Immersed-Finite-Element Particle-in-Cell Simulation of Dust-Plasma-Spacecraft-Asteroid Interactions

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1. Introduction

While the dynamics of dust transport around an airless body has been a focused area of research in recent years, various challenging aspects still remain to be addressed for small asteroids where the dust dynamics is determined by the competing effects from gravitational force, electromagnetic force, and solar radiation pressure. This work presents a numerical investigation of dust transport and distribution around irregularly shaped small asteroids. The numerical models involved include a kinetic 3D particle-in-cell (PIC) using an immersed-finite-element based field solver to simulate asteroid charging, a finite-element gravitational field model to characterized the gravitational force of complex shaped asteroids, and a dust transport model. Dust charging properties are extrapolated from laboratory experiments. Dust transport simulations incorporate results of PIC and gravity field models and charging measurements to ascertain dust trajectories and spatial distributions.

2. Model and Equations

2.1. Electric Field Model

The electrostatic field is solved using an IFE-PIC model [1] which resolves plasma interactions and surface charging at complex shaped asterorids

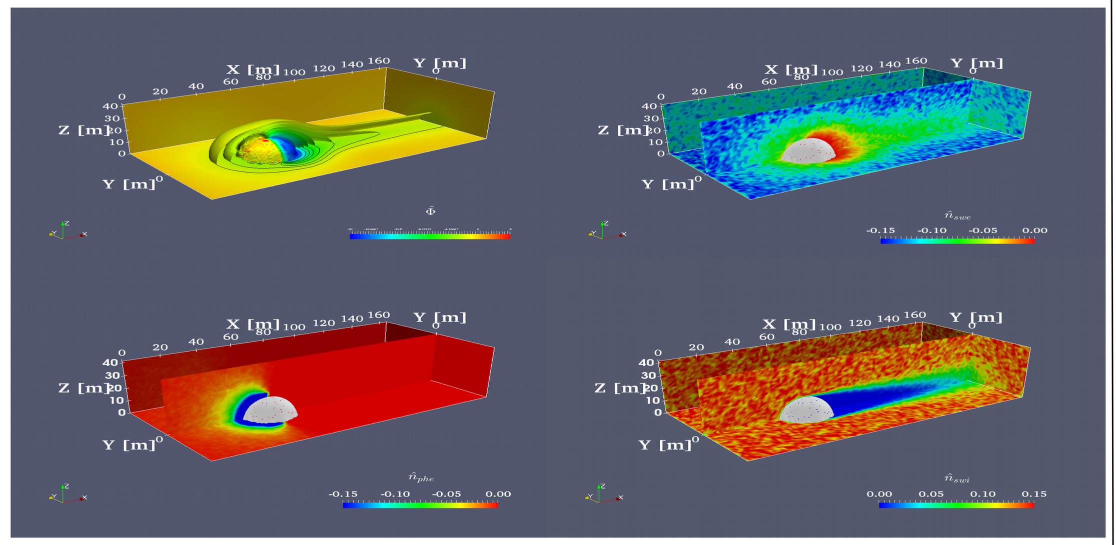

Figure 1: Electric Firld Contour
Left Top: Potential Contour, Right Top: Electron Density
Left Bottom: Photo Electron Density, Right Bottom: Ion Density

2.2. Gravity Field Model

The gravitational field is solved using the finite element MASCON model [2]

$$\nabla U_m = \frac{\partial U}{\partial r} = -\sum_{i=1}^{N} \frac{G m_i}{\| r-\rho_i \|^3}(r-\rho_i)$$

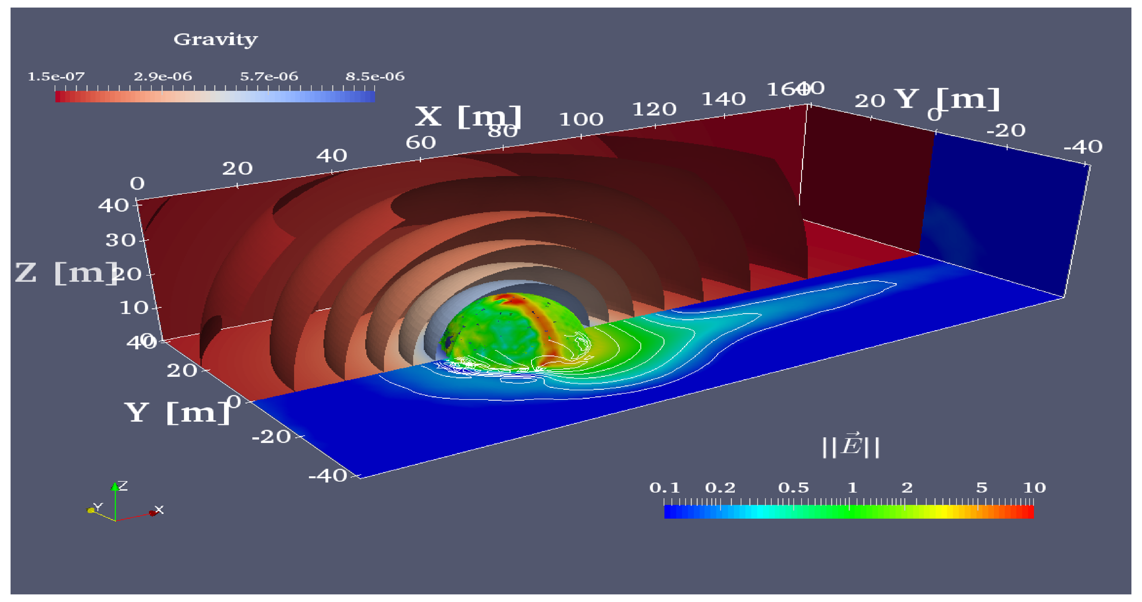

Figure 2: Gravity Field Contour V.S. E Field Contour

3. Simulation Setup

The simulations include the the effects of the electric field, gravity field, and solar radiation pressure on the dust grain.

$$m_d \frac{dv_d}{dt} = Q_d(r_0)E(r) + m_d \cdot g_a(r) + F_{SRP}(r)$$

Domain size	Mesh size	Mesh length	$\|Q_d/m_d\|$ cases
120 x 30 x 30	1	1.38 m	0 C/kg
Simulation time	**Time step**	**Sim. wall time**	$\leq 10^{-7}$ C/kg
200 mins	0.2 sec	$\sim$ 10–20 hrs	$\leq 10^{-4}$ C/kg
# of dust particles		$\sim$ 4–8 million	$\leq 10^{-1}$ C/kg

Figure 3: Simulation Setup

Asteroid geometry		spherical, 28 m	
Grain geometry		spherical	
Solar distance		1 AU (NEA)	
Bulk density	2.8 g/cm^3	**Grain density**	3.0 g/cm^3
Coefficient of restitution	0.8	**Grain size**	20 μm
Rotational period	7.6 hrs	**Dielectric constant**	4.0

Species	Number density n [cm^{-3}]	Drift velocity v_d [km/s]	Thermal velocity v_t [km/s]	Temp T [eV]	Debye length λ_D [m]
S.W. Electron	8.7	468	1450	12	8.73
S.W. Ions	8.7	468	31	10	7.97
Photoelectron	64	N/A	622	2.2	1.38

Figure 4: Plasma and asteroid properties.

4. Simulation Results

Plasma Flow/Dust Distribution: Sphere-Shaped Asteroid

The following show typical results of solar wind flow over a sphere-shaped asteroid. The effects of dust grain size, dust charge/mass ratio, and gravity field on dust dynamics are also discussed.

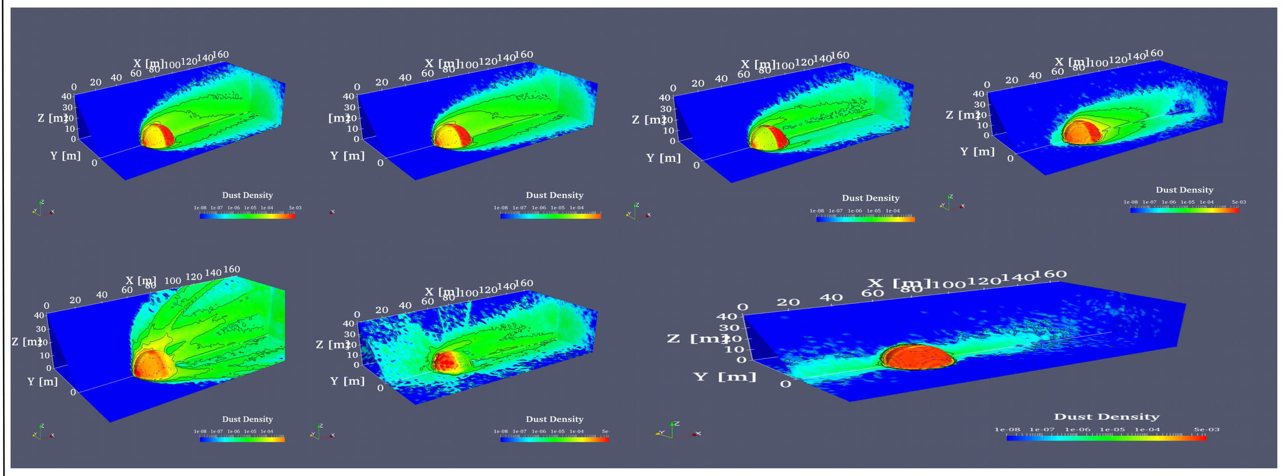

Figure 5: Charge number's effect on dust distrbituion.
Left top: Neutral
Right top: surface model
Left bottom: Q isolated
Right Bottom: 1000x Q isolated

Figure 6: Grian size's effect on dust distribution.
Left top: 1 mu
Right top: 100mu
Bottom: 1000mu

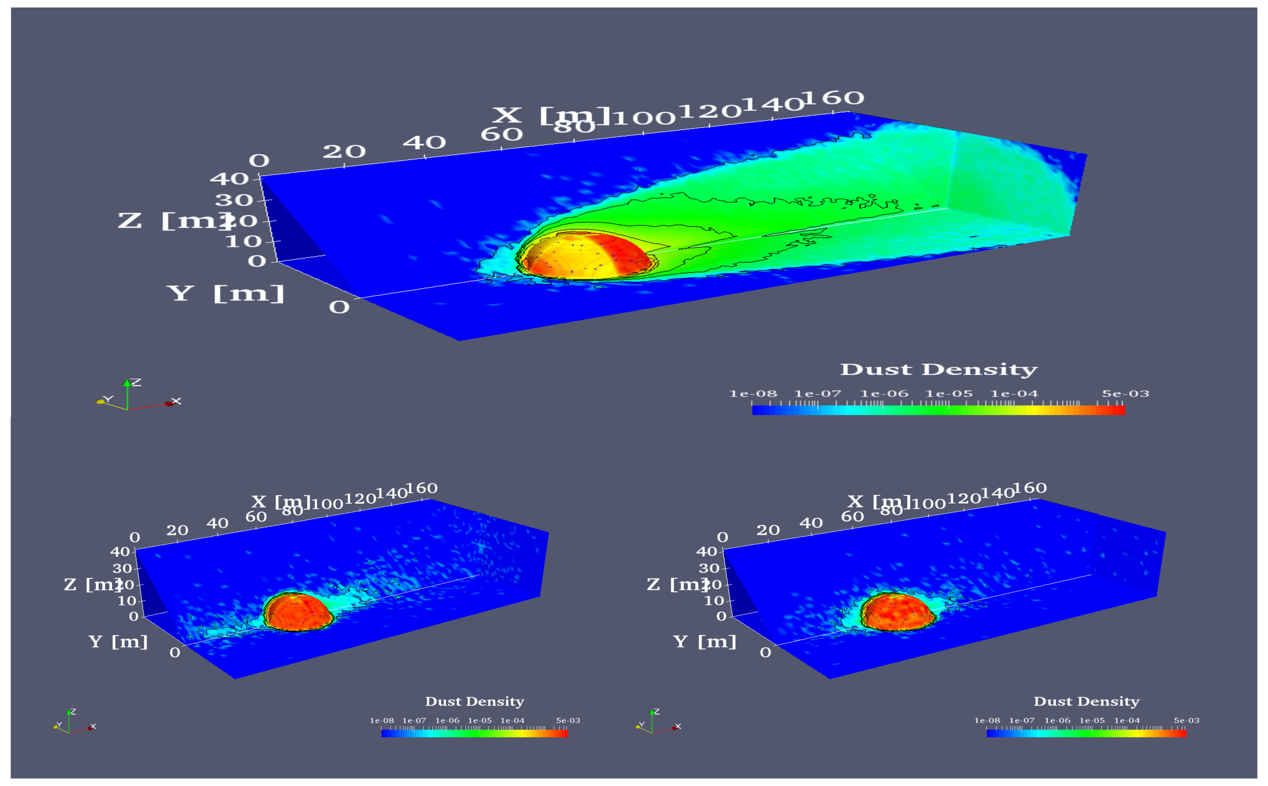

Figure 7: G Field's effect on dust distribution.
Top: 1x G Field
Left bottom: 100x G Field
Right bottom: 1000x G Field

The dust grain size and gravity field all have a strong effect on the simulation result. A stronger gravity field limits the dust distribution in a smaller space.

Plasma Flow/Dust Distribution: Bi-Sphere Shaped Asteroid

The following show typical results of solar wind flow over bi-sphere shaped or irregularly shaped asteroids. The effects of dust size on dust dynamics are also discussed.

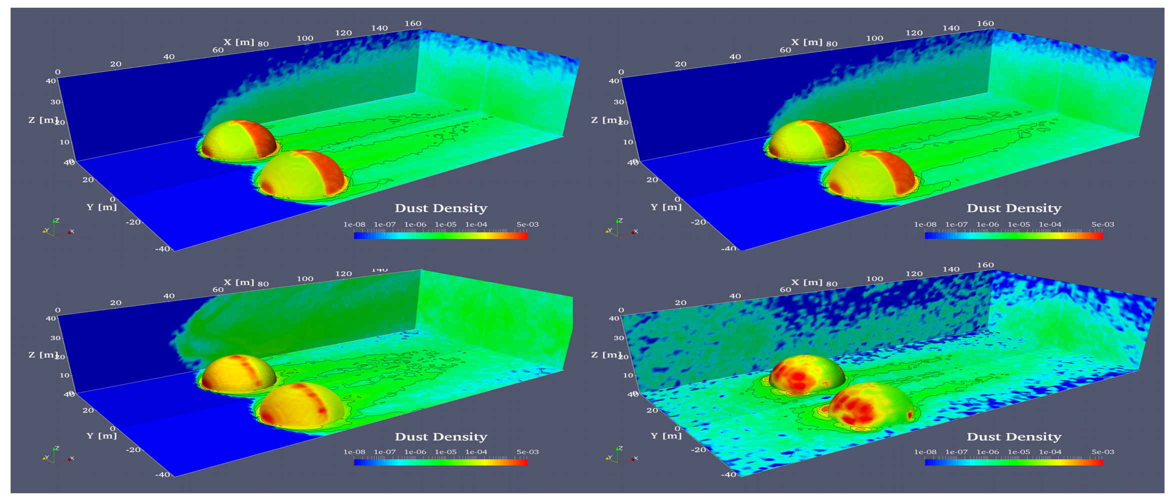

Figure 8: Plasma flow over a bi-sphere shaped asteroid (1)
Left top: Neutral Right Top: Q normal
Left Bottom: 1000x Q Right bottom: 1e6x Q

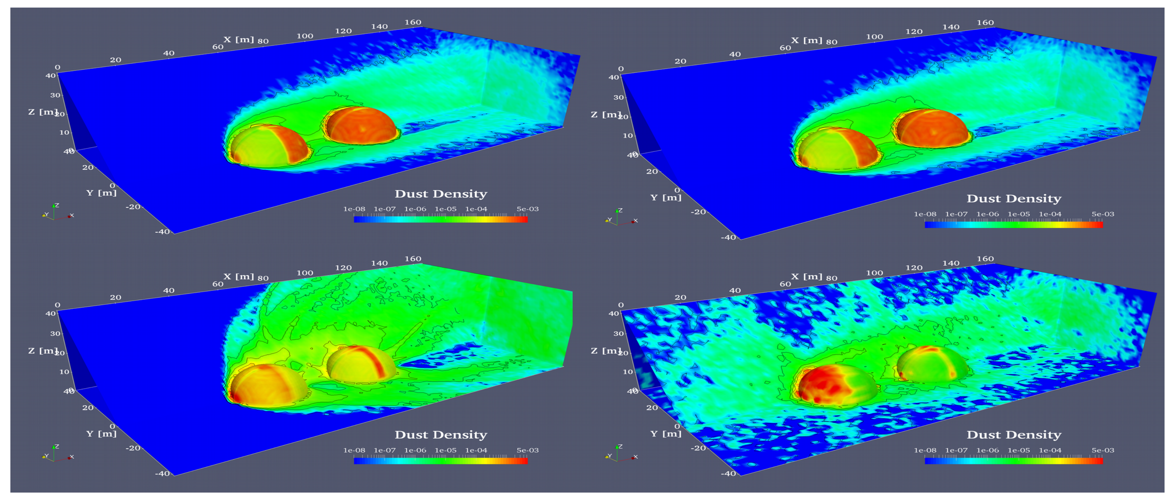

Figure 9: Plasma flow over a bi-sphere shaped asteroid (2)
Left top: Neutral Right Top: Q normal
Left Bottom: 1000x Q Right bottom: 1e6x Q

Plasma Flow/Dust Distribution: Irregularly Shape Asteroid

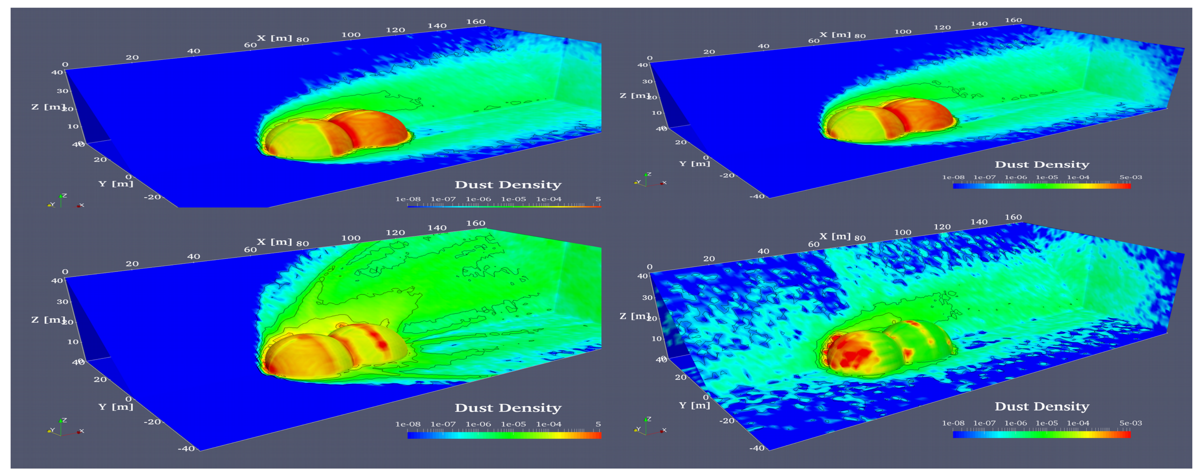

Figure 10: Plasma flow over irregular sphere
Left top: Neutral Right Top: Q normal
Left Bottom: 1000x Q Right bottom: 1e6x Q

Spacecraft-Plasma Interactions near an irregularly shaped asteroid

The following show a CubeSat near an irregularly shaped small asteroid. The simulations shown include the effects of spacecraft charging on local plasma environment.

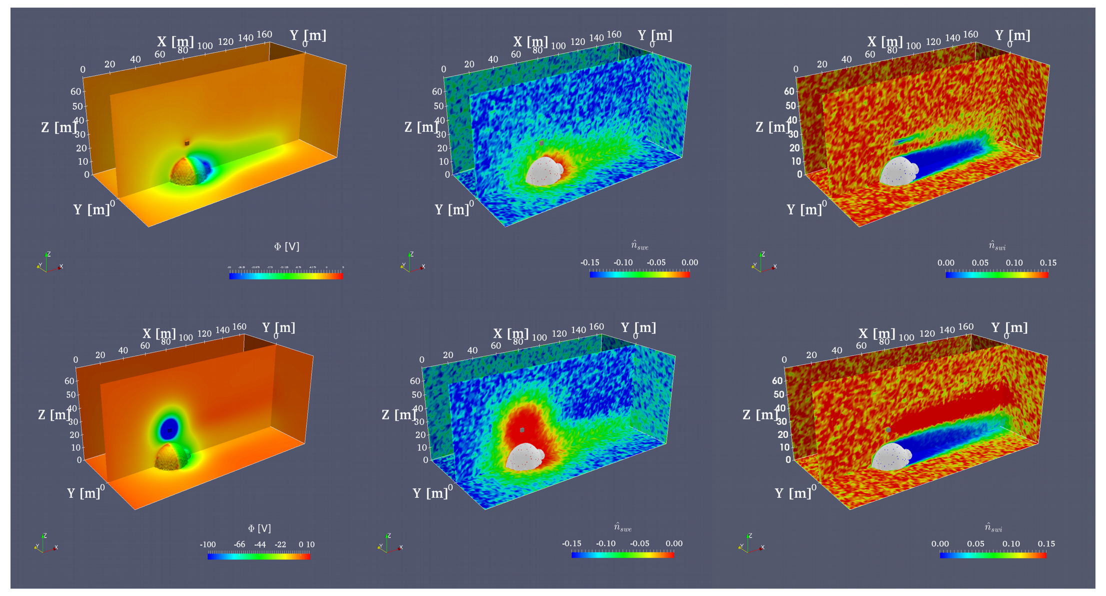

Figure 11. Cubesat near an Irrgegularly shaped asteroid
Top: Unbiased, Bottom: Negative-Biased
Left: Potential, Middle: Electron Density, Right: Ion density

6. Conclusion

Numerical simulations of dust-plasma-spacecraft-asteroid interactions are carried out. In this study we considered the effects of dust charge to mass ratio, dust grain size, and gravity field on dust dynamics near the asteroid. Results show that for a low dust charging state, the solar radiation pressure is the leading force that affects the dust distribution. A large gravity field will bound the dust in a very small region near the asteroid. Simulations are also carried out to study CubeSat-plasma interactions near an asteroid. Future studies will consider CubeSat-dust interactions near an asteroid.

7. Reference

[1]Han, Daoru. Particle-in-cell Simulations of Plasma Interactions With Asteroidal and Lunar Surfaces. Diss. University of Southern California, 2015.

[2]Park, Ryan S., Robert A. Werner, and Shyam Bhaskaran. "Estimating small-body gravity field from shape model and navigation data." Journal of guidance, control, and dynamics 33.1 (2010): 212-221.

[3]Yu, William, Daoru Han, and Joseph J. Wang. "Numerical Modeling of Dust Dynamics around Small Asteroids." AIAA SPACE 2016. 2016. 5447.

[4]Yu, William. Numerical and Ecperimental Investigations of Dust-Plasma-Asteroid Interactions, Diss. University of Southern California, 2018.

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