Exploring Outer Planet Magnetospheres with Small Focused Missions. F. Crary[1], F. Bagenal[1], G. Clark[2], P.A. Delamere[3], R. Ebert[4], A. M. Rymer[2], M. Vogt[5], and 26 other planetary magnetospheres scientists. [1]CU-LASP, Boulder CO, [2]JHU-APL , Laurel MD, [3]UAF, Fairbanks AK, [4]SWRI, San Antonio TX, [5]BU, Boston MA

Studies of magnetic and electric fields, charged particles and their interactions with planetary surfaces, atmospheres and conducting interiors all play important roles in our understanding of solar system bodies. To exploit the major contributions of magnetospheric studies we need to develop a program for the development of small, low-cost spacecraft for planetary exploration.

The Trend Towards Focused Missions: The past decades have seen a trend from broadly-focused missions to those with focused goals. This is a necessity for Discovery class missions, but also applies to larger New Frontiers and flagship missions. Spacecraft like *Galileo* and *Cassini* explored almost all aspects of the jovian and saturnian systems, from the core of the planet to the magnetotail. In contrast, *Juno* is focused on three aspects of the jovian system (the deep interior and the composition of the planet and the polar/auroral magnetosphere) and the planned Europa Multiple Flyby missions will study Europa and its subsurface ocean. While this focus has many benefits, it also creates the risk of neglecting other important aspects of planetary science.

Opportunities for New Frontiers and flagship missions are rare, and the list of important, planetary science goals is lengthy. Addressing these goals with smaller missions would be a great advantage. In the case of planetary magnetospheres, we know from terrestrial experience that small spacecraft are capable of making major discoveries. In many ways, small spacecraft can make these measurements more efficiently than they could be made on a large, multi-purpose mission. In discussing and illustrating these points, we will focus on studies of the jovian magnetosphere but the concept might be applied across the solar system.

Science Goals: *Galileo* studied and *Juno* is studying the jovian environment. While *Galileo* made key discoveries on the satellite-moon interactions and the Io plasma torus, the results were limited by the loss of the spacecraft's high gain antenna and the resulting very low data rate. Our knowledge of moon-magnetosphere interactions remains preliminary and the dynamics of the system beyond the Io torus is poorly sampled. *Juno* is making great advances in our knowledge of the aurora and polar magnetosphere but the mission does not include any satellite encounters.

Mass flow though the system. Jupiter's magnetosphere contains a huge internal source of plasma, originating from the volcanoes and atmosphere of Io. An estimated 1000 kg s^{-1} of heavy ions flow through the system. Roughly half are believed to charge exchange and leave the system as energetic (300-1000 eV) neutral atoms. The rest are transported outward and eventually flow down the magnetotail. The transport processes within the Io torus have been modeled and, to some extent, observed. Farther from the planet, the process is both poorly observed and poorly understood.

Solar wind control. Although Jupiter's magnetosphere is largely driven by the internal plasma source at Io, there is evidence that the solar wind also plays a role. Aurora and planetary radio emissions have been associated with solar wind transients. But the relative role of the solar wind is unknown. Is it 10% or 40%? This cannot be determined without systematic, simultaneous and long-term monitoring of the variable upstream solar wind.

Satellite-magnetosphere interactions. The discoveries of the *Galileo* and *Cassini* missions have shown the limits of the earlier flyby missions. In the case of magnetospheres, simply flying past a planet a few times does not provide nearly enough data to understand a structurally complex and dynamic system. The same is true of our current knowledge of the interactions between outer solar system moons and their plasma environment. The best-studied moon, Titan, proved to be in such a dynamic plasma environment, and so inherently complex, that over 100 *Cassini* encounters were inadequate.

Lessons From Earth: Studies of the Earth's magnetosphere provide a roadmap to studies of other planet's magnetospheres. In the past decades, advances have been made by employing proven instruments on small and simple spacecraft, by advances in electric field measurements and energetic neutral atom imaging, and by using multiple spacecraft to make multipoint measurements. The latter is enabled by the ability to observe from small and simple spacecraft.

Magnetospheric spacecraft can be small. Compared to many outer planets missions, highly successful magnetospheric missions have employed small and operationally simple spacecraft. For example, the FAST spacecraft had a mass of 191 kg, the THEMIS spacecraft, 77 kg, and even the Swedish Astrid 2 at 30kg made valuable measurements. While significantly larger than a CubeSat, this is very small compared to a major planetary mission. The particles and fields instrumentation on FAST and THEMIS was comparable to the equivalent instruments on *Cassini* or *Juno.* All of these spacecraft were spinning, with few turns or maneuvers, and all employed a simple operational

process of continuously collecting data in one of a small number of modes.

Multi-spacecraft measurements. Single-spacecraft magnetospheric measurements are plagued by an ambiguity between temporal and spatial variability. As studies of the Earth's magnetosphere have shown, the resolution to this problem is simultaneous, multi-spacecraft measurements. Even at Earth, this is only practical due to the potential simplicity and small size of each spacecraft. In some cases, these multi-spacecraft observations have been from independent spacecraft whose missions overlapped, either by design or a fortuitously long extended mission. In some cases, the spacecraft were part of the same mission and the coverage was coordinated. The THEMIS mission used five, identical spacecraft and arranged for frequent "conjunctions", when they were all distributed in a line extending down the magnetotail. This definitively determined how substorms and other events propagate through the magnetosphere.

Separate Magnetospheric Spacecraft: In many ways, achieving magnetospheric goals is more efficient when preformed on a separate spacecraft. Obtaining the necessary measurements from a larger mission, with diverse goals, is more difficult, limits the quality of the data, requires more resources and adds complexity to the larger spacecraft.

Spinning spacecraft. The three-axis stabilized platform preferred for remote sensing presents major challenges for many magnetospheric instruments, especially particle and plasma instruments, which need full sky coverage. On a three-axis spacecraft, they must rely on multiple sensor heads, mechanical actuation, or simply accept lower quality data from partial coverage. On a spinning spacecraft, simpler versions of these instruments can view the entire sky once per spacecraft rotation. Electric field sensors, which have proven critical to terrestrial magnetospheric missions, require long (tens of meters) antennas. These can only be deployed in the spin plane of a spinning spacecraft and, as a result, have never been flown on a planetary mission.

Electromagnetic Cleanliness. To avoid compromising magnetospheric measurements, great care is required to avoid interference from the spacecraft itself. These requirements are, in general, an annoyance for the other (e.g. remote sensing) instruments and increase the cost and complexity of a multi-purpose mission. The use of small, specialized spacecraft, with focused goals, will confine this requirement to the missions and observations which necessitate it.

Avoiding radiation exposure. For spacecraft operating in a planet's radiation belts, especially at Jupiter, radiation exposure drives spacecraft resources and limits lifetime. Not all planetary science goals require orbiting through a planet's radiation belts. For example, many of the outstanding questions about Jupiter's magnetosphere require measurements in the middle or outer magnetosphere or in the magnetotail. A mission focued on these goals need never enter the intense radiation environment of the inner magnetosphere and, therefore, these questions can be answered without the costs of severe radiation hardening or shielding.

Possible Planetary Magnetosphere Missions:

Solar wind control of dynamics. Perhaps the easiest and simplest small mission to study Jupiter's magnetosphere would be a solar wind monitor. Simply monitoring the solar wind requires very simple instruments with very low data rates (five minute averages from a magnetometer and Faraday cup would suffice.) If transported to Jupiter by another, larger mission, it could place itself in a high eccentric orbit upstream of Jupiter. Such a mission would need to operate in parallel with other observations of Jupiter, either in orbit or Earth based monitoring of radio emissions and aurora. A more capable spacecraft, but still below the 180-kg limit of ESPA-class secondary spacecraft, could monitor the jovian system on its own.

Multi-spacecraft studies of the Jovian magnetotail. The role of mass transport through Jupiter's magnetosphere, the structure of the magnetotail and its dynamics can all be studied by copying the very successful, terrestrial THEMIS mission. Multiple spacecraft would be placed on eccentric orbits with apoapsides at various distances down the magnetotail. Enhancing the THEMIS observatories for the power and communications needs of a jovian mission would increase their mass to 150-200 kg, and three/four spacecraft could be sent together to Jupiter within the scope of a Discovery mission.

Satellite-magnetosphere interactions. By 2050 we expect there to be major missions orbiting outer solar system moons. The moon-magnetosphere interaction is best-studied by small sub-spacecraft. A precedent for this is the *Apollo 15* and *16* missions, which left magnetospheric sub-spacecraft (PFS-1, -2) in lunar orbit, without distracting from the primary mission goals or adding impractical requirements on spacecraft cleanliness. Ideally, an outer planet moon orbiter would release two sub-spacecraft, one to observe the upstream plasma and a second to observe the interaction close to the moon.

Planetary Magnetospheric Exploration in 2050: The exploration of planetary magnetospheres can be accomplished using small, focused missions. These missions, often secondary payloads of larger missions, will provide an efficient and flexible framework for magnetospheric science in the outer solar system.