Final Technical Report

Jovian Substorms: A Study of Processes Leading to Transient Behavior in the Jovian Magnetosphere
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Accomplishments

Solar system magnetospheres can be divided into two groups: induced and intrinsic. The induced magnetospheres are produced in the solar wind interaction of the magnetized solar wind with planetary obstacles. Examples of these magnetospheres are those of comets, Venus and Mars. Intrinsic magnetospheres are the cavities formed in the solar wind by the magnetic fields produced by dynamo current systems inside the planets: Mercury, Earth, Jupiter, Saturn, Uranus and Neptune are known to have intrinsic magnetospheres. Intrinsic magnetospheres can be further subdivided as to how the circulating plasma is driven by external or internal processes. The magnetospheres of Mercury and Earth are driven by the solar wind. The magnetospheres of Jupiter and possibly of Saturn are principally driven by internal processes. These processes provide the energy for the powerful jovian radio signals that can be detected easily on the surface of the Earth.

The circulation process in the jovian magnetosphere is not steady. Part of this unsteadiness may be due to the engine that drives the circulation: the mass loading at Io; part of the unsteadiness may be associated with variations in the coupling of the magnetosphere with the ionosphere during the transport process, and part is due to the temporally varying nature of reconnection in planetary magnetospheres. Temporally varying reconnection on the nightside of the terrestrial magnetosphere has been called a substorm. We use the same term for the analogous process at Jupiter but in fact we have studied the entire process leading up to the onset of the substorm as well as its aftermath. Before listing the various papers presented and published as part of this effort we will review why there must be substorms in the jovian magnetosphere.

The moon Io adds about 1 ton of molecular sulfur compounds in the form of ions into the magnetosphere every second. The density of ions builds up until the rotating torus of plasma has sufficient angular momentum that it stretches out the magnetic field, and causes whole tubes of magnetic field and plasma to move outward. This cannot go on unchecked because net magnetic field cannot be removed from Jupiter. The magnetic flux is set by the currents deep within Jupiter. Thus the ions must be separated from the magnetic field. This can be done in two ways. The ions can be scattered along the magnetic field so that they are lost into the atmosphere or the field line can be stretched to the "breaking point" and a magnetized island of ions is formed where the magnetic field loops back on itself and there is no net magnetic flux. This essentially empties a magnetic flux tube which is there free to move back into the magnetosphere. At the beginning of this study grant we had only a glimmering of how this process worked but now at the end of the study we understand it quite well.

The overall circulation process from Io, through the magnetosphere to the reconnection site and back was synthesized in a series of presentation and published papers [1.1, 1.4, 1.11, 1.12, 2.4]. (These numbers refer to the papers in the attached bibliography). These ideas were also incorporated into several more general reviews of planetary magnetospheres [1.3, 1.7, 2.5]. Individual processes that contribute to the overall under steady circulation were also examined. Beginning in the region of the Io torus we created a "ring current index" to study the long term variation in the magnetodisk current [1.10, 2.7] and to attempt to understand the bizarre behavior of the star sensor background count rate an orbit C22 [1.6, 1.9, 2.8]. This study showed that the magnetic field in the inner magnetosphere of Jupiter does not vary much and pointed the finger at the volcanism of Io for disrupting the inner magnetosphere of Jupiter and energizing the particles that caused "false" counts in the star sensor.

The next part of the story involves the fluctuations seen in the middle magnetosphere which is relevant to the scattering losses of the mass loaded ions. This was supported by a separate grant. Suffice it to say that there is lots of scattering but it seems insufficient to cause the requisite loss of plasma.

Out further in the magnetosphere the rotating plasma is sufficient to stretch the field configuration into a magnetodisk, a tail-like configuration at all local times. The inner edge and the outer edge of this region are unstable. The curved magnetic field lines are in force balance so that we can use the observed magnetic configuration to determine the mass of the magnetodisk [1.2, 2.1]. The orbit to orbit variability of this force balance indicates that the circulation of the plasma is quite unsteady.

The current sheet in the magnetodisk itself is quite interesting and important for understanding the reconnection process. Small tearing islands appear to form but remain quiescent until they later grow to a size that reaches the empty lobe field lines above and below the current sheet. This control by the local plasma conditions is an important lesson for the behavior of our own magnetosphere [1.7, 2.2].

When explosive reconnection occurs, a large portion of the current sheet is disrupted and a magnetized island of heavy ions is released down the tail. This process is responsible for the large time variations seen in the near tail region from midnight to 3 AM LT and beyond 50 R_J [1.7, 2.3].

The emptied flux tubes can "float" inward again the outward flow of the heavily laden flux tubes because they have been emptied and are buoyant. Somewhere in their inward motion the region of emptied flux appears to break up into slender flux tubes. These slender flux tubes can be seen easily against the torus plasma laden tubes because they have a greater field strength. This difference in field strength makes an excellent probe of the plasma pressure and therefore of the beta of the plasma [1.5, 1.8, 2.6, 2.9].

In short, we were able to attach the entire plasma circulation process involved in the jovian substorm, from Io out to the near tail and back again.

1. Papers Presented at Meetings

1.1 C. T. Russell, The jovian magnetospheric engine, presented at IUGG XXII General Assembly, Birmingham, U.K., July, 1999.

1.2 C. T. Russell, K. K. Khurana M. G. Kivelson, D. E. Huddleston, A. Ansher, D. A. Gurnett, W. S. Kurth and J. Williams, Jovian current sheet stress balance and mass density, presented at IUGG XXII General Assembly, Birmingham, U.K., July, 1999.

1.3 C. T. Russell, Solar wind interactions with magnetospheres: A tutorial update on phenomenology and physics, presented at IUGG XXII General Assembly, Birmingham, U.K. July, 1999.

1.4 C. T. Russell, The dynamics of planetary magnetospheres, presented at the Magnetospheres of the Outer Planets Symposium, Paris, August 1999.

1.5 C. T. Russell, M. G. Kivelson, K. K. Khurana and Z. J. Yu, The interchange instability in the Io torus: Empty flux tubes, presented at the Fall AGU Meeting, (abstract) *Eos Trans. AGU*, 80(46), *Fall Meeting Suppl.*, F621, 1999.

1.6 Z. J. Yu, C. T. Russell, S. P. Joy, K. K. Khurana, M. G. Kivelson, P. D. Fieseler, D. L. Bindschadler, The time variability of the Io torus, presented at the Fall AGU Meeting, (abstract) *Eos Trans. AGU*, 80(46), *Fall Meeting Suppl.*, F621, 1999.

1.7 C. T. Russell, Reconnection in planetary magnetospheres, presented at the AGU Spring Meeting (abstract) *Eos Trans. AGU*, 81(19), Suppl., S381, 2000.

1.8 C. T. Russell, M. G. Kivelson, W. S. Kurth and D. A. Gurnett, Empty magnetic flux tubes as probes of the ion temperature of the Io torus, presented at the 33rd COSPAR Scientific Assembly, Warsaw, July, 2000.

1.9 C. T. Russell, P. D. Fieseler, D. Bindschadler, Z. J. Yu, S. P. Joy, K. K. Khurana and M. G. Kivelson, Large scale changes in the highly relativistic charged particles in the region of the Io torus, presented at the 33rd COSPAR Scientific Assembly, Warsaw, July, 2000.

1.10 C. T. Russell, Z. J. Yu, K. K. Khurana and M.G. Kivelson, Magnetic field changes in the inner magnetosphere of Jupiter, presented at the 33rd COSPAR Scientific Assembly, Warsaw, July, 2000.

1.11 Z. J. Yu, C. T. Russell, M. G. Kivelson, and K. K. Khurana, Circulation of plasma in the jovian magnetosphere as inferred from the Galileo magnetometer observations, presented at the 32nd DPS Meeting, Pasadena, CA, (abstract) BAAS, 32, 1058, 2000.

1.12 C. T. Russell, Io as a plasma source in the jovian system, presented at the AGU Fall Meeting (abstract), *Eos. Trans., AGU, 81*(48), F787, 2000.

2. Papers Published in Journals and Books

2.1 C. T. Russell, D. E. Huddleston, K. K. Khurana and M. G. Kivelson, Observations at the inner edge of the jovian current sheet: Evidence for a dynamic magnetosphere, *Planet. Space Sci., 47*, 521-527, 1999.

2.2 C. T. Russell, D. E. Huddleston, K. K. Khurana and M. G. Kivelson, Structure of the jovian magnetodisk current sheet: Initial Galileo observations, *Planet. Space Sci., 47*, 1101-1109, 1999.

2.3 C. T. Russell, K. K. Khurana, M. G. Kivelson and D. E. Huddleston, Substorms at Jupiter: Galileo observations of transient reconnection in the near tail, *Adv. Space Res., 26*(10), 1499-1504, 2000.

2.4 C. T. Russell, M. G. Kivelson, K. K. Khurana and D. E. Huddleston, Circulation and dynamics in the jovian magnetosphere, *Adv. Space Res.*, *26*(10), 1671-1676, 2000.

2.5 C. T. Russell, Reconnection in planetary magnetospheres, *Adv. Space Res.*, *26*(3), 393-404, 2000.

2.6 C. T. Russell, M. G. Kivelson, W. S. Kurth and D. A. Gurnett, Implications of depleted flux tubes in the jovian magnetosphere, *Geophys. Res. Lett.*, *27*, 3133-3136, 2000.

2.7 C. T. Russell, Z. J. Yu, K. K. Khurana and M. G. Kivelson, Magnetic field changes in the inner magnetosphere of Jupiter, *Adv. Space Res.*, submitted 2001.

2.8 C. T. Russell, P. D. Fieseler, D. Bindshadler, Z. J. Yu, S. P. Joy, K. K. Khurana and M. G. Kivelson, Large scale changes in the highly energetic charged particles in the region of the Io torus, *Adv. Space Res.*, in press, 2001.

2.9 C. T. Russell, M. G. Kivelson, W. S. Kurth and D. A. Gurnett, Depleted magnetic flux tubes as probes of the Io torus plasma, *Adv. Space Res.*, submitted, 2001.