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On the Edgeworth-Kuiper Belt dust flux to Saturn

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[1] Dust grains originating from the Edgeworth-Kuiper Belt (EKB) are believed to be the dominant species of dust in the outer solar system. These grains, evolving inward from the EKB under the influence of a variety of forces, will encounter the giant planets or their ring and moon systems. At Saturn, this influx drives several physical processes including the generation of tenuous dusty exospheres and rings, the spatial and compositional evolution of Saturn's main planetary ring system, and the generation of ionospheric and neutral gas layers in the atmospheres of Saturn and Titan. Recent comparisons between in-situ dust density measurements in the outer solar system and a dynamical dust grain tracing model have placed experimental limits on the mass production rate and power-law exponent of EKB-generated grains. Using this model and the experimental constraints, we make predictions for the influx of micron-sized, EKB-generated grains into the saturnian system, where the Cosmic Dust Analyzer onboard the Cassini mission is currently making measurements of both endogenous and exogenous dust populations. **Citation:** Poppe, A. R., and M. Horányi (2012), On the Edgeworth-Kuiper Belt dust flux to Saturn, *Geophys. Res. Lett.*, *39*, L15104, doi:10.1029/2012GL052530.

1. Introduction

[2] The Edgeworth-Kuiper Belt (EKB) produces approximately 3 × 10^{10} kg/year of dust grains with radii between 0.1 and 10.0 μm through a combination of mutual collisions and bombardment by interstellar dust grains [*Stern*, 1996; *Yamamoto and Mukai*, 1998; *Han et al.*, 2011]. These grains migrate inward through the outer solar system under the combination of gravity, solar radiation pressure, solar wind drag, and the electromagnetic Lorentz force, forming a tenuous dust halo extending from the orbit of Jupiter out past the classical EKB. While other dust sources, such as Jupiter-family or Oort-family comets, contribute dust to the outer solar system [*Nesvorný et al.*, 2010], EKB-generated grains are believed to be the dominant species of dust from Saturn outward [*Landgraf et al.*, 2002]. Gravitational interactions of EKB-generated grains and Neptune, the first massive object that the grains typically encounter, trap many grains in mean-motion resonances (MMR) with Neptune, significantly altering their equilibrium spatial density and velocity distributions [*Liou and Zook*, 1997, 1999; *Moro-Martin and Malhotra*, 2003].

[3] Any object traveling through the outer solar system will experience a variable flux of EKB grains depending upon the object's helio- and Neptune-centric position and velocity. For Saturn, the influx of EKB dust grains drives or influences several physical phenomena, depending on if the grain impacts the planet, one of Saturn's satellites, or the main ring system. Grains that strike either the planet or Titan directly will ablate in the saturnian or titanian atmosphere, contributing to the formation of neutral and ionospheric layers [*Ip*, 1990; *Molina-Cuberos et al.*, 2001, 2008], which in turn alter the atmospheric chemistry of both Titan and Saturn in distinct ways [*English et al.*, 1996; *Moses and Bass*, 2000; *Moses et al.*, 2000]. If the grain strikes one of Saturn's airless satellites, the impact will typically eject surface material with mass yields greater than unity. Ejecta that are able to subsequently escape the local satellite gravity form dusty exospheres or tenuous dust rings, including, for example, the recently-discovered ring originating from Phoebe [*Verbiscer et al.*, 2009], and the arcs associated with the small moons Methone, Anthe, and Pallene [*Hedman et al.*, 2009]. Grains that strike Saturn's main ring system can induce spatial and compositional changes, including erosion of the C ring, mass and angular momentum transport between the various rings, and shaping of the A and B ring edges [*Northrop and Connerney*, 1987; *Durisen et al.*, 1989, 1992, 1996; *Cuzzi and Estrada*, 1998]. Additionally, compositional and color changes in the rings are induced by the introduction of "polluted", non-icy material from impacting micrometeorites and such changes can be used to estimate the age of the main ring system [*Cuzzi and Estrada*, 1998]. Finally, interplanetary grains may also be captured into stable orbits around Saturn via interaction with the magnetosphere, yielding tenuous dust rings in addition to the main ring system [*Mitchell et al.*, 2005].

[4] Given the importance and breadth of the effects of exogenous micrometeoroid influx into the saturnian system, knowledge of this influx and its variability are critical; however, these values have remained relatively unconstrained, mainly due to the lack of in-situ observations. The Pioneer 10 meteoroid detector measured a nearly-constant flux of grains with radii larger than 5 μm outside the orbit of Jupiter [*Humes*, 1980], and based on these measurements, *Landgraf et al.* [2002] offered an estimate of the net mass production rate of micron-sized grains from the EKB. More recently, both the net mass production rate and power-law index of EKB grain production have been more tightly constrained by combining a dynamical dust tracing model with recent measurements of sub-micron sized grains out to

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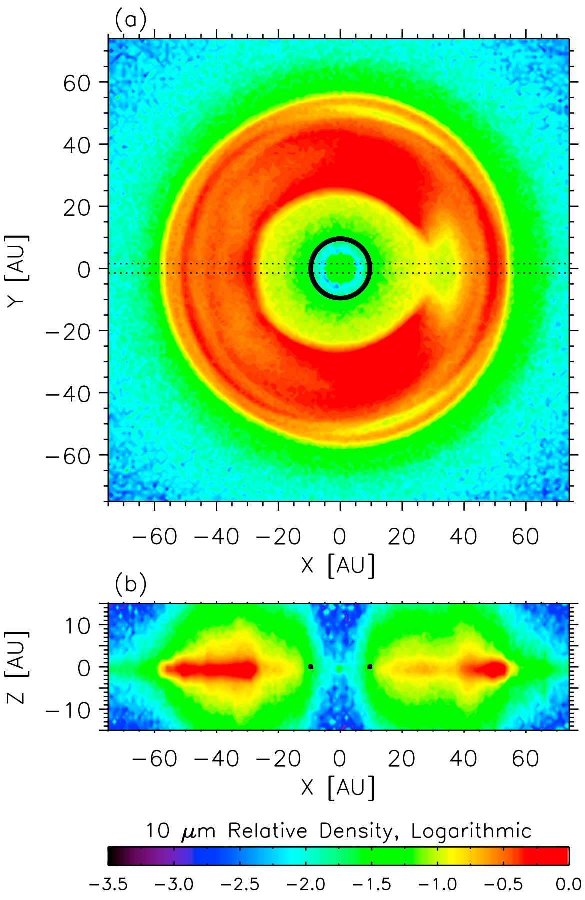

Figure 1. The logarithm of the relative density of 10 μm EKB grains in the Neptune-rotated frame viewed from (a) above the ecliptic and (b) edge-on. The dotted lines in Figure 1a denote the plane through which the x–z slice is shown in Figure 1b. The position of Saturn in the Neptune-rotated frame is over plotted on both panels in black.

approximately 20 AU by the Student Dust Counter (SDC) on the New Horizons mission [*Stern*, 2008; *Horányi et al.*, 2008; *Poppe et al.*, 2010; *Han et al.*, 2011].

[5] In this paper, we use our model that was fit to match both Pioneer 10 and SDC measurements of EKB-generated dust grain densities and velocity distributions in the outer solar system, as described in *Han et al.* [2011], to calculate the flux of EKB grains with radii between 0.1 and 10.0 μm into the saturnian system. Section 2 describes the method of calculating dust grain fluxes into Saturn from our model and presents the model results. We discuss the results and their implications for the saturnian system and conclude in Section 3.

2. Model Description and Results

[6] In order to calculate the influx of micron-sized, EKB-generated dust grains into the saturnian system, we have employed the results from a dynamical dust grain tracing model, described in detail in *Han et al.* [2011]. The model consists of a series of equilibrium density and velocity distributions with 1 × 1 × 1 AU resolution for each of eleven grain sizes, $a_d = [0.5, 1.0, 2.0, \ldots, 9.0, 10.0]$ μm. There are three sub-populations of grains for each grain size, based on the grain's parent EKB object type: classical, scattered or resonant (Plutino), and these populations are co-added together in proportions based on de-biased observational data [*Kavelaars et al.*, 2009]. The absolute density as a function of size is established by simultaneously fitting New Horizons and Pioneer 10 measurements, resulting in an overall mass production rate of 8.9×10^5 g/s and a differential mass production distribution, $d\dot{M}/dm = \dot{M}_o(m/m_o)^{-\alpha/3}$, where $\dot{M}_o$ is a normalization constant ($\approx 6.1 \times 10^{15}$), $m_o = 10^{-11}$ g, and $a = 3.02$ [*Han et al.*, 2011]. Figure 1 shows the relative density of 10 μm grains in the Neptune-rotated frame in the ecliptic x–y and x–z planes with the trajectory of Saturn (in the same frame) over plotted for comparison, showing that Saturn resides within the EKB dust halo.

[7] We trace along Saturn's trajectory in the Neptune-rotated frame and interpolate the dust grain density and mean velocity from the set of nearest 1 × 1 × 1 AU grid points for each grain size and type. The dust grain velocities are vectorially added to Saturn's velocity at each point in order to establish the impact velocity distribution into Saturn at infinity (i.e., before any gravitational acceleration due to Saturn). The differential influx at each grain size,

$$\Gamma_a = \sum_{i}^{\{c,s,r\}} n_i^a \langle v_i^a \rangle, \qquad (1)$$

is then calculated, where n_i^a and v_i^a are the density and impact velocity distribution for grain size a and type i, respectively, while c, s and r denote the classical, scattered, and resonant sub-populations of EKB objects. Figure 2a shows the mean impact speed of EKB-generated grains into Saturn as a function of grain radius averaged over time, before any local gravitational acceleration or focusing. Impact speeds for 2 μm-sized grains and larger are typical of low-inclination, low-eccentricity orbits crossing the orbit of Saturn, while impact speeds for grains less than 2 μm are somewhat higher. This increase is due to solar radiation pressure, which causes grains to orbit slower than a classical Kepler orbit [*Burns et al.*, 1979]. Consequently, smaller grains ($a < 2$ μm) have greater relative impact speeds with respect to Saturn.

[8] Figure 2b shows the differential flux of EKB grains with radii, $0.1 < a < 10$ μm, into Saturn, before any gravitational focusing. For comparison, the differential flux from two different models are shown: (a) the *Grün et al.* [1985] model at 1 AU, appropriately scaled to 10 AU by assuming that the heliocentric velocity of the grain (and therefore the flux) scales as $1/\sqrt{R}$, where R is the heliocentric distance, and that the dust maintains a constant spatial density, and (b) the *Divine* [1993] model, using the 'halo' dust population, which is the only source present at 10 AU for grains less than 10^{-6} g. Both models, frequently used to estimate meteoritic influx to objects in the outer solar system, are significantly different than our modeled influx, with our model showing a higher influx of relatively smaller grains and a lower influx of relatively larger grains. Indeed, the differences in slope between our model and the *Grün et al.* [1985] and *Divine* [1993] models are so great that for 10 μm grains, we predict an EKB influx far from Saturn that is approximately one and two-and-a-half orders of magnitude less than *Divine* [1993] and *Grün et al.* [1985]

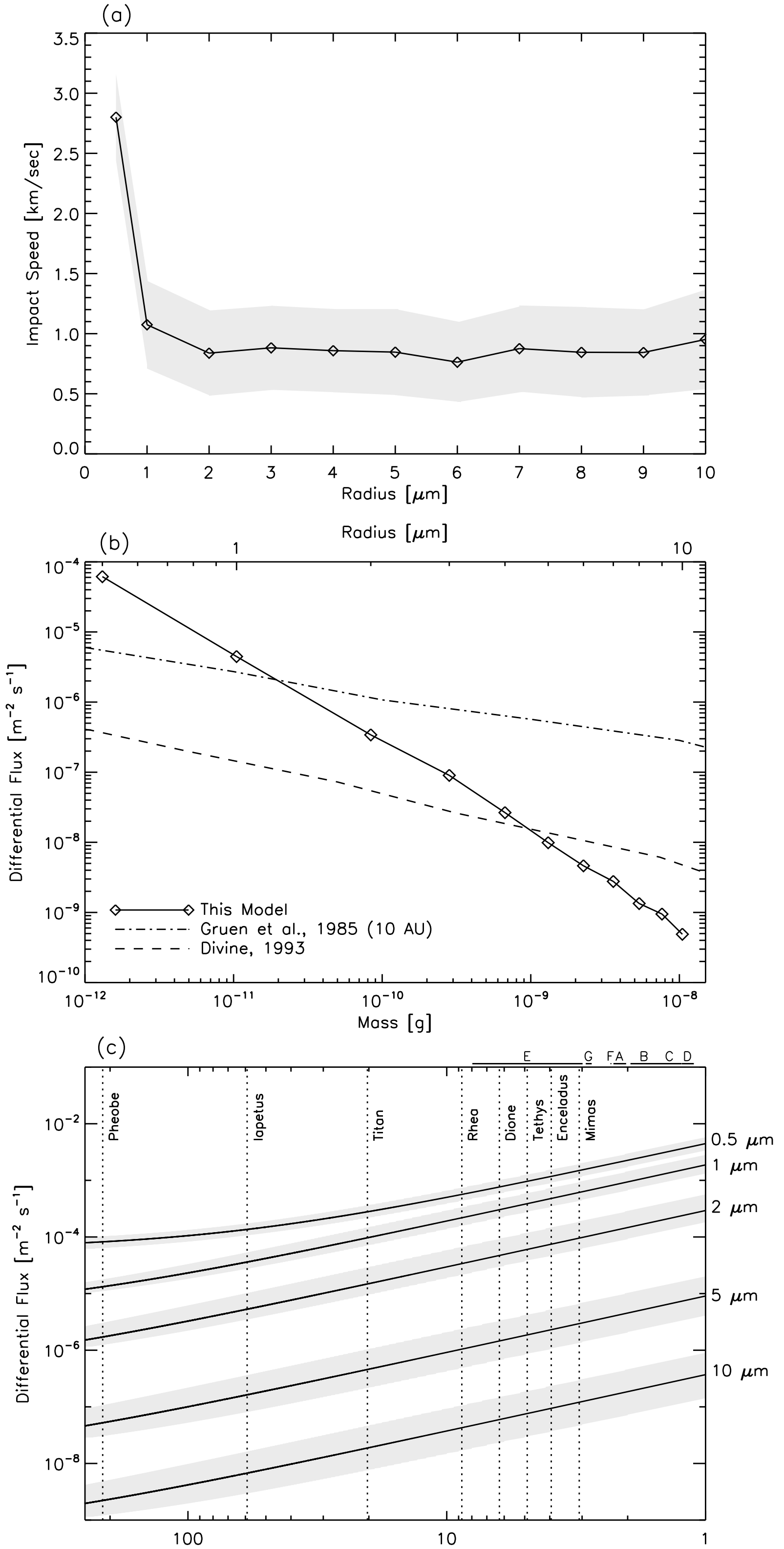

Figure 2. (a) The mean impact velocity at Saturn's Hill radius as a function of grain size. The shaded bars denote the standard deviation in impact velocities. (b) A comparison of the model-predicted differential flux of EKB grains into Saturn as a function of grain size with the *Grün et al.* [1985] and *Divine* [1993] micrometeoroid flux models, appropriately scaled to 10 AU. All curves are shown before any gravitational focusing by Saturn. (c) The differential flux of EKB grains for a selection of grain sizes as a function of distance from Saturn, taking into account the gravitational increase in cross section. The shaded gray regions around each line are the one-sigma variability in the differential flux. Also, marked on the plot are the mean positions of the major saturnian satellites and the saturnian ring system.

predict, respectively. The discrepancies between these models is not necessarily surprising, given that the *Grün et al.* [1985] model is based on measurements at 1 AU and knowingly does not include any information about dust grain sources and dynamics in the outer solar system, and the *Divine* [1993] model's only data in the outer solar system comes from the Pioneer 10 and 11 probes.

[9] To calculate the EKB dust grain flux at any point *within* the saturnian system, we must account for the increase in cross section for each grain size that results from the acceleration of dust grains into Saturn's gravity well,

$$G^a(r) = 1 + \frac{1}{2}\left(\frac{v_{esc}(r)}{v_\infty^a}\right)^2, \qquad (2)$$

where $v_{esc}(r)$ is the escape velocity as a function of distance from Saturn, r, and v_∞^a is the grain impact velocity at infinity [*Colwell*, 1994]. We note that equation (2) is approximate, given that it assumes an impacting flux normal to the satellite orbit plane. A complete calculation of the flux enhancement requires integration of individual incoming trajectories and is beyond the scope of this paper; however, equation (2) does provide a good first-order estimate. Figure 2c shows the differential flux for a selection of EKB dust grain sizes as a function of distance from Saturn, taking into account the gravitational cross section increase. The flux at each grain size increases by approximately two orders of magnitude from infinity to Saturn's cloud tops, with the 0.5 μm grain flux increasing the least due to its typical impact speed at infinity ($\approx$3 km/sec) being slightly higher than that of the larger grain sizes ($\approx$1 km/sec). Each of Saturn's moons and rings will experience different fluxes and velocity distributions given their differing orbital distance from Saturn.

[10] Using the EKB dust grain velocity distribution at each point along Saturn's orbit, we can also calculate the apparent impact direction of EKB dust grains to an observer at the Hill radius of Saturn as a function of grain size. Figure 3 shows the time-averaged, relative flux of 0.5, 2.0 and 10.0 μm grains as a function of ecliptic azimuthal and polar angles, with the ram ('R'), solar ('S') and anti-solar ('AS') directions denoted. The 0.5 μm grains impact Saturn from the ram direction exclusively, since, as discussed earlier, solar radiation pressure causes smaller grains to orbit the Sun slower than a classical Kepler orbit [*Burns et al.*, 1979], and thus, Saturn effectively "sweeps up" the 0.5 μm grains. The 2.0 and 10.0 μm grains impact Saturn along four distinct peaks placed above and below the ecliptic plane along the solar and anti-solar directions, respectively. In contrast to the 0.5 μm grains, the 2.0 and 10.0 μm grains are less affected by solar radiation pressure (their β parameter is smaller [*Burns et al.*, 1979]), and therefore orbit at speeds much closer to the local Kepler speed. Thus, the impact velocity for the larger grains increases in the radial and out-of-plane components relative to the azimuthal component and, correspondingly, the grains impact Saturn from directions along the sun/anti-sun plane, inclined out of the ecliptic plane. Finally, Saturn's orbital eccentricity ($e \approx 0.055$) and inclination ($i \approx 2.5°$) cause the influx direction to alternate slightly in time; for example, the anti-solar-ward peak in the 0.5 μm impact direction is strongest when Saturn is traveling from

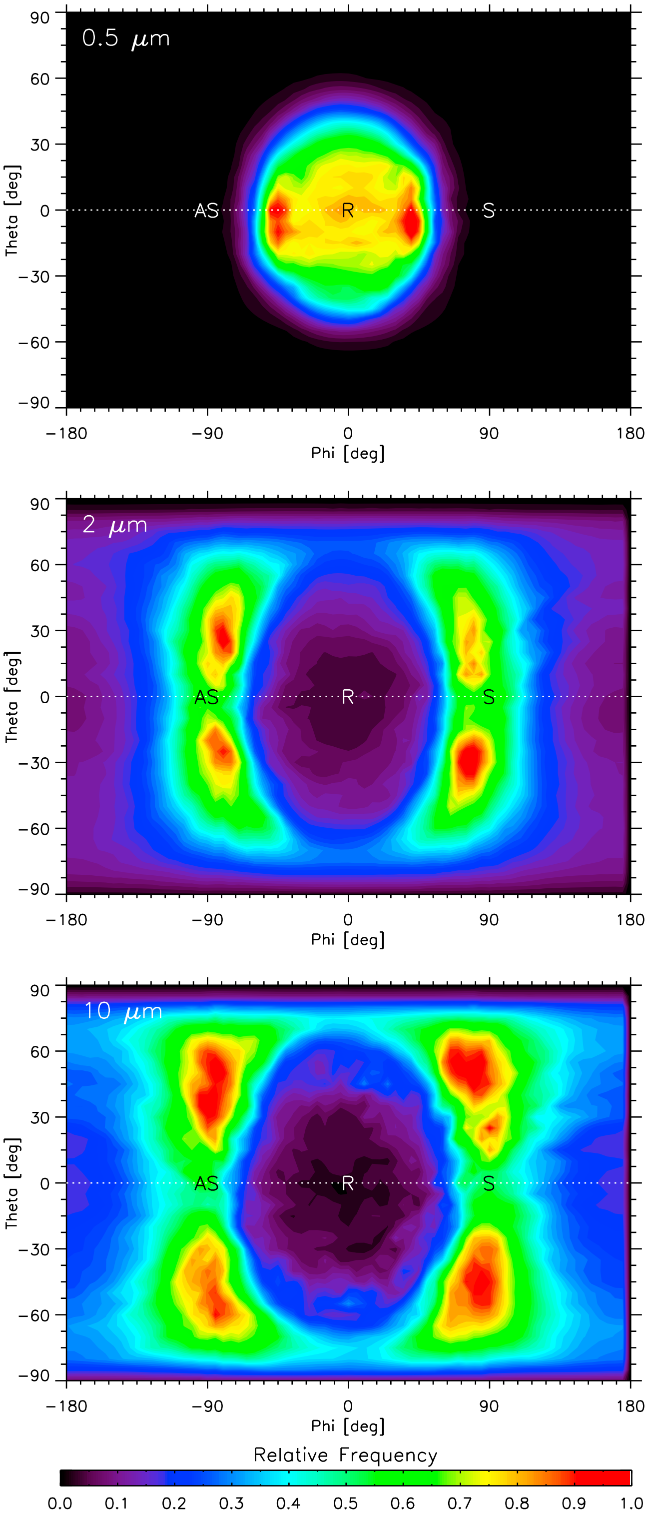

Figure 3. The relative frequency of EKB dust grain impact directions into Saturn for 0.5, 2.0 and 10.0 μm grains averaged over time, shown in the ecliptic frame. The labels 'S', 'AS', and 'R' denote the solar, anti-solar, and ram directions, respectively, and the dotted lines marks the ecliptic.

perihelion to aphelion, while the sunward peak is strongest from aphelion to perihelion.

3. Discussion and Conclusion

[11] The model predictions presented in this paper for the influx of Edgeworth-Kuiper Belt grains into Saturn are a critical step in quantifying and understanding a variety of physical phenomena in the saturnian system. Our model, constrained overall by both New Horizons Student Dust Counter and Pioneer 10 meteoroid detector measurements, yields a distinctly different flux and mass distribution than is typically assumed for the outer planets with either the *Grün et al.* [1985] or the *Divine* [1993] models. The steeper slope of the mass distribution presented in our model implies a concentration of mass in smaller grain sizes relative to previous models; however, a full evaluation of the net mass influx at points within the Saturnian system also depends on the relative velocity of the dust grain with respect to Saturn at infinity. Previous analyses of dust influx to Saturn have typically assumed a high-eccentricity, high-inclination dust source, which will yield higher impact speeds and, in turn, less gravitational focusing by Saturn. Our model predicts a lower relative velocity and, therefore, while the net EKB influx far from Saturn may be less than that estimated by the *Grün et al.* [1985] or the *Divine* [1993] models, gravitational focusing will increase the EKB flux significantly within the Saturnian system. Additionally, as has been noted in previous work [*Moses et al.*, 2000; *Landgraf et al.*, 2002], Saturn may occupy a region in the outer solar system where a single species of dust grains does not dominate the meteoritic influx. Instead, a combination of sources, including EKB grains, interstellar grains, cometary grains, and for Saturn in particular, planetary satellite or ring grains, may all contribute in relatively significant amounts. Future work will aim to model and quantify the influx of other grain species in order to understand the net exogenous mass influx into the saturnian system.

[12] Further in-situ observational verification of this model can be obtained from the Cassini Cosmic Dust Analyzer (CDA), currently operating in orbit around Saturn [*Srama et al.*, 2004]. The CDA measures the mass, impact velocity, and impact direction of dust grains both endogenous and exogenous to Saturn with masses in the approximate range of 10^{-19} to 10^{-9} g. Additionally, if the dust grain happens to strike a small sensor within the CDA, a time-of-flight mass spectrometry analysis is undertaken, with the goal of measuring the elemental composition of the impacting dust grain. CDA has been accumulating dust grain measurements both along its interplanetary cruise and within the saturnian system, offering a rich dataset with which to compare with our model [*Srama et al.*, 2006; *Altobelli et al.*, 2007]. Verification of the predicted flux, and velocity and size distributions of incoming EKB dust grains with the CDA will help to further constrain our model and understand the flux of exogenous micrometeoroids into Saturn. Finally, a measurement of the composition of exogenous dust grains at Saturn could shed light on the composition of EKB parent objects [*Dumas et al.*, 2007; *Schaller and Brown*, 2007; *Brown et al.*, 2011].

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