MODELING THE EVOLUTION OF EJECTA CLOUDS OFF SMALL BODIES: AN N-BODY PARTICLE APPROACH WITH *REBOUND* J. Larson[1] and G. Sarid[2], [1]Department of Physics, University of Central Florida, [2]Florida Space Institute, University of Central Florida.

Introduction: The study of impacts on small bodies can be applied to a variety of scenarios in our solar system as well as developing solar systems. Understanding how debris interact with surrounding perturbers will help to find ways to defend Earth from asteroid impacts. In addition, the code developed here may be further developed to study the formation of ring systems, including the formation of Centaur rings. Additionally, this model will support modeling efforts for the Asteroid Impact and Deflection Assessment (AIDA) mission to predict the trajectory of the debris created by the Double Asteroid Redirection Test (DART) impact [1,2].

The Python module REBOUND [4] makes it possible to do N-body calculations at a higher temporal resolution at a lower performance cost than most commonly used schemes [3]. In addition, REBOUND offers a collision function that allows for particle-particle interactions [4]. With this function we can model disks and rings using an N-body particle method rather than a hydrodynamic approach. The N-body particle approach allows us to study the microdynamics of a particle cloud with a varied size distribution of particles whereas in the hydrodynamic approach some of these finer interactions are lost [5].

Here we implement the REBOUND to track the evolution of ejecta clouds. The following section describes the methodology of implementing REBOUND. Next, we outline several effects to consider in the development of this model. Finally, a few preliminary results and upcoming work are discussed.

Methodology: The REBOUND Python module used in this study is an N-body integrator developed by [3] to model collisions, dust grains, ring dynamics, etc. The Python module offers a symplectic Wisdom-Holman integrator (WHFast) [6] as well as a non-symplectic IAS15 integrator [7].

First, a REBOUND simulation is created and the systems units are defined. For this model, we choose days, AU, and kg as our unit system. A target body with a given mass, radius, and orbital coordinates is defined. For an example, we define a small body similar to asteroid (596) Scheila [8,9] with a mass of 4.27×10^{18} kg (assuming a density of 2 g cm^{-3}). Next, the surrounding perturbers, such as a central star and surrounding planets, are defined. Our test case considers our current solar system of the sun and the eight planets. Particles representing individual grains of dust are initially defined using Cartesian coordinates with respect to the target body. All position and velocity coordinates are randomized by 10^{-4}. Since the particles represent the individual particles in a cloud of ejecta exiting the surface, the initial velocity is non-zero and represents the exit velocity of material (roughly the escape velocity). During each time-step, any particle within 1 AU or beyond 50 AU is removed from the simulation.

Considerations: Table 1 shows the various effects to be considered in future development of this model. The initial model follows particles immediately after impact. Therefore, the initial conditions of the particles are set such that the particle conditions are essentially the same as the conditions of the target body. This will not be an exact replication of the impact since at this stage only gravitational effects are considered.

Next, we will implement a varied size distribution with particles with diameters of several microns to several centimeters. This varies the sizes of the particles in the ejecta cloud, allowing for small particles to interact and clump together [10]. Larger particles will have different trajectories than the smaller particles.

Thirdly, we will examine the effects of non-axisymmetric gravity within the target body. Small bodies such as asteroids commonly have non-spherical shapes causing the gravitational potential to vary across the surface [11,12]. Since these variations affect the smaller particles differently than the larger particles, we will implement non-axisymetric gravitational forces after determining the size distribution of particles.

Forth, we will include radiation pressure to introduce effects of solar radiation. While this effect is not large, its effect on the distribution of particles will vary depending on the power of the distribution.

Next, we will consider binary and triple systems. This step will be implemented next to last in order to first ensure that all of the previously mentioned effects are accurate for a system with a single body. Adding a second or third body to the system changes the gravitational potential of the system slightly with respect to the non-axisymetric gravitational potentials of the new bodies [13]. This will allow us to model how the ejecta plume will interact with the Didymos system based on the DART impact initial conditions.

Finally, we will implement the collision function in REBOUND to track particle-particle interactions. This function allows for particles to either merge or bounce

off of each other, or a custom interaction can be defined [4]. With this function, we can model disks using an N-body approach rather than a hydrodynamic method.

Effects of solar and planetary tides will not be implemented due to their relatively negligible affects on the particles. However, particles will feel gravitational perturbations from the surrounding bodies in the system

Results: The initial model presented here does not yet include the considerations discussed in the previous section; however, it does consider the simple case of a cluster of particles exiting the surface of a target body. To test our model, we compare our results to the observations of asteroid (596) Scheila [8,9]. Figure 1 shows (a) the ideal model of an ejecta distribution and (b) an actual representation of the forces and interactions involved in the formation of an ejecta cloud. In the idealized representation (Fig. 1a) of an ejecta cloud, the gravitational potential is uniform about the surface, creating very uniform and predictable particle trajectories. Also, the particle cloud has a uniform size distribution. Figure 1b shows an actual representation of an ejecta cloud. Variations in the local mass distribution and shape cause variations in the local surface gravity of the body. In addition, particles of varying sizes interact with each other through collisions. Larger bodies in the system gravitationally perturb the particle orbits. Finally, radiation pressure accelerates the particles according to their size and shape.

Currently our setup is benchmarked with the situation diagrammed in Fig. 1a. We will show how implementing the considerations discussed in the previous section will enable an accurate model of ejecta trajectories.

Upcoming Work: Currently this initial model only considers gravitational effects of ejecta particles leaving the surface of a target body. In the future, we plan to implement the steps outlined in Table 1 to create a more realistic representation of an ejecta cloud that will be applied to various types of systems. With this model we will study the formation of rings systems, such as Centaur rings. In addition, this model will support the ejecta modeling efforts for the AIDA mission. Finally we will implement particle-particle collisions in order to develop a particle-based disk model.

References: [1] Cheng A. F. et al. (2016) *Planet. & Space Sci., 121,* 27-35. [2] Schwartz S. R. et al. (2016) *Advances in Space Research, 57,* 1832-1846. [3] Rein H. and Tamayo D. (2017) *Mon. Not. R. Astron. Soc.* Preprint. [4] Rein H. and Liu S.-F. (2012) *A & A, 537,* A128. [5] Artemieva N. (2008) *Large Meteorite Impacts and Planet. Evo. IV,* 3082. [6] Rein H. and Tamayo D. (2015) *Mon. Not. R. Astron. Soc., 452,* 376-388. [7] Rein, H. and Spiegel D. S. (2014) *Mon. Not. R. Astron. Soc., 446,* 1424-1437. [8] Jewitt D. et al. (2011) *ApJ Letters*, *733,* L4. [9] Ishiguro M. et al. (2011) *ApJ Letters, 741*, L24. [10] Brisset J. et al. (2015) *AGU, Fall Meeting 2015,* Abstract #P51B-2059. [11] Durech J. et al. (2015) *Asteroids IV,* 183-202. [12] Takahashi Y. et al. (2013) *J. Guidance, Control, and Dyn.,* 362-374. [13] Margot J.-L. Et al. (2015) *Asteroids IV,* 355-374.

Order	Effect
1	Develop basic model of particles being ejected from small body (compare to (596) Scheila observations)
2	Determine size distribution of particles
3	Implement non-axisymmetric gravity
4	Implement radiation pressure effects (dependent on particle size, material, porosity, and shape)
5	Apply to binary/triple systems
6	Allow particle-particle interactions using REBOUND's collision function

Table 1. List of physical effects that will be implemented into the model in future work. Effects are organized by the order in which they will be implemented.

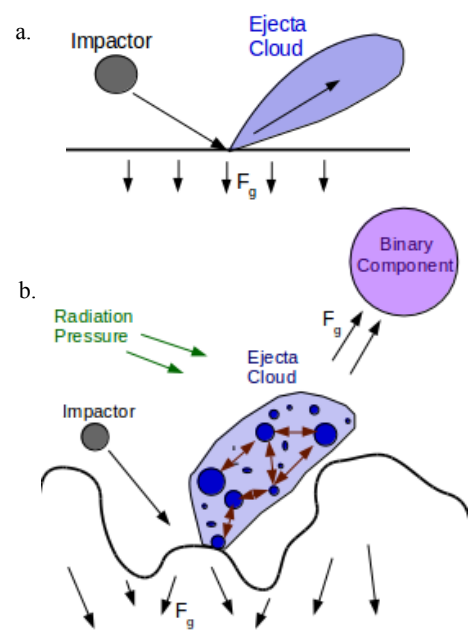

Figure 1. The simplistic, ideal model of an ejecta cloud (a) in comparison to an actual model (b). (a) The ideal model has a uniform gravitational force and uniform particle distribution. (b) The actual model has an uneven surface resulting in varying gravitational forces. Arrows between the particles represent potential collisions between particles of varying sizes.