Processes in planetary magnetospheres occur on a variety of scales. On the largest scales are the plasma circulations induced in the magnetospheric plasma externally by the solar wind interaction or internally by processes such as mass loading of the jovian magnetosphere by the moon Io. These large-scale processes are influenced by small-scale processes such as particle scattering by waves, gyro motion, and charge exchange. It is not always clear which of two coupled processes are in control. For example, many believe that the onset of reconnection requires a microscale instability but it is possible that external forcing leads to the magnetic configuration at which reconnection eventually occurs, and it is only the existence of the appropriate magnetic configuration over a sufficiently large region that is required to cause the macroscopic flows. This paper reviews such coupling in the magnetospheres of the Earth and Jupiter.
MAGNETOPAUSE RECONNECTION

Magnetic reconnection occurs when oppositely directed magnetic fields, initially separated by a current sheet with no interconnection of the magnetic field across the current sheet, establish a connection across that current sheet. Figure 1 shows the geometry of this process [Scudder et al., 2001]. On either side of the current sheet plasma moves inward toward the center once reconnection has begun and “reconnected” plasma is exhausted from the central region allowing the inflow to proceed. The energy in the exhaust flow is provided by the Lorentz or $J \times B$ force of the bent field lines. The boundary between the topologically distinct magnetic field lines is called the separatrix.

The high resolution plasma and magnetic data from the Polar spacecraft have been used to study this process concentrating on a few hour period on May 29, 1996 when the spacecraft was near apogee and the solar wind dynamic pressure was of sufficient strength to keep the magnetopause in the vicinity of the spacecraft [Scudder et al., 2001]. Figure 2 shows the magnetic field measurements at 54 Hz for 400 msec across a magnetic field null. The temporal variation has been converted to a spatial variation with the measured plasma velocity. We see that the scale lengths are of the order of the electron inertial length $c/\omega_{pe}$.

The scale lengths of the magnetic field measured as a fraction of the electron inertial length and the electron thermal gyro radius are shown in Figure 3 together with the electron beta, all plotted versus the minimum magnetic field in the depression. It is clear from this display that the scale size is ordered by the ion inertial length and not the electron thermal gyro radius and also that the electron beta can be extremely large in these field nulls. Thus on the finest possible scales in the plasma the enabling physics is taking place that controls the flows on the largest possible scales in the magnetosphere but what controls the rate of reconnection?

THE EFFECT OF THE BOW SHOCK ON RECONNECTION

An important factor in controlling the rate of reconnection is the nature of the plasma in which the reconnection is taking place. The accelerated plasma reaches the Alfven velocity based on the normal component of the magnetic field and the local plasma density. The ISEE 1 and 2 measurements at the dayside magnetopause were the first to show this [Paschmann et al., 1979]. The properties of the plasma in the region depend on the conditions at the bow shock. Figure 4 shows a sketch of the solar wind interaction with the Earth’s magnetosphere. The shock front deflects the flow, heats, compresses and slows the solar wind plasma. It also bends the magnetic field. The structure of the shock depends in part on the orientation of the magnetic field. The shaded region denotes the foreshock region where heated ions flow upstream against the solar wind flow and interact with the solar wind. As
illustrated here, the magnetic field typically makes a 45° angle with the solar wind flow. However, at times the magnetic field can become aligned with the flow and when it does it is not compressed at the subsolar shock. The plasma that intersects the subsolar point paints the magnetopause and, when the magnetopause is covered with a weak field, reconnection appears to be slow [Scurry and Russell, 1991].

Another situation that can weaken the magnetic field in the sheath is the occurrence of a high Mach number at the bow shock that causes a high beta downstream so that the pressure applied to the magnetosphere is due to the plasma and not the magnetic field. Figure 5 shows a proxy measure of the reconnection rate based on the level of geomagnetic activity. At low Mach numbers geomagnetic activity is fairly constant but, as the Mach number increases, geomagnetic activity suddenly decreases at about 8. This is not generally important at Earth where such Mach numbers are rare but this can be important in the magnetospheres of the outer planets where the Mach number is typically in this range.

RECONNECTION IN THE JOVIAN MAGNETOSPHERE

The solar wind dynamic pressure establishes a magnetic cavity at Jupiter much like that at the Earth but much grander in scale. The high Mach number of the solar wind affects the rate of reconnection but in any event the rapid rotation and vast scale of the jovian magnetosphere causes a circulation pattern that is little affected by the solar wind except to determine its overall scale size. Nevertheless, there is a circulation pattern in the jovian magnetosphere that is intimately tied to reconnection but this circulation has an internal driver.

Figure 6 shows a sketch of the interaction of Io with the jovian magnetosphere. Jupiter rotates rapidly and drags its magnetospheric plasma with it because of the very high electrical conductivity of the magnetosphere along field lines. This is similar to the corotation of the Earth’s plasmasphere. Io orbits at 5.9 jovian radii (R_J) at an orbital speed of 17 km/s while the magnetospheric plasma moves at 74 km/s. The net difference in velocity of 57 km/s means that newly formed ions from the exosphere of Io will experience an electric field, VxB, that rapidly accelerates the ion and causes it to drift with the other plasma. These ions build up in intensity to form a torus of about 4000 ions/cm³ density extending out to about 7.7 R_J. At Io the massloading is strong enough to bend the magnetic field, leading to field-aligned currents that close in the ionosphere. The massloading process as discussed at greater length in a later section involves the production of fast neutrals that cross the magnetic field lines and help spread the torus over the region observed.
Fig. 5. The efficiency of the interplanetary electric field in generating geomagnetic activity as a function of the solar wind magnetosonic Mach number.

The inexorable outward march of the iogenic plasma allows us to examine the radial evolution of the structure of the plasma sheet as a temporal evolution. Figure 7 shows a sequence of crossings of the current sheet in the jovian magnetodisk beginning at 25.8 R_J [Russell et al., 1999]. The coordinate system has been chosen so that the magnetic field component crossing the current sheet is in the $b$ direction. The $a$ direction is the direction that reverses across the sheet. There is always some high frequency structure in the current sheet but as one moves outward the component across the average sheet direction begins to become more variable. Part of this variability is due to the bending of the current sheet but part of it must also be due to the growth of tearing in the current. This is especially evident at 54.6 R_J where sharp downward spikes are seen.

Figure 8 shows a 21-day period near midnight where the current sheet has rocked back and forth across the spacecraft because of the tilt of the dipole [Russell et al., 1998]. The $B_s$ component here is the component across the average current sheet. A dipolar field would have a positive (southward) direction in this coordinate system. There are frequent glitches in this component. Some of these are very large and all of them are real, not telemetry dropouts.

Figure 9 shows an enlargement of one of these events. One hour of data is shown. The magnetic field goes strongly vertical, reaching a magnetic field strength over three times that seen in the lobes above and below the current sheet. This rapid and extremely strong event is interpreted to be reconnection. We believe the reconnection event is so strong because reconnection has reached the very low plasma density conditions in the lobes. In 45 minutes the magnetodisk has returned to normal.

Figure 10 shows the magnetospheric circulation pattern that we believe is consistent with this reconnection [Vasyliunas 1983]. Throughout the inner magnetosphere, the plasma corotates and slowly moves outward. In the distant nightside magnetosphere reconnection occurs making a magnetic island that contains ions but the net magnetic flux is zero. The flux tube on the closed side of the reconnection region has been emptied of much of its plasma and returns to the inner magnetosphere floating against the outgoing flow. The emptied tubes appear to breakup into slender tubes that can move inward rapidly, reaching the Io orbit and repeating the massloading circuit [Russell et al., 2000].
Fig. 7. Radial evolution of the structure in the jovian current sheet. Component $a$ shows the magnetic field that changes across the current sheet; $b$ shows the component that is approximately constant and normal to the current sheet; $c$ shows the component that is approximately zero and in the direction of the “azimuthal” current [Russell et al., 1999]. With increasing radial distance, increasing structure in the component crossing the current sheet, $B_b$, is observed. At 54.6 RJ the structure looks like tearing islands.

Fig. 8. Twenty-one days of magnetic measurements in the night side jovian current sheet. The radial, $B_r$, southward, $B_s$ and tangential or azimuthal, $B_z$, components are shown. The glitches in the north-south component show the presence of the jovian equivalent of substorms [after Russell et al., 1998].

Fig. 9. An expansion of event A in Figure 8. Coordinate system is the same as in Figure 8 [after Russell et al., 1998].
Magnetopause

Magnetic X-Line

Magnetic O-Line

Fig. 10. Schematic diagram of the circulation of plasma in the jovian magnetosphere [after Vasyliunas, 1983]. The left-hand panel shows the circulation in the equatorial plane and the right-hand panel shows the plasma circulation and magnetic configuration in four planes whose locations are given in the left-hand panel. When the flow reaches plane 2, reconnection begins producing an X-O neutral line pair that grows as the flow advances to earlier local times.

A LESSON FOR EARTH

Returning to the Earth’s magnetosphere for a moment we can draw a lesson for substorm genesis from both the Earth’s dayside magnetopause and the jovian magnetodisk. One of the puzzles of substorm onsets is what causes the substorm expansion phase. Other questions include why northward turnings of the IMF trigger substorms, why sometimes there is a pseudo breakup when a substorm seems to slow and then stops before it proceeds far and double onset substorms. Figure 11 shows a sketch of a model substorm that uses the fact that the reconnection depends on the Alfven velocity at the reconnection point [Russell, 2000]. In this model a distant neutral point is reconnecting magnetic flux in the tail lobe while flux is being added by dayside reconnection. A second neutral point has formed near the Earth. It proceeds slowly and cannot reach the open flux of the lobes because the distant neutral point provides plasma sheet that keeps the Alfven velocity low at the inner neutral point. The formation of the near Earth neutral point signals the first onset of dual onset substorms and/or the pseudo-breakup onset. If the IMF turns northward the distant neutral point will stop and the near Earth neutral point will continue to reconnect and eventually reach the lobes. There the reconnection rate jumps and the main expansion phase can occur. If the IMF returns southward before the near Earth neutral point reaches the open field lines, the rate of reconnection can be slowed at the near Earth neutral point and a pseudo-breakup result.

MULTISCALE COUPLING IN A PARTIALLY IONIZED GAS

Returning to Jupiter we take a closer look at the Io massloading process as shown in Figure 12. The torus plasma flows into the Io exosphere and, because it is strongly magnetized, there is a strong electric field radially outward from Jupiter. When exospheric neutrals are ionized they rapidly accelerate and gyrate and drift in a cycloidal path. Some fraction of these new ions can charge exchange with exospheric neutrals and then travel rapidly across the magnetic field until photoionization or some other process takes the neutral back to the ionized state at which time it gyrates and drifts as before. This process creates a disk of massloading in the direction downstream from Io, both inward and outward, but not upstream [Wang et al., 2001].

Figure 13 shows the neutral cloud produced by following the process in a simulation starting from a state with no neutral cloud present. As time proceeds and Io orbits, a steady state evolves in which the characteristic neutral cloud of Io is seen. This neutral cloud is being eroded by ionization with a much longer time scale. The picked up ions rotate faster than Io and eventually form a complete ring about Jupiter as shown in Figure 14.
Fig. 11. Schematic diagram illustrating how the presence of two neutral points can produce many of the subtleties of substorm phenomena such as pseudo-breakups and northward turning triggering of substorm expansions [Russell, 2000]. The top panel shows the magnetic configuration in the noon-midnight meridian of the Earth’s magnetosphere well after the interplanetary has turned southward and two neutral points have formed. The middle panel shows the flux transport rates: reconnection at the magnetopause, M; at the distant neutral point, RD; at the near-Earth neutral point, RN; and the convection to the dayside, C. The five dashed lines mark the southward turning of the IMF, S; the onset of plasmoid formation, P, when the near-Earth neutral point forms; the northward turning, N; the time at which the near-Earth neutral point reaches the tail lobe, L; and the time at which the recovery phase ends, R. The bottom panel shows how the magnetic flux varies in each region during the substorm in the closed dayside magnetosphere, Day; the open lobe, Lobe; the plasmoid, PM; and the distant plasma sheet, DPS.
Fig. 12. Schematic diagram of the details of the massloading process at Io showing how the transport of neutral particles across the field lines increases the extent of the massloading region. Ions produced near Io are accelerated in the electric field of the corotating magnetosphere and then neutralized by charge exchange close to Io. On the Jupiter side of Io these fast neutrals collide with Io but on the anti-Jupiter side they spread out to form a disk of massloading particles mainly outward and downstream of Io.

Fig. 13. Simulation of the production of the cloud of neutrals around Io [Wang et al., 2001]. Simulation is started with no neutral cloud at $t=0$. After 9.3 hours the neutral cloud, eroded by ionization is close to steady state.

Fig. 14. Simulation of the production of the Io torus from the neutral cloud [Wang et al., 2001]. The ions produced in the neutral cloud shown in Figure 13 drift with the corotating magnetospheric plasma to eventually produce a complete torus.
Fig. 15. Gyro velocity of newly born ions as a function of jovicentric distance in the model of Wang et al. [2000]. The inner torus is produced “cool” and the outer torus “warm” in this model.

This process emplaces ions both inside Io’s orbit and outside. The gyro velocity of this process varies with radius as illustrated in Figure 15. The plasma produced inside has a much lower gyro velocity than outside. Since this gyro velocity produces the perpendicular pressure in the plasma, this emplacement results in an initially cooler plasma inside than outside Io. These temperatures from the simulation are generally warmer than those observed in the torus but the full corotation velocity was used in the pickup process and some cooling is expected due to Coulomb collisions with the neutrals. The important point here is that a microscale process has set the large scale thermal structure of the torus.

SUMMARY AND CONCLUSIONS

There are many examples of multiscale coupling in space plasma. Many more have been proposed than discussed herein. Sometimes the microscale process is driven by the macroscale process such as when ULF waves in the magnetosphere are generated by particles accelerated in a substorm. At times microscale processes have been thought to control the threshold for some instability when the process was actually controlled by macroscale processes. For example, the breaking of field line connectivity in reconnection is a microscale process but its rate may be governed by large scale boundary conditions that set the geometry and plasma conditions at the reconnection site.

In many places in planetary magnetospheres the properties are dependent on microscale processes. The magnetosheath is produced by the shock and its properties are determined by microscale processes. These flows in turn may control the reconnection process at the subsolar point through altering the conditions in the plasma. At the reconnecting magnetopause the partner-shifting mechanism occurs on a microscopic scale resulting in reconnection flows that are global. In one example we showed how an externally driven reconnection picture could explain many of the features found for substorms on Earth, even though internal microscopic processes must be acting at the reconnection point itself.

Finally, we examined a partially ionized gas and showed how the charge-exchange process could lead to significant mass transport at Io and help set in place the properties of the Io torus. The intimate connection of ionized and neutral gases that the charge-exchange process enables needs to be considered in many settings in magnetized plasmas, not just at Jupiter.

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