MODELING THE DYNAMICAL EVOLUTION OF SATURN'S E RING FOLLOWING A CRYOVOLCANIC ERUPTION ON ENCELADUS.

S. G. Zaidi[1] and S. J. Morrison[1], [1]Center for Exoplanets and Habitable Worlds, 525 Davey Laboratory, The Pennsylvania State University, University Park, PA 16802, USA (shirin.gul.zaidi@gmail.com; smorrison@psu.edu)

Introduction: Enceladus' south polar region is known to have active cryovolcanic plumes that erupt material and likely supply most of the material in Saturn's E ring [1][2]. However, most past work on Enceladus' interaction with the E ring has been explored only within the vicinity of Enceladus itself [3][4] or in terms of the ring's 'steady state' conditions to produce the observed properties of the E ring [4-6]. Here we investigate the dynamical timescales of particles contributing to the E ring from individual eruptive events on Enceladus. We examine the dynamical outcomes of the material that leaves Enceladus following an eruption, including what mechanisms promote radial transport of erupted material into the outer portions of the E ring, the properties of the material undergoing that transport, and the timescales for this evolution to occur. We perform analytical and numerical calculations of the orbit evolution of particles erupted from the surface of Enceladus as a function of initial latitude, surface ejection speed, and grain size.

Investigating the Dynamical Evolution of Saturn's E ring: To numerically simulate the system including the most gravitationally relevant moons, we employed the N-body numerical integrator packages REBOUND IAS15 and REBOUNDx [7-9]. In our simulations we include Saturn, Mimas, Enceladus, Tethys, Dione, Rhea, Titan, Hyperion, and Iapetus with initial conditions from JPL Horizons [10][11]. Our simulations include the gravitational effects of Saturn on its moon system due to its oblateness with the included implementation of the J_2 and J_4 gravitational coefficients. We further implemented a plasma drag force within the E ring, as the drag force from collisions with the co-rotating plasma in Saturn's magnetosphere causes E ring particles to drift outward on a timescale:

$$\frac{1}{t_p} = \left|\frac{1}{r}\frac{dr}{dt}\right| \cong \frac{2\pi k\rho^* R^2 r}{m}\frac{(\Omega-\Omega^*)^2}{\Omega}$$

where *r*, *R*, and *m* are the orbital radius, radius, and mass of the particle, *k* is of order unity, ρ^* is the plasma density, and Ω and Ω^* are the angular speeds of the particle and planet [12]. For Saturn's E ring, the drift rate is about 0.03 Saturn radii per year at Enceladus' orbit distance for a one micron erupted grain [6].

Timescale Comparisons: Without plasma drag, our simulations resulted in ejecta falling back or continuing to exist within the vicinity of Enceladus even after 30,000 days post eruption. These early results are representative outcomes of the portion of an eruption consisting of larger grains and erupted at speeds near and exceeding the escape speed of Enceladus. Larger particles erupted from Enceladus that are larger than one micron are not as influenced by plasma drag, and would not reach beyond the orbit of Dione within 30,000 days.

To build intuition for whether smaller grained cryovolcanic material drifting outward due to plasma drag will reach other moons in the E ring, we compare analytic estimates of timescales of drift from plasma drag across the annulus region a moon can clear near its orbit (its chaotic zone) and clearing for the closest two moons exterior to Enceladus, Tethys and Dione. Using the equation above to estimate time it take erupted material to drift across Tethys' and Dione's chaotic zone, we find the plasma drift time to be about 5 years for Tethys and 7.5 years for Dione.

To find the clearing timescale for the individual moons, we use the relation from [13] for the time in number of orbit periods that it takes for a moon with a moon-planet mass ratio, μ, to clear half the material from its chaotic zone:

$$T_{cl}(\mu) = \frac{2T_b}{(\frac{\mu}{\mu_b})^{-\alpha_1} + (\frac{\mu}{\mu_b})^{-\alpha_2}}$$

Where $\log_{10}T_b$ is the clearing timescale at transition mass with value 3.10 ± 0.28, $\log_{10}\mu_b$ is the transition mass itself with value -3.43 ± 0.35, and α_1 and α_2 are the asymptotic power-law slopes at $\mu \ll \mu_b$ and $\mu \gg \mu_b$ with values of -0.34 ± 0.05 and -1.48 ± 0.19 respectively. This timescale corresponds to 2.8 years and 3.5 years for Tethys and Dione, respectively. Given that this timescale is only slightly shorter than the drift timescale, a portion of micron-sized particles are cleared from the E ring and may reach each moon's surface, but some will drift past the orbits of these moons.

Discussion: Populations of smaller grains erupted from Enceladus on escape trajectories are less likely to be dynamically cleared by Tethys and Dione since they will drift outward faster than these moons can clear them on average. Therefore, E ring grains smaller than about 0.5 microns are not as likely to contribute significantly to the surface regolith of Tethys and Dione. This is consistent with the observed lack of thick regolith cover and surface optical properties indicative of only a thin veneer of E ring particles on Tethys and Dione [14-16]. This implies that if the E ring is sourced solely by Enceladus, only smaller grains would be remaining in the outer E ring as there is a higher density of one micron-sized grains as compared to much larger sized grains. Observational constraints from both the Cassini Radio and Plasma Wave Science and Cosmic Dust Analyser instruments on grain sizes in the Saturnian system find grain size distributions will dominate the overall particle size distribution of the E ring. The grain sizes within the larger E ring (from three to six Saturn radii) were seen to lack radial distinction [4][17]. Moreover, observational constraints of Enceladus' plume from Cassini's Visible and Infrared Mapping Spectrometer suggest the portion of the plume that supplies the rest of the E ring will be comprised mainly of small grains [18]. Using results from our numerical simulations we discuss and quantify the efficiency of these processes along with the dynamical timescales and final fates of the portion of the material that leaves the vicinity of Enceladus from a single eruptive event.

References: [1] Kempf S. and Beckmann U. (2010) *Icarus 206*, 446–457. [2] Porco C. and Helfenstein P. (2006) *Science 311*, 1393–1401. [3] Mitchell, C. et al. (2015) *AJ* 149, 156. [4] Kempf S. et al. (2008) *Icarus 193*, 420-437. [5] Hill T. (1984) *Icarus 4*, 149-157. [6] Horányi M. et al. (2008) *GRL 35*. [7] Rein, H. and Liu (2012) *A&A* 537, A128. [8] Rein, H. and Spiegel, D. S. (2015) *MNRAS* 446, 1424-1437. [9] Tamayo, D. et al. (2015) *BAAS* 47, 6. [10] ssd.jpl.nasa.gov [11] Jacobson et al. (2006) *AJ* 132, 2520-2526. [12] Goldreich P. (1982) *ARAA 20*, 249-283 [13] Morrison S. and Malhotra R. (2015) *ApJ 799-1*. [14] Verbiscer, A. et al. (2007) *Science 315*, 815. [15] Howett, C. et al. (2009) *Icarus 206*, 573-593. [16] Filacchione, G. et al. (2010) *Icarus 206*, 507-523. [17] Ye, S. Y. and Gurnett, D. A. (2016) *Icarus 279*, 51-61. [18] Hedman M. M. and Nicholson, P. (2009) *ApJ 693*, 1749-1762.