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Kinetic simulations of finite gyroradius effects in the lunar plasma environment on global, meso, and microscales

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ABSTRACT

The recent *in situ* particle measurements near the Moon by Chandrayaan-1 and Kaguya missions as well as the earlier observation by the Lunar Prospector have shown that the Moon-solar wind interaction is more complicated than believed earlier. The new observations have arisen the need for a detailed modelling of the near surface plasma-surface processes and regions near the lunar magnetic anomalies. Especially, interpretation of ion, electron, and energetic neutral atoms (ENA) observations have shown that the plasma cannot be treated as a single fluid but that kinetic effects have to be taken into account.

We have studied the kinetic effects and, especially, the role of finite gyro-radius effects at the Moon by kinetic plasma simulations at three different length-scales which exist in the Moon-solar wind interaction. The solar wind interaction with a magnetic dipole, which mimics the lunar magnetic anomalies in this study, is investigated by a 3D self-consistent hybrid model (HYB-Moon) where protons are particles and electrons form a charge neutralizing mass less fluid. This study shows that the particle flux and density and the bulk velocity of the solar wind protons that hit the lunar surface just above the dipole are decreased compared to their undisturbed values. In addition, a particle "halo" region was identified in the simulation, a region around the dipole where the proton density and the particle flux are higher than in the solar wind, qualitatively in agreement with energetic hydrogen atom observations made by the Chandrayaan-1 mission.

The near surface plasma within the magnetic anomaly within a Debye sheath is studied by an electromagnetic Particle-in-Cell, PIC, simulation (HYB-es). In the PIC simulation both ions and electrons are treated as particles. Further, we assume in the PIC simulation that the magnetic anomaly blocks away all solar wind particles and the simulation contains only photo-electrons. The analysis shows that the increased magnetic field decreases the strength of the electric potential and results in a thinner potential sheath than without the magnetic field. Overall, the simulations give support for the suggestions that kinetic effects play an important role on the properties of the lunar plasma environment.

1. Introduction

Several new *in situ* observations have shown that the lunar plasma environment is much more complicated and interesting than earlier believed. On the charged particle (ions and electrons) and energetic neutral atoms (ENAs) point of view especially the recent measurements from Kaguya and Chandrayaan-1 missions have provided new insight of the plasma processes near the lunar surface. Kaguya had Electron Spectrum Analyzer (MAPPACE ESA), Ion Mass Analyzer (MAPPACE IMA), Ion Energy Analyzer (MAPPACE IEA), Lunar MAGnetometer (MAPLMAG) and Lunar Radar Sounder (LRS) (see e.g. Nishino et al., 2010). Chandrayaan-1 had on-board an energetic neutral atom instrument (CENA, see. e.g. Wieser et al., 2010) and ion spectrometer (SARA) (see, e.g. Lue et al., 2011). These

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new detailed observations of ions (see e.g. Saito et al., 2008; Holmström et al., 2010; Lue et al., 2011), electrons (e.g. Harada et al., 2012) and ENAs (see e.g. Wieser et al., 2009) have shown that one has to take into account the motion of individual charged particles in order to interpret the observations near the lunar surface and magnetic anomalies.

The new observations have arisen the need for a detailed kinetic modelling of ions and electrons near the Moon. Generally speaking, a dedicated self-consistent plasma model for the Moon has to take into account several key elements affecting the Moon–solar wind interaction. The properties of the lunar plasma environment are affected by the Moon, the Sun and the nearby space. The Moon does not have a noticeable global intrinsic magnetic field and it does not have an atmosphere. Therefore charged particles originating from the Sun and outside of the Solar System can freely hit the lunar surface. The Sun is the source of the solar wind, a continuous flow of ions (mainly protons, H^+, and alpha particles, He^{++}) and electrons. The Sun is also the source of the interplanetary magnetic field (IMF), magnetising the solar wind plasma. The Sun also emits extreme ultraviolet (EUV) radiation that ionises both the lunar surface and neutral atoms above the surface.

The interaction of the external plasma and radiation with the Moon determines the properties of the charged particles, ions and electrons, and, consequently, the electric and magnetic fields of the lunar environment (e.g. Halekas et al., 2010a). The electric field, in turn, lifts charged dust particles (see e.g. Nitter et al., 1998), creating a heavy charged particle population with variable charge, acting as a source and sink of electrons (e.g. Stubbs et al., 2011). The properties of the plasma near the Moon have various spatial and temporal variations. For example, variations are due to (1) local lunar magnetic anomalies (e.g., Lin et al., 1998; Purucker and Nicholas, 2010), (2) as a result of the Moon revolving around the Earth (during which the Moon passes through various plasma regions in the Earth's magnetosphere and during which the solar illumination conditions on the lunar surface vary) and (3) temporal variations in the Sun and, consequently, variations in solar UV radiation (see, e.g. Sternovsky et al., 2008, and references therein) and in the solar wind.

Modelling of the properties of the lunar plasma environment is, therefore, a challenging task because a fully comprehensive self-consistent model should include all major plasma populations, electric and magnetic fields, and dust particles. Modelling is also complicated by the fact that the electric conductivity of the lunar surface is not well established. Moreover, local effects caused by geography (craters, slopes, hills etc.) and the magnetic anomalies are neither well known. Modelling of the regions near the lunar North and South poles is especially challenging because of the varying illumination conditions with the associated change in surface charging, and because of the nearby lunar plasma wake (see e.g. Farrell et al., 2007). Modelling is further complicated by temporal variability and the wide range of spatial scales involved, both in terms of the plasma physics scales and the size of the regions where they occur, which in the lunar environment often are comparable.

Presently, we focus on study of the finite gyroradius effects near the lunar plasma environments associated with the motion of ions and electrons around the magnetic field. In the solar wind the charged particles rotate around the interplanetary magnetic field (IMF). Near the lunar surface also the magnetic field associated with the lunar magnetic anomalies affects the motion and the velocity of the charged particles within their range of influence. We use two kinetic models to illustrate and to study finite gyroradius effects near the lunar plasma environment at three different length scales: (1) the "global length scale" where the modelled region includes the whole Moon, (2) the "mesoscale" where the modelled region includes a magnetic dipole and (3) the "microscale" that contains a thin photo-electron sheath above the lunar surface.

In the global scale and mesoscale case the term kinetic effect refers in this paper to the phenomena associated with the finite ion gyroradius effects because these length scales are modelled by hybrid models where ions are particles while electrons form a massless charge neutralizing fluid. Earlier hybrid model calculations for three dimensional (3D) models (e.g. Kallio, 2005; Wang et al., 2011; Holmström et al., 2010, 2012) and 2D models (e.g. Birch and Chapman, 2002; Trávníček et al., 2005) have shown to provide new insights in the investigation of the lunar plasma environment, especially when the lunar tail region has been investigated. Before the availability of hybrid models the solar wind interaction with the magnetic anomalies was studied by 2D magnetohydrodynamic (MHD) models (Harnett and Winglee, 2000) and 2D kinetic models (Harnett and Winglee, 2002). Recently, the solar wind interaction with a Moon-like conducting obstacle was studied with a Vlasov model (Umeda, 2012).

The detailed analysis of properties of photo-electrons within a strong magnetic anomaly is done by an electrostatic full Particle-in-Cell (PIC) simulation where both ions and electrons are modelled as particles and where the magnetic field is kept constant during the simulation. Such a small spatial scale, which is referred to as the microscale in this paper, cannot be modelled by a hybrid model because it assumes quasi-neutrality which is not a valid assumption within the Debye sheath near the lunar surface. A PIC simulation without a magnetic field has recently been used to study various aspects of the lunar plasma environment in 1D and 2D, including dust particles (Poppe and Horányi, 2010). Further, the electrostatic PIC approach enables us to study finite gyroradius effects of both ions and electrons.

The goal of the paper is twofold. First, to give a brief summary of several kinetic effects near the Moon and, especially, the role of the magnetic field which causes charged particle gyromotion around the magnetic field lines. Second, to study the effects of the magnetic field on the particles and fields near and within a lunar magnetic anomaly by applying two kinetic models, by a hybrid model and a PIC model. The current paper is organized as follows: first, the main characteristic features of the lunar plasma environment are introduced; second, the basic properties of the hybrid and PIC model are presented. After that the models are used to study finite gyroradius effects at three length scales. Finally the limitations and consequences of the results are discussed.

2. Lunar plasma environment

Fig. 1 summarises some of the major particle and field aspects of the lunar plasma environment. The Sun is the source of protons (H^+_{sw}) and electrons (e^-_{sw}), and sunlight ionises the lunar surface, causing photo-electron emissions and charging of its surface. In addition, the impacts of ions and electrons onto the surface result in secondary ion and electron emissions. Part of the solar wind particles can be reflected away from the surface due to the electric and magnetic fields. Near the lunar surface the length scale for the electric potential sheath, or the Debye sheath, is the Debye length, λ_D ($=\sqrt{\epsilon_0 k T_e / n_e e^2}$, where ϵ_0 is the electric permittivity, k is the Boltzmann constant, T_e is the temperature of electrons, n_e is the density of electrons and e is the unit charge). The focus of this paper is to study the finite gyroradius effects when the charged particles rotate around the magnetic field lines of both the IMF and, near certain regions on the lunar surface, of the lunar magnetic anomaly fields.