Interactions of Earth's Magnetotail Plasma with the Surface, Plasma, and Magnetic Anomalies of the Moon

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Abstract

Chapter 1 provides an outline of plasma interactions with solar system bodies and solid surfaces, a brief overview of past observations and models regarding the lunar plasma environment, and objectives of the thesis. Moon-plasma interactions are characterized by the absence of both a substantial atmosphere and a global intrinsic magnetic field. The Moon orbits the Earth, passing through various regions including the solar wind, the terrestrial magnetosheath, the magnetotail lobes, and the plasma sheet. In each of these regions, the plasma conditions near the Moon vary widely in density and energy. In the supersonic solar wind, a plasma void is left behind the body and the surrounding plasma expand into the body's "wake". Since the Apollo era, the solar wind interactions with the Moon and the lunar crustal magnetic anomalies have extensively studied. Recent observations indicated the importance of kinetic effects of plasma in many places around the Moon such as in the lunar wake and above the magnetic anomalies. With the aim of establishing a fundamental framework of airless-body plasma physics, this thesis provides key observational information of Moon-plasma interactions with a particular emphasis on those in the Earth's magnetotail plasma regime. I have analyzed the plasma, neutral-atom, and electromagnetic-field data from three lunar missions: Kaguya, ARTEMIS, and Chandrayaan-1. These near-lunar observations in the Earth's magnetotail have extended our knowledge on the Moon-solar wind interactions to an entirely different plasma regime and revealed new aspects of the physical processes working in the lunar environment. The comparison between the plasma characteristics in the solar wind and those in the terrestrial magnetospheric plasma will help us understand the Moon-plasma interactions from more general and comprehensive viewpoints.

In Chapter 2, I show the first lunar-orbiter observations by Kaguya of a non-gyrotropic partial loss in the electron velocity distribution function (VDF) caused by interaction between the terrestrial plasma sheet electrons and the lunar surface. Kaguya observed a non-gyrotropic partial loss in the electron VDF created by electron absorption by the lunar surface combined with electron gyromotion.

Chapter 3 contains further data analysis and theoretical considerations regarding the non-gyrotropic electron VDFs observed near the lunar surface. Comparison of the observed empty regions with the forbidden regions derived from particle-trace calculations suggests that lunar-surface charging, perpendicular electric fields, and nonuniform magnetic fields caused by diamagnetic-current systems can modify the characteristics of the non-gyrotropic electron VDFs.

Chapter 4 shows an application of the kinetic behavior of electrons near the Moon to remote measurements of small-scale magnetic fields on the lunar surface. Non-adiabatic scattering of plasma sheet electrons by lunar crustal magnetic fields can be used to map small-scale magnetic fields on the lunar surface. I developed a new mapping technique and applied it to the electron and magnetic-field data from Kaguya. The obtained map implies significant kilometer-scale magnetic fields correlated with larger-scale magnetization on the Moon's far side for the first time.

In Chapter 5, I demonstrate an important role of plasma of lunar origin in the Earth's magnetotail from observations by the dual-probe ARTEMIS mission of Moon-related electron and ion signatures obtained above the dayside lunar surface in the magnetotail lobes. Two-point observations reveal that the density of plasma of lunar origin is higher than that of the ambient lobe plasma even several hundreds of kilometers above the Moon's dayside. Meanwhile, the distributions of incoming electrons exhibit modifications correlated with Moon-related populations, suggesting direct or indirect interactions of the lobe electrons with plasma of lunar origin. High-energy photoelectron emission from the dayside lunar surface was also observed, supporting the existence of large positive potentials on the lunar surface.

Chapter 6 presents the observations of energetic neutral atoms (ENAs) produced at the lunar surface in the Earth's magnetotail. When the Moon was located in the terrestrial plasma sheet, Chandrayaan-1 detected hydrogen ENAs backscattered from the lunar surface. The analysis of the ENA data and test-particle simulations suggest that magnetic shielding of the lunar surface from the plasma sheet protons with broad VDFs is less effective than from the solar wind protons with beam VDFs.

Chapter 7 summarizes the new results from the three lunar missions with implications for other airless bodies. The near-lunar observations of plasma, electric and magnetic fields, and ENAs in the Earth's magnetotail with a wide range of ambient plasma parameters not only complement our current understanding of the Moon-solar wind interactions, which have been extensively studied for decades, but also provide implications for other space and planetary environments. The new findings regarding the remarkable Moon-related features of the near-lunar plasma in the Earth's magnetotail help understand the Moon-plasma interactions from a more general and comprehensive perspective in the context of future endeavors to establish a fundamental framework of airless-body plasma physics.