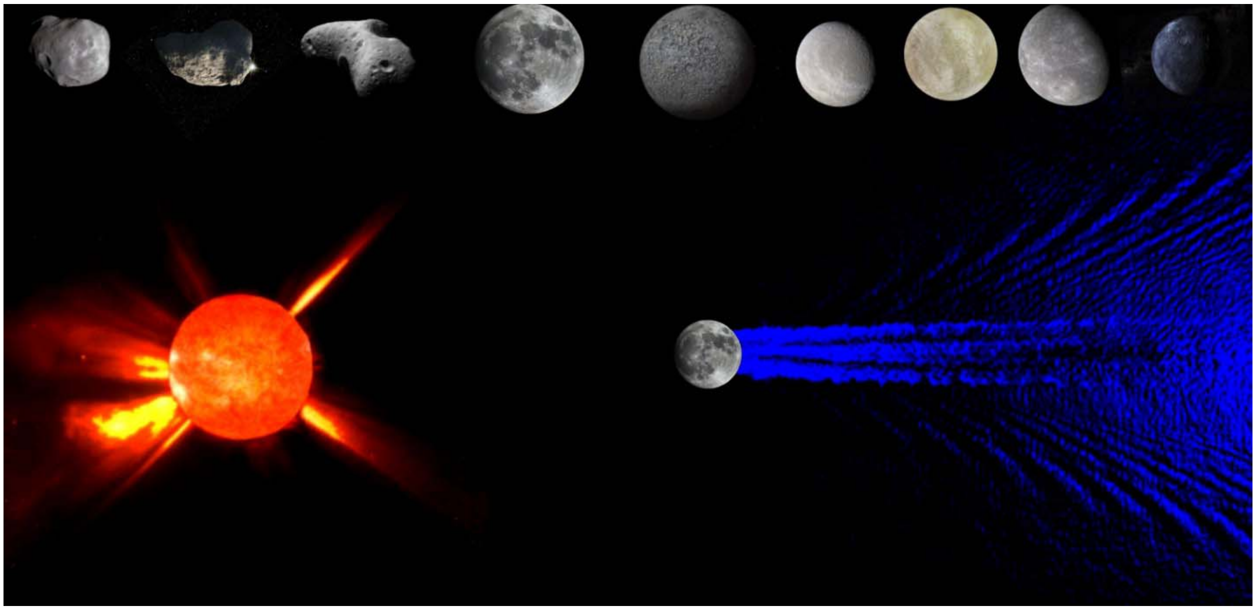

Kinetic Plasma Processes at Airless Bodies

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in response to ISSI's 2012 Call for Proposals for International Teams in Space Science

Abstract

Airless, non-magnetized bodies in the Solar System respond to external plasma and magnetic fields in ways quite different from bodies possessing substantial atmospheres or substantial global magnetic fields. In the absence of a protective, conductive atmosphere or significant magnetic boundary, external plasma can directly impact the surface, resulting in a broad array of surface-plasma interactions and the creation of a plasma wake downstream of the body. These interactions result in the creation of a variety of non-equilibrium plasma distributions that can in turn drive wave turbulence. Since, during these interactions, the plasma cannot be described as a single fluid, it is essential to examine kinetic plasma processes to interpret the observations. We propose to create an ISSI Team to study such kinetic plasma processes occurring at airless bodies in the Solar System. The goal of the Team is to characterize and compare the kinetic plasma processes occurring around airless bodies including the Moon, asteroids, and the airless satellites of Mars, Jupiter, and Saturn where plasma and/or magnetic field measurements exist. We plan to focus on the non-equilibrium plasma distributions produced by the interaction of solar wind and/or magnetospheric plasma with airless bodies (and the localized electric and magnetic fields associated with such bodies) and the plasma processes that both generate and grow from such these distributions. Additionally, we plan to study the plasma wave environment around airless bodies and determine how the observed wave activity is related to the observed non-equilibrium plasma distributions. These objectives will be achieved through a combination of analysis of observational data and simulation results. Both recent and historic data from airless bodies will be essential in understanding the plasma processes occurring there. These activities seek to advance our understanding of the basic plasma processes occurring in the Solar System.

Scientific Rationale

Airless bodies in the Solar System respond to external plasma and magnetic fields much differently than bodies possessing substantial atmospheres. Energetic photons and particles ionize atmospheres, creating conductive ionospheres that can deflect external plasma and magnetic fields, shielding the surface from direct impacts. Similarly, a large scale, coherent, global magnetic field impedes the direct propagation of incident charged particles and fields (though not photons). Airless, non-magnetized bodies, in contrast, have little or no such protection, and respond directly to incident plasma. External magnetic fields also pass through an airless body relatively unimpeded, unless the body has significant internal conductivity. Meanwhile, energetic photons and particles directly impact the surface. This results in a broad array of surface-plasma interactions, and the creation of a void or wake on the downstream side of the external plasma flow, whose extent and properties depend on the parameters of the plasma flowing past the obstacle. Some objects, such as the Moon, possess localized remanent magnetization. These fields, while not able to stand off the plasma on a global scale, can significantly affect the local plasma interactions, as displayed by the fascinating recent Chang'E, Kaguya, and ARTEMIS observations. Energetic photons and particles which impact the surface can liberate material contributing to the formation of exospheres surrounding airless bodies; these neutral gases eventually become ionized, often escaping the local environment.

The interaction of flowing plasma with solid obstacles, with weak and/or small scale crustal magnetic fields, and with charged particles derived from the surface and exosphere naturally produces unstable, anisotropic, and even non-gyrotropic plasma distributions, which drive many fascinating fundamental plasma physics processes. One of the **main goals** of the proposed activities is to *identify the formation mechanisms for the non-equilibrium distributions observed around airless bodies.* In addition, we will *determine the consequences of such distributions* on wave generation and plasma modification. These investigations will be done *using a combination of observational data and simulations*.

Much of the data available related to airless bodies comes from the Moon, since it is the most easily accessible. However, many of the fundamental processes occurring there should also occur at other airless bodies, and significant progress in understanding non-equilibrium distributions can be made by comparing measurements from bodies with different properties, in different plasma environments. Insights gained from the Moon can be applied to other similar objects in the Solar System, and in turn the differences between the lunar case and others can inform us as to the fundamental physics and scaling of the interactions. Appreciable plasma and/or magnetic field data also exists from Mars' moon Phobos, several asteroids (including Gaspra, Ida, Braille, Eros, Šteins, and Lutetia), and many of the airless moons of Jupiter and Saturn. This team will consider observations from all of these bodies.

Photoelectrons accelerated by near-surface electric fields, as well as electrostatically and magnetically reflected plasma electrons, can stream outwards along magnetic field lines from the Moon, generating electromagnetic and electrostatic waves through anisotropy and streaming instabilities. Such waves have been observed at many airless bodies in the inner and outer Solar System including the Moon, asteroids, and outer planet satellites. These waves can in turn affect the incoming plasma, with significant perpendicular heating observed during periods with strong electromagnetic whistler waves, likely as a result of cyclotron damping. The outward-going electrons also provide a remote tracer of the distribution of electric and magnetic fields between the spacecraft and the surface, and indicate the presence of non-monotonic electrostatic potential distributions in the surface photoelectron sheath.

Part of the incident plasma population (solar wind in the inner heliosphere and magnetospheric at the satellites of the outer planets) can be backscattered by the surface. This backscattered population, filling a region of phase space different from the incident plasma, contributes to highly unstable distributions. In the lunar example, surprisingly high proton reflection from crustal fields is observed despite the sub-ion-inertial-length and sub-gyro-radius scale of lunar crustal magnetic sources. This may result from electric fields produced by electron-ion coupling. The reflected protons, which have fundamentally non-gyrotropic distributions, feel the effects of solar wind fields and follow cycloidal trajectories. The resulting plume, which can have densities of ~10% of the solar wind even thousands of km from the Moon, generates waves whose properties are not yet fully understood.

Heavier ions generated by ionization of neutral exospheric constituents and/or charged particle sputtering from the surface are also observed at many airless bodies. These pickup ions feel the external electric and magnetic fields and follow cycloidal trajectories, producing a narrow beam that can reach much higher energies. Both reflected protons and pickup ions can constitute a particle population with a significant velocity with respect to the incident plasma, and a corresponding source of free energy that can drive plasma waves.

On the nightside, downstream side of the Moon, a plasma void or wake is formed as the solar wind streams past. This flow typically has a high Mach number in the solar wind, but can take a range of values for the Moon in the terrestrial magnetosphere. Refilling of the lunar plasma wake can occur both parallel and perpendicular to the magnetic field by distinct processes. Perpendicular to the field, protons reflected from the day side follow cycloidal trajectories into the wake; the charge density of these ions in turn accelerates electrons along magnetic field lines to restore quasi-neutrality. Parallel to the magnetic field, meanwhile, an ambipolar electric field pulls ions into the wake along field lines, producing counter-streaming distributions of protons and alpha particles. Electrons are velocity-filtered by these fields and can also form counter-streaming distributions. These counter-streaming populations in turn drive significant plasma wave activity.

Similar to the Moon, Phobos and asteroids spend most of their time exposed to the supersonic solar wind. Plasma wakes similar to that observed at the Moon are expected to be seen at these objects. However, due to their small size (smaller than both the solar wind proton gyroradius and inertial length), the wake structure may be significantly altered. Phobos and the asteroids visited thus far by plasma and/or magnetic field instruments are quite small: from just a few km (Braille) to over 100 km (Lutetia), comparable to the Debye length at the low end, and the ion inertial length at the high end. These bodies therefore fall in a very different regime of scale size than the Moon, possibly leading to different kinetic plasma processes especially in the limit of small obstacle size, as Debye-scale physics becomes comparable to wake-scale physics.

Meanwhile, most of the major airless satellites of Jupiter and Saturn reside within the planetary magnetosphere, where they are immersed in a very energetic plasma flow driven and energized by the planetary rotation. The magnetospheric flow can vary from supersonic to transonic to subsonic depending upon the location of the satellites. Intriguingly, this plasma bombardment does not in general come from the same direction as the solar photon flux, leading to complexities never seen at the Earth's Moon. Additionally, as the satellites move from one plasma regime to another within the magnetosphere (e.g., from the plasma sheet to lobe), the external plasma conditions can change abruptly leading to dynamic reconfiguration of the wakes. Recent Cassini observations of Rhea and other Moons of Saturn already speak to the complexity of the resulting interactions.

Although plasma data from New Horizons won't be returned from Pluto and other Kuiper Belt Objects until 2015, the same basic plasma processes should take place that these bodies. Additionally, several missions to visit near Earth objects/asteroids are in the planning stages. The results of the Team's activities is expected to aid in the interpretation of this future plasma data.

Goals

As noted above, the goals of the Team activities are to investigate and compare the kinetic plasma processes occurring at airless bodies in the Solar System including the Moon, Phobos, asteroids, and the airless moons of Jupiter and Saturn. We will focus on the formation mechanisms and consequences of unstable, non-equilibrium plasma distributions and on the plasma wave activity in relation to the non-equilibrium distributions. This work will be done using a combination of observational data, plasma wave theory, and simulation results. Our list of tasks includes

- *characterizing non-equilibrium plasma distributions observed at airless bodies*;
- *identifying possible formation mechanisms*;
- *determining the consequences of unstable distributions* (e.g., wave generation, plasma heating) given the different plasma environments of the various objects;
- *characterizing plasma wave observations* at airless bodies;
- *identifying possible wave modes* paying close attention to wave modes identified as resulting from unstable distributions;
- *determining the consequences of observed waves* (e.g., scattering, heating) and address whether the observed waves could contribute to some of the observed plasma distributions;
- finally, *specifying what new observations are required* to further our understanding.

Timeliness

Recent years have seen new observations from an international fleet of lunar probes (including, but not limited to, Kaguya (SELENE), Chang'e 1, Chandrayaan-1, and ARTEMIS). Data continues to come back from ARTEMIS (Moon), Mars Express (Phobos), and from Cassini (moons of Saturn). Large amounts of historic data exist from the Moon, asteroids, and Jupiter's moons. In its first year orbiting the Moon, ARTEMIS has provided a wealth of new data and has already contributed important new observations regarding non-equilibrium distributions and plasma waves. As the volume of data increases, so does the sophistication of the models of these objects. Now we feel the time is ripe to assimilate the abundance of data with current models to address some of the fundamental plasma processes occurring under a variety of conditions at airless bodies throughout the Solar System.

Output

The main output of the Team's work will be papers published in international, peer-reviewed journals focusing on the various aspects of the plasma interactions with airless bodies. Results will also be disseminated by presentations at international conferences highlighting the works in progress and the results of the Team's activities. These activities will culminate in (at least) one comprehensive review paper of comparative plasma processes at airless bodies.

Value Provided by ISSI

The resources and facilities provided by ISSI will enable the joint analysis of data from several different space missions and bring together researchers with expertise in analyzing variety of data sets and a wide range of theoretical simulation tools. This venue will also allow for comparisons of observations with model output and for inter-comparisons of model output from several different groups. Bringing together scientists from such typically disparate fields to concentrate on basic plasma physics is not possible during large conferences or individual travel. The ISSI facilities will promote dynamic and collaborative analysis and discussions during the meetings. Within this framework, rather than focusing on the individual planetary objects, as is often done for individual investigations, these meetings will focus on the ***fundamental plasma processes*** occurring at airless bodies, which we anticipate to be a fruitful way to move forward in our understanding as a community.

List of Confirmed Members

The list of Team members includes a combination of established and younger scientists with international reputations and recognized expertise in our target areas. We plan to add two to three Young Scientists to the Team upon acceptance.

Matthew Fillingim (leader): University of California, Berkeley, CA, USA
Jasper Halekas (co-leader): University of California, Berkeley, CA, USA
David Brain: University of Colorado, Boulder, CO, USA
William Farrell: NASA Goddard Space Flight Center, Greenbelt, MD, USA
Yoshifumi Futaana: Institutet för Rymdfysik, Kiruna, Sweden
Mats Holmström: Institutet för Rymdfysik, Kiruna, Sweden
Geraint Jones: University College London, Dorking, Surrey, United Kingdom
Esa Kallio: Finnish Meteorological Institute, Helsinki, Finland
Tomoko Nakagawa: Tohoku Institute of Technology, Sendai, Miyagi, Japan
Elias Roussos: Max-Planck-Institut für Sonnensystemforschung, Katlenburg-Lindau, Germany
Yoshifumi Saito: Japan Aerospace Exploration Agency, Sagamihara, Kanagawa, Japan

Additional Experts:
Vassilis Angelopoulos: University of California, Los Angeles, CA, USA
Greg Delory: University of California, Berkeley, CA, USA.
(These members will contribute to the Team on a time limited basis at no cost to ISSI.)

Project Schedule

The Team plans to have two one-week meetings at ISSI. The first meeting would be planned for late summer or early autumn (e.g., September) 2012, subject to ISSI and team member schedules. The second meeting would take place in the late spring or early summer (e.g., June) 2013. In addition, we plan to leverage informal meetings at large international conferences (e.g., AGU Fall Meeting, EGU General Assembly) to discuss the Team's progress.

Facilities Required

While at ISSI, our Team will require a room that can seat all participants; a computer, projector, and screen for presentations; and internet access for the participants' laptop computers.

Financial Support

We request financial support to cover subsistence and accommodation for 11 participants (excluding those noted above) for two one-week Team meetings at ISSI. In addition, we request financial support to cover travel costs to and from ISSI for both meetings for the Team leader.