the maximum ejecta velocity is 140 m s$^{-1}$ for the conical ejecta, $Y_t < \rho_t (v_{\text{max}}/10)^2 \sim 0.3$ MPa. Our result on the ejecta velocity suggests that the surface on (596) Scheila was covered by materials with low tensile strength.

4. SUMMARY

So far we have outlined a plausible explanation for the peculiar dust cloud of (596) Scheila. We constructed a model of the morphology based on experiments of high-velocity impacts. The values of the parameters were free and obtained from fitting the observed image on 2011 December 12. We found that the morphologies on 2011 December 17 and 19 (Ishiguro et al. 2011) were also reproduced with the same model parameters. In summary, we find the following.

1. The morphology of (596) Scheila can be reproduced by an impact-driven ejecta plume consisting of an impact cone and downrange plume.
2. The maximum ejection velocity of the dust particles exceeded 100 m s$^{-1}$.
3. Assuming that an impact angle of 45°, the impactor collided with (596) Scheila from the direction of (60°, −40°) in J2000 coordinates.
4. The surface of (596) Scheila consists of materials with low tensile strength (~0.3 MPa).

With the previous studies (Jewitt et al. 2011; Hsieh et al. 2011; Bodewits et al. 2011; Ishiguro et al. 2011), we definitively conclude that a decameter-sized asteroid collided with (596) Scheila from behind on 2010 December 3.

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