Future Directions in Magnetospheric Research

Present Understanding and Accomplishments

- The Earth is a rotating magnetized body with a significant atmosphere and ionosphere that is immersed in the solar wind.
- The Earth's magnetic field is strong enough to stand off the solar wind at about 10 Re in the upstream direction, creating a bow shock and a magnetosphere that is dynamically coupled to the solar wind.
- At the bow shock the solar wind is thermalized and transmitted to the magnetosphere while at the same time some ions are reflected and propagate upstream in the solar wind, producing a foreshock region.
- Two competing sources of plasma are the entry of solar-wind plasma at about the 1% level and the outflow of ionospheric plasma. Both of these two plasma sources significantly populate the plasma sheet in the geomagnetic tail.
- The coupling of mass, momentum, and energy across the magnetospheric boundary occurs mainly through reconnection between the interplanetary magnetic field and the geomagnetic field. Reconnection is strongest when the solar-wind magnetic field has a large southward component.
- Magnetic field-aligned currents resulting from reconnection flow into and across the ionosphere, causing potential drops that map along magnetic field lines, thereby producing a global system of plasma convection.
- Open field lines produced by reconnection are dragged over the poles to the geomagnetic tail where they are convected through the plasma sheet, allowing the northern and southern hemisphere field lines to reconnect, thereby producing a stretched closed magnetic field topology and freeing the solar-wind magnetic field to flow away in the solar wind.
- Dissipation at the ion scale (Hall reconnection) has been shown to explain the decoupling of the ions from the magnetic field.
- Depending on the efficiency of dayside magnetic reconnection (i.e., the strength of the southward component of the solar-wind magnetic field) the reconnection event in the tail and the subsequent relaxation of the stretched field line combine either to produce quiet auroral displays or a global magnetic disturbance (the substorm), which is accompanied by widespread and active auroras.
- Discrete auroral forms occur more or less continuously along an oval-shaped region located at about 75° latitude at noon and at about 65°-70° at midnight. This oval expands to both higher and lower latitudes during strong events. The discrete auroras are produced mainly by keV-range electrons that are accelerated either by field-aligned electric fields in density cavities at altitudes of several thousand kilometers or by Alfvén waves propagating toward the ionosphere from the tail. The Alfvén wave events are generally stronger and located at the highest latitudes.

At lower latitudes diffuse auroras produced by wave-scattering of trapped electrons typically occur.

- A byproduct of the auroral density cavities is the powerful auroral kilometric radiation (AKR) that is known to be caused by a relativistic electron process known as the cyclotron maser.
- Another byproduct of the field-aligned electric fields in the auroral cavities is the acceleration of keV-range ionospheric H^+ and O^+ upward along magnetic field lines. In adjacent regions low-frequency turbulence associated with the auroral return currents accelerates somewhat lower-energy ions upward into the magnetosphere.
- At mid-latitudes below the auroral oval, ionospheric ions (primarily H^+ and He^+), flow upward along the magnetic field to produce the torus-shaped plasmasphere, which populates the inner magnetosphere where the rotational forces dominate over convection. The waxing and waning of magnetic storms produces the inward and outward motion of the plasmasphere outer boundary (the plasmapause) and produce long plasma tails that stretch through the afternoon-sector, eventually intersecting the boundary of the magnetosphere.
- In strong and multiple substorm events, magnetospheric convection causes the build-up of a ring current that eventually surrounds the Earth causing a magnetic storm. The ring current contains significant fractions of both solar-wind and ionospheric plasma.
- Subsequent inward radial diffusion populates the radiation belts with very high energy particles. The slot region between the two radiation belts is maintained by wave-particle scattering in the background plasma of the plasmasphere. In extreme events, the plasmasphere is eroded inside the slot region, cutting off this loss process and allowing a transient radiation belt to exist there.
- During strong disturbances significant changes in the plasma environment of the magnetosphere and ionosphere occur, and these changes can have strong effects or orbital assets, astronauts, GPS signal, and ground-based conductors like power grids and oil pipelines. Collectively, these changes are known as space weather, which should eventually be able to be predicted so as to protect these various entities.

New Knowledge Needed

- As the primary driver of the magnetosphere, magnetic reconnection, and specifically the physical processes responsible for it, must be understood. Specifically the electron-scale processes need to be identified in three dimensions and tested experimentally.
- Magnetic reconnection is generated at the microscale (electron and ion diffusion lengths), but it has global effects through cross-scale coupling. Tracing the

coupling throughout the hierarchy of magnetospheric scales will require extensive modeling and coordinated measurements at the micro-, meso- and macro scales.

- Many questions remain regarding the acceleration processes of auroral electrons. We know that some 30% of total auroral power is produced by Alfvén wave acceleration, but the wave generation mechanism and its location is not known.
- The auroral parallel electric field was identified many years ago, but we do not know the vertical extent of the auroral potential structures or how they vary with altitude. The processes governing the formation of the auroral potential structures, and the role of the ionosphere in controlling their magnitude are futher important outstanding questions. Answers to such questions will require three-dimensional modeling and probing with multiple spacecraft with both horizontal and vertical separations.
- During substorms, ions and electrons are accelerated to very high energies (at least an order of magnitude higher than the reconnection potential drops), and this acceleration has not yet been explained.

Application to Other Environments

- Other planets have magnetospheres that are vastly different from Earth's. In some cases phenomena common at Earth (reconnection, particle acceleration, auroras) are found but with very different characteristics (e. g., Jupiter and Saturn). In other cases phenomena that are relatively unimportant at Earth have great consequences at other planets. These include plasma sources from satellites (Jupiter and Saturn), interchange instabilities (Jupiter and especially Saturn) resulting from the dominance of corotation, and the occurrence of dynamic phenomena like substorms without an ionospheric connection (Mercury). These and other planetary magnetospheres provide important additional laboratories to test the theories developed at Earth as well as to address vastly different phenomena which themselves can have counterparts elsewhere in the universe.
- Magnetic reconnection is known to be crucially important in the solar corona in connections with solar flares and coronal mass ejections. While remote sensing of these phenomena provides vast amounts of information on their scale sizes, temporal development, and energy transfer; the lack of in-situ measurements within them limits the information that can be applied to determining the processes that drive reconnection.
- Examples of astrophysical examples of reconnection include gravitationally-bound magnetized accretion disks within which magnetic fields are continuously created by a differential-rotation dynamo and annihilated by magnetic reconnection. Similar to the solar corona, magnetic loops form and reconnecting while producing X-ray emissions.
- Reconnection has been inferred from the spin-down of Pulsars, during which open field lines are converted to closed field lines, and from their high-energy

emissions, which have been related to intense current sheets and the acceleration of particles.

- Plasma processes that occur in the magnetosphere are also known to limit the operation of Tokamaks. Examples include the transport of plasma through the confinement boundary by the ion drift wave instability and the occurrence of magnetic reconnection in connection with sawtooth crashes of the electron temperature.
- Laboratory studies reconnection are now entering the collisionless regime, which will allow for coordinated studies in the near future that involve computer simulations, laboratory experimentation and multi-spacecraft probes of reconnection.

Existing and Needed Capabilities

- Multi-spacecraft in-situ measurements of composition-resolved plasmas, energetic particles, 3D electric fields and 3D magnetic fields with separations and time resolutions appropriate to the micro-, meso- and macro-scales are needed to identify in three dimensions the physical process responsible for reconnection along with the coupling of the effects of reconnection throughout the magnetosphere.
- Global imaging of magnetospheric plasmas with energetic neutral atoms (ENA) and EUV photons.
- Global imaging of energetic particles with ENA.
- Imaging of electron and proton auroras with FUV photons.
- Imaging of foreshock and magnetosheath plasma densities using soft X-rays.
- Continued developed of modeling capabilities leading to three-dimensional studies of phenomena like magnetic reconnection with realistic mass ratios.