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Grid-free 2D plasma simulations of the complex interaction between the solar wind and small, near-Earth asteroids

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We present results from a new grid-free 2D plasma simulation code applied to a small, unmagnetized body immersed in the streaming solar wind plasma. The body was purposely modeled as an irregular shape in order to examine photoemission and solar wind plasma flow in high detail on the dayside, nightside, terminator and surface-depressed 'pocket' regions. Our objective is to examine the overall morphology of the various plasma interaction regions that form around a small body like a small near-Earth asteroid (NEA). We find that the object obstructs the solar wind flow and creates a trailing wake region downstream, which involves the interplay between surface charging and ambipolar plasma expansion. Photoemission is modeled as a steady outflow of electrons from illuminated portions of the surface, and under direct illumination the surface forms a non-monotonic or "double-sheath" electric potential upstream of the body, which is important for understanding trajectories and equilibria of lofted dust grains in the presence of a complex asteroid geometry. The largest electric fields are found at the terminators, where ambipolar plasma expansion in the body-sized nightside wake merges seamlessly with the thin photoelectric sheath on the dayside. The pocket regions are found to be especially complex, with nearby sunlit regions of positive potential electrically connected to unlit negative potentials and forming adjacent natural electric dipoles. For objects near the surface, we find electrical dissipation times (through collection of local environmental solar wind currents) that vary over at least 5 orders of magnitude: from 39 μs inside the near-surface photoelectron cloud under direct sunlight to ≫1 s inside the particle-depleted nightside wake and shadowed pocket regions.

1. Introduction

Airless bodies in the Solar System – from tiny dust grains to large moons – obstruct the local flow of solar wind, collect its charged particles, and create plasma wakes, generating complex and interesting electric field and potential structure. On the larger side of the spectrum is Earth's Moon, which at radius $R_M \sim 1740$ km creates a global plasma wake that typically extends tens of lunar radii downstream. The lunar dayside is dominated by photoemission, which generates a dense layer of photoelectrons within just meters above the surface (Poppe and Horányi, 2010). The lunar nightside collects the most energetic solar wind electrons penetrating the wake and can charge to thousands of Volts negative (Halekas et al., 2005). Regional irregularities in the surface topography – such as craters and outcroppings – can generate their own mini-wakes that significantly affect the local particle fluxes and electric field, most notably near the lunar terminator and poles (Farrell et al., 2010; Zimmerman et al., 2011, 2012, 2013; Poppe et al., 2012). Some of the most important factors governing the plasma–Moon interaction are the effective body size R, the typical solar wind Debye length $\lambda_{sw} \sim 10$ m, the dayside photoelectron Debye length $\lambda_{pe} \sim 1$ m, the thermal ion and electron gyroradii in the interplanetary magnetic field, $\rho_i \sim 120$ km and $\rho_e \sim 3$ km, the ion Mach angle $\theta_M = \tan^{-1}(c_s/v_{sw}) \sim 6°$, where $c_s = 4 \times 10^4$ m/s is the ion sound speed and $v_{sw} = 4 \times 10^5$ m/s is the solar wind flow speed.

Lunar-relevant processes should also be important at intermediate body sizes, such as at asteroids tens to hundreds of meters in size (or even lunar rocks, boulders, and craters at these scales). However, given the smaller spatial scale of an asteroid, namely the closer proximity of sunlit and shadowed surfaces with respect to the solar wind Debye length of about 10 m, the day and night

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processes that would seem quite distinct and separate on larger scales at the Moon may be more strongly intertwined. For instance, it is unclear how the thin dayside sheath merges with an asteroid's nightside global wake, how minor surface irregularities could modulate the formation of adjacent mini-wakes and photoemissive regions across the body, and what electric field, electric potential, and surface charging distributions exist in various unique geographic regions around the asteroid. In the present work plasma treecode simulations are used to address these issues, which will be very important to future asteroid rendezvous and retrieval missions. This new focus on the complex plasma environment of a small asteroid represents the natural evolution of long-standing computational efforts for the NASA Lunar Science Institute/Dynamic Response of the Environment At the Moon (DREAM) team to understand the airless lunar plasma and electrostatic environment. Anticipating the local ground potential and electric field environment at an asteroid will help in efforts to mitigate electrostatic charging hazards for sensitive instrumentation and electronics, especially if repeated contact is planned during a future mission.

An accurate knowledge of the electrostatic plasma environment at airless bodies, including both Earth's Moon and asteroids, is also critical for understanding the electrostatic charging and possible levitation/transport of micron and sub-micron sized dust grains. Electrostatic dust levitation has been confirmed in laboratory experiments relevant to airless Solar System environments (Sickafoose et al., 2000, 2001, 2002; Wang et al., 2009, 2010, 2011). Yet, it remains unverified *in situ* despite a small handful of evidence provided by excess brightness in Apollo-era lunar photographs (McCoy and Criswell, 1974; Glenar et al., 2011; Rennilson and Criswell, 1974) and dust detector experiments (Berg et al., 1973, 1974), as well as more recent detailed observations of dust "ponds" on Asteroid 433 Eros (Robinson et al., 2001; Veverka et al., 2001; Cheng et al., 2002). Recent numerical studies have constrained the size of levitating dust near the photoelectron-rich lunar dayside surface to no more than 0.1 μm (Poppe and Horányi, 2010), and have highlighted the important role that particle cohesion plays in preventing sub-micron grains from lifting off airless, near-Earth regoliths (Hartzell and Scheeres, 2011; Hartzell et al., 2013). However, it has long been proposed that extremely strong electric fields (>10 kV m^{-1}) arise near abrupt day/night boundaries, where neighboring sunlit (photoelectron-emitting) and shadowed (electron-collecting) patches could develop large charge differences (Criswell and De, 1977; De and Criswell, 1977; Wang et al., 2007). Such extreme electric fields would certainly be capable of supporting dust grains electrostatically; however, more recent simulations that have included the presence of the neutralizing background solar wind plasma have shown that such strong electric fields are suppressed, even with neighboring sunlit/shadowed patches (Poppe et al., 2012). Such simulations did show electric field enhancements near the terminator regions roughly three to five times the nominal dayside strength and left open the possibility of electric field enhancements of this magnitude on asteroidal surfaces with complex topographies, such as considered here.

In the present work we use a newly-developed electrostatic treecode to simulate the field and plasma environment around an asteroid tens to hundreds of meters in size. A number of plasma simulation and analytical efforts already exist in the small-asteroid size regime, primarily aimed at investigating the effects of strong intrinsic magnetization and bow shock formation on multi-km scales (Simon et al., 2006; Wang and Kivelson, 1996; Baumgartel et al., 1997). However, for the small, unmagnetized bodies of interest herein these electromagnetic complications may be neglected since $R \ll \rho_e \ll \rho_i$. In this small-body regime the particles effectively feel no appreciable magnetic force while traversing the length of the obstructing object. A more recent 2D simulation effort was carried out by Nakagawa (2013), who used a two-dimensional particle-in-cell code to study the solar wind interaction with an $R \sim 30$ m spherical asteroid that was not illuminated by the Sun (i.e., no photoemission). The present work differs significantly in that it incorporates a full photoemission model that is dependent on solar incidence angle as well as the shadowing effects of any upstream topography. With this technical advancement, as well as several other computational advantages of tree-based field solvers that will be discussed in Section 2, the treecode represents an extremely powerful physics-based tool for simulating the plasma environment of small asteroids in 2D. In two dimensions any non-trivial topographic variations in the third dimension are neglected (e.g. an object with a circular 2D cross-section effectively models an infinitely long cylinder). However, our treecode implementation provides a high-quality quantitative tool for beginning to understand the many complexities of solar wind–asteroid–photoelectron interactions at intermediate length scales. While we cannot reproduce additional topographic complexities of being in 3D, simulating the basic interesting and relevant plasma physics does not require three dimensions. It will be demonstrated that two spatial dimensions are enough to provide a clear picture of wake and photoelectron sheath formation under a wide range of local illumination and plasma flow conditions.

Poppe et al. (2012) performed 1D particle-in-cell simulations showing that modulation of the photoelectron sheath due to changing solar zenith angle can significantly affect the plasma environment of a small, 5 m-diameter lunar crater. Ergun et al. (2010) performed hybrid 3D simulations of spacecraft charging near the Sun and characterized the resulting photoelectron and wake environment. Here, in Section 3, we present basic plasma physics results for an irregularly shaped asteroid about 200 m in length and 50–100 m in width, which is much larger in scale than these previous simulations, particularly in the ratio of body size to photoelectron and solar wind Debye lengths. The primary objective will be to identify and understand key morphological plasma/surface interaction regions that form about a small asteroid body. Particular attention is paid to (1) how the transition from sunlight to shadow affects surface charging and the resulting near-surface electric field and particle flows, (2) how a mini-wake forms in a small, shadowed pocket, and (3) how all of these smaller structures merge into the larger "global" wake created downstream of the body. Other, finer details such as quantifying the shapes of particle distribution functions, wave activity, electric potential and field profiles, and magnetic field effects are deferred in favor of a broader investigation of the baseline, quasi-static plasma environment. The direct relevance of the plasma and field environment to future exploration efforts is discussed in Section 4, and concluding remarks are given in Section 5.

2. Computational methodology

Gridless treecodes were first developed to accelerate the computation of O(N^2) interparticle gravitational forces in an astrodynamical context (e.g., Barnes and Hut, 1986). An excellent review of the treecode paradigm as adapted to kinetic plasma simulations – where electric rather than gravitational forces are computed – is given by Christlieb et al. (2006), and we have based our present 2D electric field and potential solvers on the formalism laid out in their paper. Our treecode essentially divides plasma simulation particles (each representing a finite group of many real particles) into small "clusters" and then efficiently calculates cluster-particle forces by way of a multipole approximation. Once the self-consistent electric field is sampled by all particles they are advanced in time via Newton's second law and accumulated on