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Dynamics of the Jovian Magnetosphere

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25.1 INTRODUCTION

Understanding the dynamic processes in the largest magnetosphere of our solar system is one of the outstanding goals of magnetospheric physics. These processes are associated with temporal and/or spatial variations of the global configuration. Their timescales range from several tens of minutes to sizeable fractions of the planetary rotation period to long-term variations which take several days to develop. They occur on both local and global spatial scales, out to dimensions representing a large fraction of the magnetosphere.

Early indications of a "living", varying jovian magnetosphere came from ground-based observations of jovian radio emissions. It was found that some of the jovian decametric emissions are correlated with changes in solar wind parameters (see e.g., Teresawa *et al.* 1978), and in addition there was evidence of solar wind influence on hectometric radio emissions and on jovian aurora (Baron *et al.* 1996, Gurnett *et al.* 2002). Most of the information we have today, however, about dynamical processes at Jupiter has come from in situ spacecraft observations. Of the seven spacecraft that have visited the gas giant over the last 30 years, six only flew past the planet and hence provided only snapshots, each lasting a few days or a week at most, of the state of the magnetosphere. These flyby missions – *Pioneer 10* (1973) and *11* (1974), *Voyager 1* and *2* (both in 1979), *Ulysses* (1992), and *Cassini* (2000/2001) – offered very limited possibilities to observe and investigate transient processes, because of the short duration of the flyby and the inability to distinguish between temporal and spatial variations. The state of knowledge derived from the early flyby missions has been summarized in the books by Gehrels (1976) and Dessler (1983) for *Pioneer* and *Voyager* and in a series of special journal issues (*Science* Vol. 257, *Planet. Space Science* Vol. 41 and *J. Geophys. Res.* Vol. 98) for *Ulysses.*

A whole new dimension in studying Jupiter's magnetosphere became possible with *Galileo*, the first orbiting spacecraft in the magnetosphere of an outer planet. In orbit around Jupiter for almost 8 years (1995–2003), *Galileo* has collected in situ data of the jovian system over an extended duration and has for the first time made possible the study of Jupiter on timescales of weeks, months, and even years, using the same instrumentation. New regions of the jovian magnetosphere have been explored, especially the jovian magnetotail which was not visited by any of the previous spacecraft (except, to a very minor extent, by *Voyager 2*). Additional inputs have become available from ground-based and Earth-orbit-based measurements and from advanced global magnetohydrodynamic (MHD) simulations of the jovian magnetosphere. Ideally, of course, all such resources should be combined together. The dual spacecraft constellation of *Galileo* and *Cassini* in and near the jovian system at the end of 2000 and the beginning of 2001, together with a simultaneous observational campaign from Earth, provided a partial opportunity for such a combined study, from which transient processes on a wide range of temporal and spatial scales could be identified and their physical nature disentangled, at least in part.

A comparison of the dynamical plasma processes between Jupiter and Earth reveals both similarities and differences (e.g., Russell 2001). Within the magnetospheres of both planets, plasma and energetic particles undergo large-scale flows, there are identifiable sources that supply the plasma, and large amounts of energy are transported and dissipated. At Earth, the primary flow is a large-scale circulation, called magnetospheric convection, driven primarily by the solar wind. Furthermore, the solar wind constitutes the major source for the magnetospheric plasma content (although the contribution of Earth's ionosphere is also significant) and provides almost all of the energy that is stored and dissipated in the magnetosphere–ionosphere system. The energy flow is strongly modulated by solar-wind parameters (especially the angle between the interplanetary magnetic field and Earth's dipole) and is highly unsteady, with prolonged periods of enhanced activity

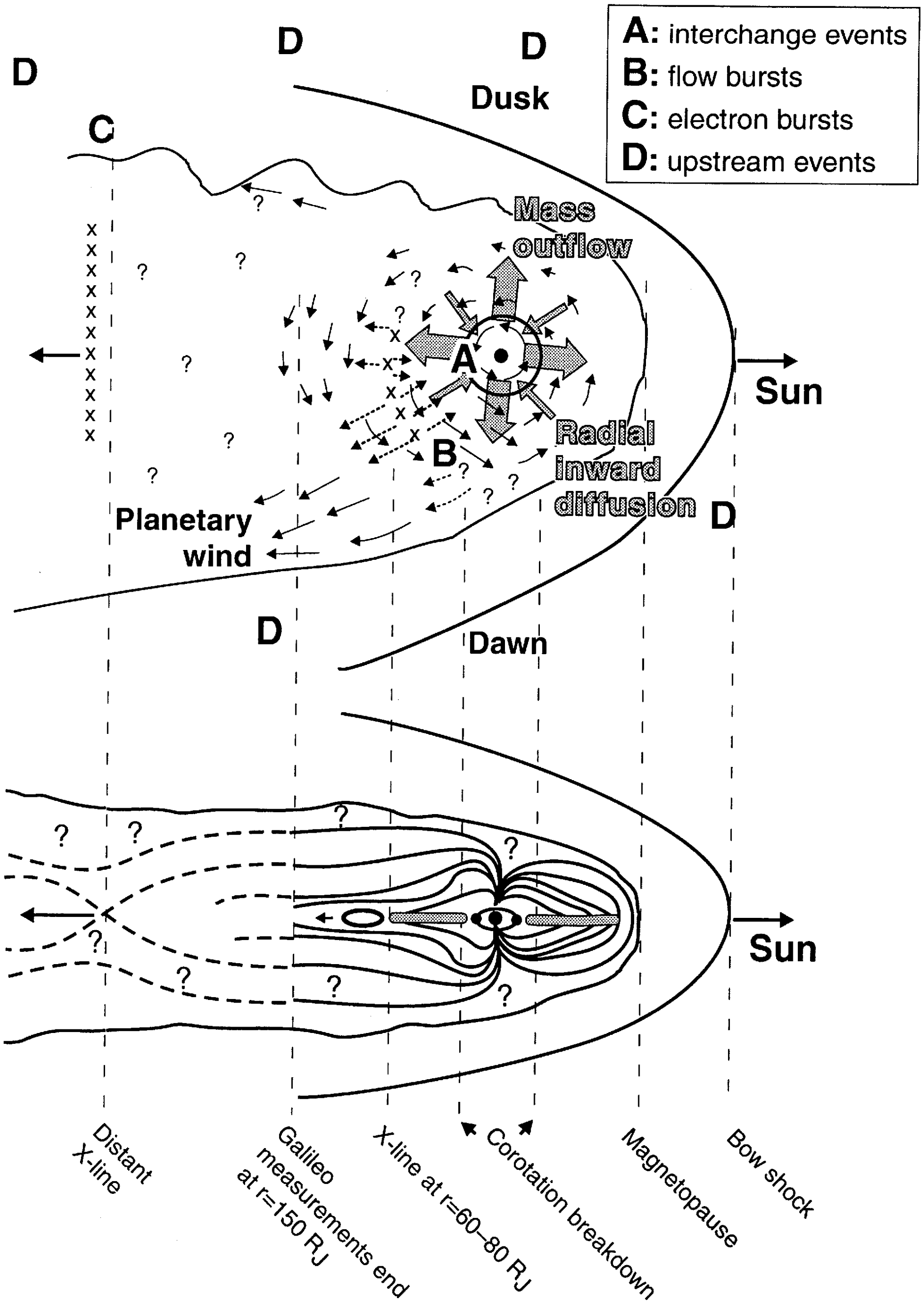

Figure 25.1. Sketch of the jovian magnetosphere in the equatorial plane (top) and a noon–midnight meridional cut (bottom). Question marks indicate regions where no data are available as yet. Black arrows represent the particle flow directions, grey arrows the mass outflow and the inward diffusion. The x-symbols show the location of a magnetic x-line in the jovian magnetotail, and the letters A-D mark the positions where various dynamic features have been inferred from in situ data. During the two spacecraft (*Galileo* and *Cassini*) measurements in 2000/2001 there was evidence for wavy structure of the dusk magnetopause as indicated. The spatial extent of these unstable boundaries, however, is not fully known and may be as prevalent (or more so) on the dawn side. Dotted lines are drawn to separate magnetospheric regions. The solid and dashed lines in the bottom sketch represent magnetic field lines; the dashed portions lie beyond the distances reached by *Galileo*. The fat grey bar indicates the equatorial current/plasmasheet.

(magnetic storms) and with sudden global reconfigurations of the magnetosphere probably connected with internal instabilities (magnetospheric substorms, originally thought to be just sub-units of magnetic storms but now recognized as a distinct phenomenon). At Jupiter the situation is more complex. The solar wind still constitutes an external energy and mass source, which may not be negligible and may well drive or at least trigger some internal processes or disturbances. However, there are internal sources of energy and mass that are much more important than those from the solar wind, unlike the case at Earth. The average plasma flow is driven primarily by the rotation of the planet throughout most of the jovian magnetosphere (see Chapter 24 and, e.g., Hill and Dessler 1991). The plasma in the jovian magnetosphere is supplied mainly by internal sources, predominantly Io (see Chapter 23). Planetary rotation is also the dominant source of energy for much of jovian magnetospheric dynamics. We may therefore expect magnetospheric transient processes at Jupiter to be significally different from those at Earth. There is evidence that reconfigurations, possibly involving large-scale instabilities and resembling terrestrial substorms in some ways, occur at Jupiter. The mechanism, however, may involve energy extracted by torques on the rotating planet and stresses exerted by rotating mass-loaded flux tubes, in place of stresses from solar wind flow. Similarities with Earth may be related in part to the common role of magnetic field line reconnection.

Although Jupiter's magnetosphere is the second best-known of all explored magnetospheres, it still ranks far behind Earth's in this respect, and only a tiny fraction of it has already been explored with in situ measurements. If one scales all positions by the normal stand-off distance of the magnetopause (10 $\mathrm{R_E}$ at Earth and $\approx$60–90 $\mathrm{R_J}$ at Jupiter), the most distant measurements taken onboard *Galileo* in Jupiter's magnetotail (150 $\mathrm{R_J}$) correspond to only about 20–25 $\mathrm{R_E}$ in the Earth's case (Woch *et al.* 2003). In fact, there is evidence that the jovian magnetotail may extend as far out as 5 AU, to the orbit of Saturn, thereby influencing (occasionally!) the dynamics of the second largest gas giant in our solar system (Desch 1983).

Dynamic processes dealt with in this chapter can be considered as transient deviations from the average or "ground-state" configuration of Jupiter's magnetosphere described in Chapter 24. The main features of this average configuration are a concentration of plasma and energetic particles in an equatorial plasmasheet, with a flow that is primarily in the direction of the planet's rotation, but with azimuthal velocity components that are generally much smaller than rigid corotation and components in the radial and north–south directions smaller still, and a well-ordered magnetic field with a dominant radial component (reversing across the plasmasheet) in the middle magnetosphere but more nearly dipolar in the inner and outer regions.

Figure 25.1 shows a sketch of the jovian magnetosphere as currently visualized, mainly on the basis of inferences from in situ measurements. Two cuts through the magnetosphere are shown: the equatorial plane at the top and the noon–midnight meridian at the bottom. Dotted lines separate various magnetospheric regions. Question marks indicate regions that are still largely unknown. Black arrows point in the direction of plasma and energetic particle flow; grey arrows represent the radially outward plasma transport from its source region near Io and the radially inward particle diffusion which populates the radiation belts. In the inner magnetosphere the plasma is nearly corotating with the planet out to a particular distance (black circle) beyond which rigid corotation breaks down (see, e.g., McNutt *et al.* (1979) and Krupp *et al.* (2001)), an effect well understood as the result of an inertial limit (Hill 1979): the ionosphere of Jupiter cannot exert enough torque to supply the increasing angular momentum that rigid corotation of outwardly transported plasma would require. The distance (Hill radius) at which rigid corotation breaks down lies typically between 15 and 30 $\mathrm{R_J}$ from the planet. Beyond it, the plasma is still moving predominantly in the corotation direction but with velocities around 200–400 km $\mathrm{s^{-1}}$, less than the rigid corotation speed. The flow is larger at dawn than at dusk (see Chapter 24). Beyond a comparable distance the magnetic field becomes too weak to exert a radial inward force sufficient to balance the centripetal acceleration of a rigidly corotating plasma, although it does balance the acceleration of the actual sub–corotating plasma flow.

Dynamic processes in the jovian magnetosphere are evidenced by deviations from the average configuration. The letters A-D in Figure 25.1 indicate the typical locations, inside and outside the magnetosphere, where such deviations (to be discussed in more detail below) have been observed. The magnetopause is often unstable to surface waves at the boundary. During the two spacecraft (*Galileo* and *Cassini*) measurements in 2000/2001 there was evidence for wavy motion of the magnetopause on the dusk flank of the magnetosphere as indicated in Figure 25.1. The spatial extent of surface waves, however, is not fully known and the dawn magnetopause surface could well be less stable. The planetary or magnetospheric wind as inferred from *Voyager* observations (Krimigis *et al.* 1981) is shown at distances beyond 130 $\mathrm{R_J}$ in the pre-dawn section of the magnetosphere.

In this chapter we will focus on the observational evidence and possible explanations for these various deviations from the average state of the jovian magnetosphere. We will concentrate on in situ observations within the magnetosphere and only briefly mention the highly promising possibilities for investigating magnetospheric processes that are offered by auroral imaging or by a combination of in situ and auroral observations (a topic dealt with more fully in Chapter 26).

As an example, Figure 25.2 shows data from three different instruments (plasma wave experiment PWS; energetic particles detector EPD; and magnetic field instrument MAG) onboard *Galileo* as measured on orbit G2 in 1996. The plot shows from top to bottom: radio emissions in the frequency range between 10^2 and 5×10^6 Hz, intensity of protons in the energy range between 80 and 220 keV and components of their relative anisotropy (describing the direction of flow); total magnetic field strength and magnetic field components. At distances between 80 and 115 $\mathrm{R_J}$, extensive deviations from the "ground state" are apparent: dramatic quasi-periodic increases of the radial anisotropy component, indicative of dramatic changes in the global flow pattern; simultaneously, enhancement of radio emissions in various frequency ranges, indicative of changes in plasmasheet thickness; and increases of auroral radio emissions. The purpose of this chapter is to describe and interpret observed dynamic features such as these.

25.2 RADIAL TRANSPORT

Jupiter's magnetosphere must rid itself of $\approx$1 ton $\mathrm{s^{-1}}$ of gas and plasma emitted from the atmosphere of the volcanic moon Io (see Chapter 23). The materials are mostly in the form of SO_2 gas and of ions, electrons and neutral atoms derived from SO_2 constituents. These gases and plasma accumulate first in tori that drift around Jupiter in the vicinity of Io's orbit at $\approx$5.9 $\mathrm{R_J}$. The plasmas are electromagnetically accelerated to roughly the rotational speed of Jupiter. The

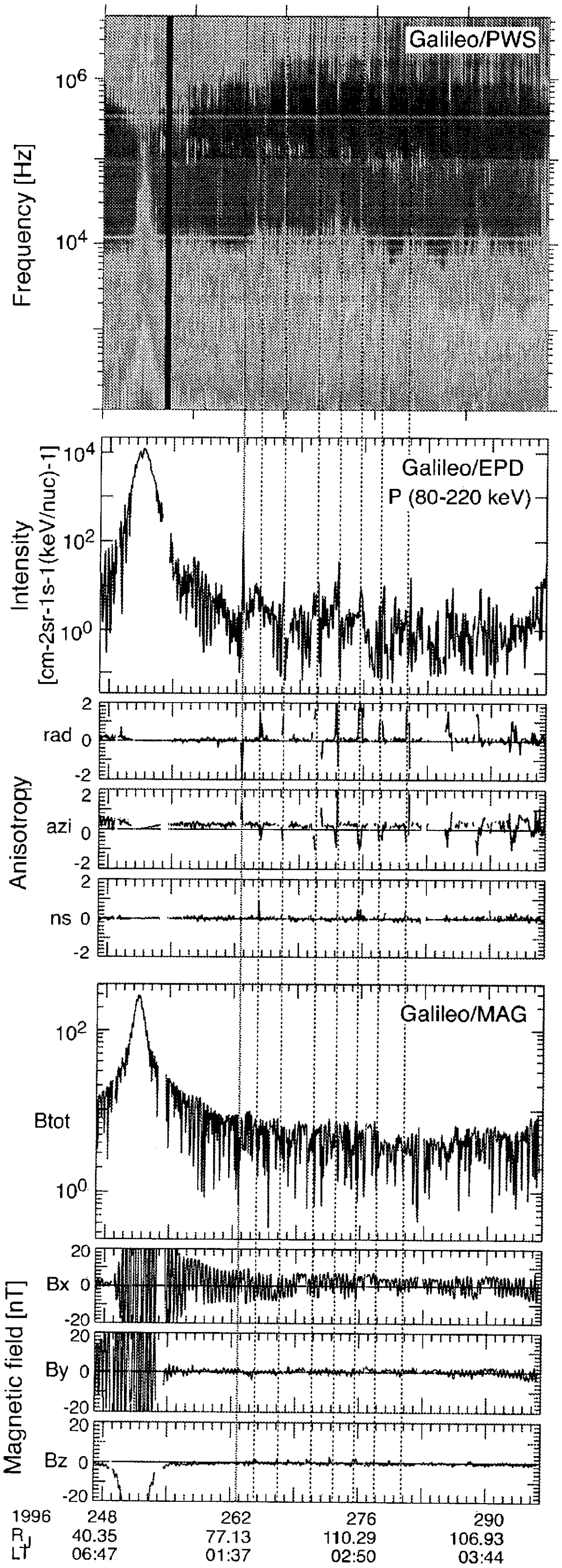

Figure 25.2. Data from *Galileo* orbit G2 inside the jovian magnetosphere. From top to bottom: radio emissions; two-hour averaged intensity and relative anisotropy components of protons (80–220 keV); total magnetic field strength and magnetic field components in the JSE coordinate system (x axis towards the Sun, y axis towards dusk, z axis towards north); date (day of year); radial distance (R_J); solar local time (hour:minute).

gases move in Keplerian orbits distributed around a base orbit established by the motion of Io. The neutral gases are removed in part by being ionized (primarily by electron impact; photoionization is mostly negligible) and thus added to the plasma and in part by undergoing charge-exchange collisions with the ions (Lagg *et al.* 1998), resulting in a wind of energetic neutral atoms leaving the Io region which have been observed directly by the neutral-particle detector on board the *Cassini* spacecraft (Krimigis *et al.* 2002). The plasmas are removed incrementally via electromagnetic processes that move the plasma slowly outward. Various processes move the plasmas through the quasi-dipolar magnetic configuration between ≈6 and 10 R_J, through the region of transition between ≈10 and 20 R_J, beyond which the neutral sheet magnetic configuration of Jupiter's magnetodisk prevails, and finally through the tens of R_J of Jupiter's rotating magnetodisk to the vicinity of Jupiter's magnetopause and to a region within Jupiter's magnetotail where some plasmas are removed down the tail via large, transient, tailward flows. The plasma transport in all regions appears to involve transient processes. Several such transient processes have been identified in *Galileo* measurements. They may be classified as short-term variations with timescales smaller than or comparable to the 10-hour planetary rotation period (plasma interchange events occurring over tens of minutes and observed mostly in the quasi-dipolar regions, and hot plasma injections occurring on an hour timescale and observed mostly in the transition region) and as long-term variations with characteristic periods much longer than 10 hours (global reconfiguration events occurring on a timescale of days and observed mostly in the magnetodisk regions and beyond, and tailward flow bursts observed deep within the magnetotail and accompanying the global reconfiguration events).

25.3 SHORT-TERM VARIATIONS

25.3.1 Plasma Interchange

The need to transport the plasma outward through the various regions, including the quasi-dipolar regions between ≈6 and 10 R_J where the deformation of the magnetic field by plasma forces is relatively small (e.g., Mauk *et al.* 1996), together with the condition that only plasma but no net magnetic flux is to be removed, implies that only interchange motions can be considered for the transport process. These are motions of circulation of entire flux tubes of plasma, without any significant change of magnetic field configuration. In the context of magnetospheric physics, interchange motions were proposed by Gold (1959), the paper in which the term "magnetosphere" was first used; magnetospheric convection (Axford and Hines 1961) was one of the first examples where the concept was applied. Solar wind driven magnetospheric convection of the terrestrial type is not thought to be important at Jupiter (see Chapter 24), and interchange motions producing the plasma transport are generally assumed to be random, relatively small-scale circulations, arising out of an instability driven by centrifugal stresses of the corotating plasma. This mechanism, first proposed for Jupiter by Ioannidis and Brice (1971), has been studied by many authors (Siscoe *et al.* 1981, Siscoe and Summers 1981, Southwood and Kivelson 1987, 1989, Yang *et al.* 1994, and others).

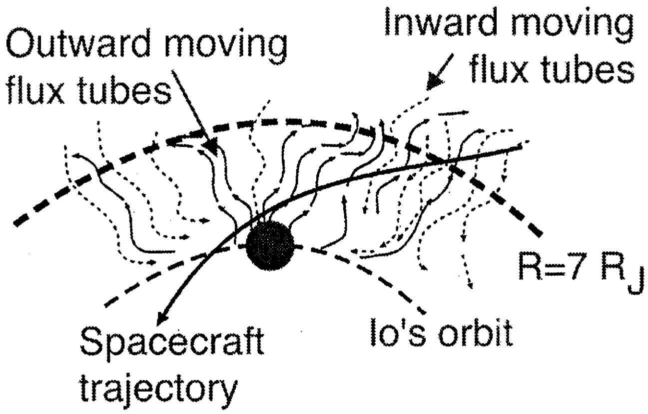

Figure 25.3. Sketch of plasma transport due to interchange notions involving outward- and inward-moving flux tubes in the vicinity of Io (adapted from Kivelson *et al.* 1997).

The centrifugal interchange instability is similar to the Rayleigh–Taylor instability that occurs when a dense fluid is resting on top of a light fluid within a gravitational field. For the Io plasma transport situation, the centripetal acceleration associated with Jupiter's rapid rotation takes the place of the gravitational field. The cool and dense torus plasma plays the role of the heavy fluid, while the magnetic field plays the role of the light fluid. In the simplest case of a cold plasma (when the thermal energy is small compared to kinetic energy of corotation) the condition for instability is that the plasma content per unit magnetic flux decrease outward. The Io plasma torus has its maximum flux tube plasma content approximately at Io's orbit: it is thus unstable at larger distances and stable at its inner edge. Figure 25.3 shows a simplified sketch of the plasma transport near Io due to interchange motion. There are both outward-moving (more dense) and inward-moving (less dense) flux tubes, which could be detected by a spacecraft passing through this region. If the mass input occurs primarily near Io itself (a plausible but still controversial hypothesis), outward moving flux tubes may predominate within about 2 R_J of Io.

The transport resulting from the instability can be described, on the average, by a diffusion equation with diffusion coefficient $D \approx \lambda^2/\tau$, where λ is the typical length scale of the circulating interchange motions and τ the timescale of circulation. The transport is always in the direction of decreasing density; thus the cool and dense torus plasma produced near Io diffuses outward, while a hot but sparse plasma with much higher particle energies produced (presumably) by acceleration processes in the middle and /or outer regions diffuses planetward. The mean timescale of the plasma transport (in most cases much longer than τ) can be determined empirically by dividing the observed mass of the torus by the observed mass input rate (see Chapter 23) and is found to be quite long, about 50 days or 120 Jupiter rotations. This long timescale implies that the mean transport speed is correspondingly slow and hence difficult to observe.

There has been much controversy about the plasma interchange process near Io. Estimating the circulation or overturning time τ is rather straightforward (Siscoe and Summers 1981, Vasyliunas 1994): τ is somewhat longer than Jupiter's rotation period and depends on ionospheric conductivity and mean radial gradient of plasma content but not on the length scale λ. Estimating λ, on the other hand, has proved quite intractable, theory providing no basis for choosing any particular scale out of the entire range from $<R_J$ (the effective thickness of the Io source region) to R, the radial distance itself (for $\lambda \sim$ R the flow turns into the two-cell circulation pattern known as corotating convection (Hill *et al.* 1983, Vasyliunas 1983). Neither has there been agreement on the shape of the interchange flow patterns. Suggested shapes include quasi-circular eddies (Siscoe and Summers 1981), radially elongated "fingers" (Yang *et al.* 1994), and "droplets" of high plasma density drifting outward within a less dense quasi-uniform background (Pontius *et al.* 1986). Since the interchange motions involve entire flux tubes and preserve the plasma content per unit magnetic flux, it was expected that outward-moving or inward-moving plasma elements would preserve the initial high or low density of their respective source region, and therefore the density values observed by a spacecraft should fluctuate between high and low on a timescale of order $\lambda/\Omega R$. The *Voyager* plasma sensor, however, recorded only a smooth density profile, with no indication of the anticipated fluctuations (Richardson and McNutt 1987). Their absence led to suggestions that the anticipated fine structure could be smoothed by simultaneously acting microdiffusion processes (Pontius and Hill 1989) or, alternatively, by repeated splitting in the random eddy flow combined with smoothing by energy-dependent drifts (Vasyliunas 1989).

One of the exciting outcomes of the *Galileo* fields and particle investigations of Jupiter is the discovery of what may be, at long last, direct evidence for the occurrence of plasma interchange near Io (Bolton *et al.* 1997, Kivelson *et al.* 1997, Thorne *et al.* 1997): the observation of short-lived (as seen from the spacecraft) events of reduced plasma density, increased magnetic field strength, and (inferred) rapid flow toward Jupiter.

All this suggests an interchange flow pattern complementary to the "droplet" model of Pontius *et al.* (1986): small "droplets" of low-density plasma drifting inward within a dense quasi-uniform background (this complementary picture was in fact also described by Pontius *et al.* 1986). An example is the event associated with the spike in phase space densities observed around 17:34 UT during the inbound leg of the first Io encounter of the *Galileo* spacecraft in December 1995 (see Figure 25.4).

A small-scale magnetic flux tube of hot energetic particles, associated with a step-like increase in the magnetic field magnitude was inferred (based on energetic particle phase-space-density analysis) to have moved planetward at a speed of $\approx$100 km s^{-1} over a distance of $\approx$0.3 R_J to its observed radial position at $\approx$6.03 R_J(Thorne *et al.* 1997). This scenario is supported by the disappearance of ion cyclotron waves (sinusoidal fluctuations in the radial and north–south components of the magnetic field) which are normally present in Io's vicinity. Pressure-balance arguments associated with the magnetic field strength increase imply that the flux tube was nearly empty of the dense torus plasmas. *Galileo* observed many such events during the same pass to Jupiter's inner regions and during other passes as well. The duration was 26 s on average from magnetometer measurements and

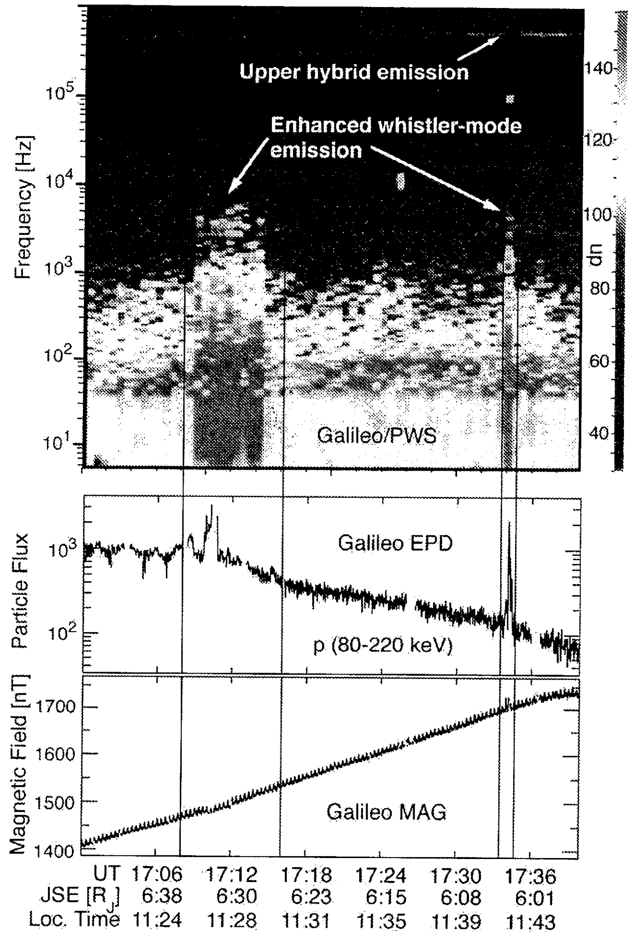

Figure 25.4. *Galileo* measurements of interchange events close to the moon Io. From top to bottom: Observation from the plasma wave subsystem (PWS), fluxes of protons (80–220 keV) measured by the Energetic Particles Detector (EPD) and total magnetic field strength from the magnetometer MAG onboard *Galileo*. The two shaded regions indicate the periods where whistler mode enhancements together with changes in particle and field data have been observed. The small spike marked by an arrow corresponds to the peak in the phase space density (Figure 25.5).

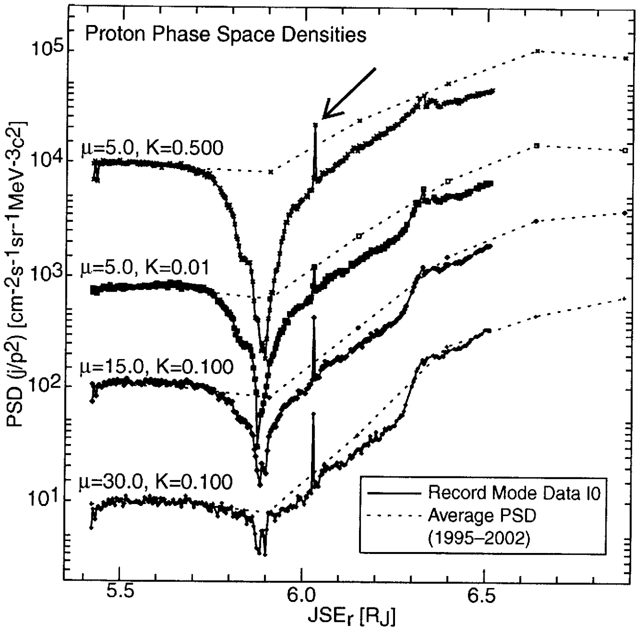

Figure 25.5. Phase space densities (PSD) of protons as derived from *Galileo* energetic particle measurements. The various curves for each of the selected channels represent PSD measurements from fixed μ and K values. Dotted lines indicate the mission-long time and longitude average of the PSD profile over the localized deep decrease associated with absorption by Io. The arrow indicates a prominent example of an interchange event near Io in 1995, where the PSD at a distance of 6.03 R_J is as high as normally at 6.3 R_J, indicative of inward transported plasma.

the average change in magnetic field magnitude was 15.8 nT (Kivelson *et al.* 1997).

The torus plasmas, which deviate by ~4% from rigid corotation with Jupiter out to a radial distance of ≈7 R_J and to be slower at greater radial distances (see Chapter 23), exhibited fluctuations of the bulk ion speeds and densities superposed upon the general pattern of corotation; qualitatively, these fluctuations are suggestive of interchange of magnetic flux tubes in the plasma torus (Frank and Paterson 2000).

Another indicator for interchange events, besides magnetic field and wave emissions measurements, is the variation in phase space density, f, the number of particles per unit volume and momentum space. A natural set of variables describing the phase space density are the three adiabatic invariants, μ, K and L. This set of variables is determined by the three dominant timescales for the motion of a charged particle in a magnetic field: the gyration, the bounce period and the gradient-curvature drift period. For interchange motions, μ and K are constant and the phase space density averaged over all longitudes obeys a radial diffusion equation, dependent only on the L-diffusion coefficient D_{LL} and on the sources S and sinks Q:

$$\frac{\partial f}{\partial t} = L^2 \frac{\partial}{\partial L}\left(\frac{D_{LL}(L)}{L^2}\frac{\partial f}{\partial L}\right) + Q - S \qquad (25.1)$$

in which L is the generalized L-value, defining the radial distance to the equatorial points of a particle's drift shell if all non-dipolar perturbations of the trapping field are adiabatically turned off (Roederer 1970). Figure 25.5 shows the phase space densities derived for energetic protons in the energy range from 42 to 1040 keV for different values of the first and second adiabatic invariant μ and K, defined as follows:

$$\mu = \frac{p_\perp^2}{2\,m_0\,B} \qquad (25.2)$$

$$K = \int_{s_1}^{s_2} (B_\mathrm{m} - B)^{1/2} \mathrm{d}s \qquad (25.3)$$

where $p_\perp$ is the momentum of the charged particle perpendicular to the magnetic field direction, m_0 the rest mass of the particle, B (B_m) the magnetic field magnitude (at the mirror point), and ds the element of arc length along the field line. The phase space densities for protons of different energies (μ-values) and pitch angles (K-value) show a gradual decrease with decreasing distance in the Io torus, indicating that particles at these energies, unlike the bulk of the plasma, have their source at larger distances and are diffusing inward. The large drop near Io itself is due to localized absorption which is not described by the longitude-averaged equation (25.25.1). The dotted line in Figure 25.5 represents the mission-long average of the phase space density for these distances. The observed radial gradient is roughly consistent with a diffusion coefficient of $D_{LL} \approx 2.1 \times 10^{-6}$ R$_J$ s^{-1} at 6 R$_J$ and a power-law dependence of D_{LL} ($D_{LL}(L) = D_0 L^n$, $n \approx 2$ to 4).

Not all mysteries concerning near-Io transport have been solved with the discovery of plasma interchange events. The short observed timescale of the events reflects simply the small spatial scale of structures carried past the spacecraft by the corotating plasma; the intrinsic timescale of the events remains unknown. The evidence that these are *some* type of interchange motions is strong, but whether these are *the* interchange motions responsible for the plasma transport remains to be proved; it has not yet been quantitatively established that they are sufficient to transport plasma at the needed rate. Small-scale flux tubes of inward-moving hot plasmas have been observed, but the compensating flow of outward-moving cool plasmas has not been identified. The spatial scale of outward flow regions is expected to be complementary to the inward-moving small flux tubes, filling the separation between them, hence large; the expected outward flow velocity is correspondingly slow and probably unobservable.

25.3.2 Injection Events

Beyond ≈9 R$_J$, a somewhat different transient phenomenon is commonly observed (Mauk *et al.* 1998, 1999). Figure 25.6 shows an example.

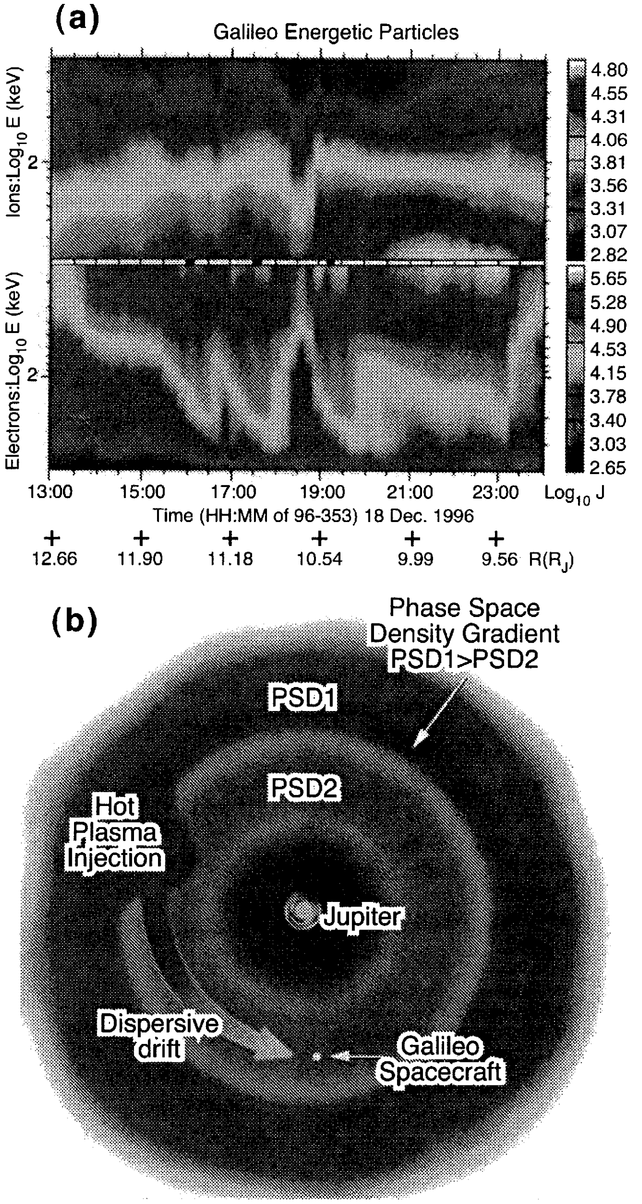

Figure 25.6. (a) Energy–time–intensity spectrogram of energetic ions (top) and electrons (bottom) showing 3 energy dispersed electron injections observed by *Galileo* near 16:00, 17:30, and 19:30 UT. After Mauk *et al.* (1998); (b) Conceptual model for explaining energetic charged particle injections signatures observed by *Galileo*. After Mauk *et al.* (1998). (See accompanying CD for color version.)

The events are called plasma "injections" because they are quite similar in appearance to what are called injections observed within the Earth's middle magnetosphere. Transient (≈1 hour) enhancements in intensity are observed in the electron portion of this energy–time–intensity spectrogram with energy-dispersed characteristics. Specifically, lower energies arrive at the spacecraft before the higher energies do. Figure 25.6b shows an interpretation of the events. At first, hot plasmas are quickly displaced planetward over a confined region of azimuth. These hot plasmas then rotate around with Jupiter in an energy-dispersed fashion. The motion is energy dispersed because the energy-dependent magnetic gradient and curvature drifts act in addition to the dominant $E \times B$ drift of rotational flow. Ions are also injected with the electrons, and dispersed ion signatures are sometimes observed (with higher energy ions arriving prior to the arrival of the lower energy ions). However, the ion signatures are often not observed because: (1) the radial gradient of the ion phase space density is substantially smaller than that of the electrons, yielding low-contrast ion events, and (2) multiple ionic charge states can smear the distinctiveness of the injection signatures because the drift rates depend on charge. Quantitative dispersion analysis of >100 injection events reveals that injections occur at all System III longitudes and all local times. The absence of a preferred local time makes these injections fundamentally distinct from injections observed in Earth's magnetosphere. At Earth, local-time ordering points to an origin in the magnetotail, hence associated with magnetic field lines stretched out by action of the solar wind. By contrast, injections at Jupiter are associated with the magnetodisk, whose field lines are stretched out predominantly by planetary rotation.

Injections constitute a transport process that, in a large-scale average sense, constitutes radial diffusion and may be able to account for the needed motion of Io-generated (iogenic) plasmas through the transition zone (10–20 R$_J$). While injections are observed to transport mostly hot plasmas towards Jupiter, they must be accompanied by a balancing flow away from Jupiter in adjacent regions, in order not to produce a net radial transport of magnetic flux. This outward flow will be largely that of cool iogenic plasmas, simply because their density per unit magnetic flux increases with decreasing distance from Jupiter. (The radial motions themselves are predominantly E×B drifts and thus act equally on all plasmas, hot and cool.)

The radial displacement δL of hot plasmas during the injections can be estimated by considering the motion of the hot plasmas and the intensity contrast between injected electrons and adjacent electron populations, together with estimates of radial phase-space density gradients (Ye and Armstrong 1993), to obtain values of $\approx$1 to several $\mathrm{R_J}$ at $\approx$12 $\mathrm{R_J}$; we adopt $\delta L \approx 2\ \mathrm{R_J}$ as typical. The azimuthal extent of individual injections is $\delta\phi \approx 36°$. The occurrence rate is $\nu \approx 5$ injections/day during moderately active periods (6 times fewer than was observed during a "storm"). The corresponding parameters for the associated regions of outward flow are not known, but the product $\delta L \delta\phi \nu$ must have the same value in order to have no net transport of magnetic flux. Then the average radial "diffusion" velocity describing the net transport of all hot plasmas at a given radial distance (12 $\mathrm{R_J}$) may be estimated as

$$V_\mathrm{D} \approx \delta L \cdot (\delta\phi/2\pi) \cdot \nu \cdot (\delta n/n) \tag{25.4}$$

where $\delta n/n$ is the fractional excess of hot plasma in the injection compared to outflow regions, which can be related to the average spatial gradient of the phase space density f of the hot particles:

$$\delta n/n \approx \delta L\ \partial \log f/\partial L \tag{25.5}$$

The diffusion velocity can be related to the radial diffusion coefficient (D_{LL}) by the expression

$$V_\mathrm{D} \approx D_{LL}\ \partial \log f/\partial L \tag{25.6}$$

Equations (25.25.4) to (25.25.6) provide an expression for the radial diffusion coefficient:

$$D_{LL} \approx \nu\ (\delta L)^2\ (\delta\phi/2\pi) \approx 10^{-5}\ \mathrm{R_J}^2\ \mathrm{s}^{-1} \tag{25.7}$$

This value of D_{LL} at $\approx$ 12 $\mathrm{R_J}$ estimated from injections is comparable to the upper limit value provided by Gehrels and Stone (1983), who combined results from the analysis of outward diffusing cool plasmas and inward diffusing hot plasmas.

The relationship, if any, between injections in the transition region and plasma interchange events in the dipolar regions is not known. Interchange-like events have been observed in an environment where the dispersive signatures of injections were also present ($\approx$11 $\mathrm{R_J}$). Thus, these two phenomena may be aspects of the same process. However, the typical characteristic scale size for injections ($\approx$36° of azimuth at $\approx$12 $\mathrm{R_J}$) is substantially larger than that of identified interchange events (<several degrees). Also, both types of events have narrow inward-flow regions with high flow speed, presumably balanced by (unobserved) broad regions of very slow outward flow, in contrast to theoretical models of interchange which usually (Yang *et al.* 1994) assume the inward and outward flow regions to be of comparable width and with about the same slow speed. Relevant in this connection is the speculative idea that injections at Jupiter may be similar to injection phenomena at Earth in that they may involve the storage and release of magnetic energies, a process that could substantially speed up the injection process. In the transition region, beyond $\approx$10 $\mathrm{R_J}$, particle energy densities are comparable to magnetic energy densities (Mauk *et al.* 1996), and large distortions of the field by the plasma are possible. A process analogous to the magnetospheric substorm (with its associated injections events) at Earth can then be envisaged: stress builds up within a stretched magnetic field configuration, only to be suddenly released by the sudden onset of some instability and/or stress imbalance (whose occurrence at Earth is unquestioned, although its nature is the subject of intense controversy (Baker *et al.* 1999, Lui 2000). To date, however, this speculative relationship between magnetic variations (dipolarization of field lines) and hot plasma injections has not been established.

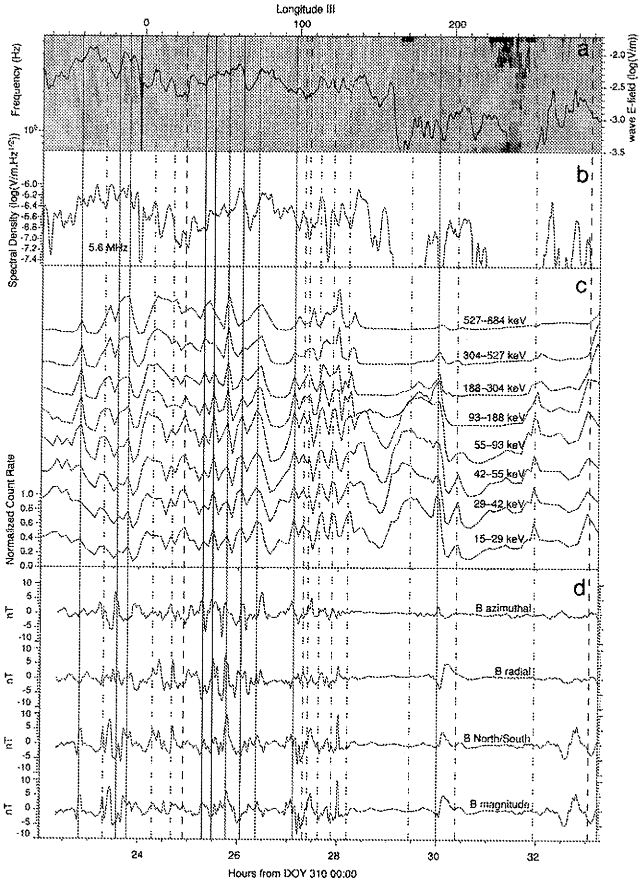

Figure 25.7. Wave, energetic particle, and magnetic field measurements during several injection events in the jovian magnetosphere as observed onboard the *Galileo* spacecraft on day 310 in 1996. From top to bottom: wave dynamic spectra (0.7–5.6 MHz) and corresponding integrated electric field (black line); wave spectral density at 5.6 MHz; normalized energetic electron rates (20–800 keV); components and magnitude of the fluctuating magnetic field. The vertical lines correspond to dispersionless (solid line) and weakly dispersed (dashed lines) injections. After Louarn *et al.* (2001).

It has been reported that injections can be highly clustered in time over many hours for periods of time referred to as "storms" by Mauk *et al.* (1999). Figure 25.7 shows wave and particle measurements from the *Galileo* spacecraft during a whole series of injection events (Louarn *et al.* 2001).

Louarn *et al.* (2001) could show that these injections were associated with the development of an instability in the external part of the Io torus, leading to the generation of periodic fluctuations (18 minutes) in particle intensities and radio emissions. Fluctuations of this kind are also observed at Earth during large-scale magnetospheric disturbances (Pi-pulsations) such as substorms. Injections found by Louarn *et al.* (2001) had the same signature in radio emissions as the quasi-periodic flow bursts of Krupp *et al.* (1998) which will be discussed below. Thus, clustered injections would appear to be the inner-magnetosphere signature of the more global reconfiguration events in the middle and outer part of the magnetosphere.

The joint observation campaign between *Galileo*, *Cassini*, *Hubble*, and *Chandra* observations in 2000/2001, when *Cassini* was flying past Jupiter, has shed new light on our understanding of these injection events and their relationship to phenomena in the aurora. Mauk *et al.* (2002) have found a direct connection between electron injection events (similar to those shown in Figure 25.6) observed by *Galileo* deep in the inner jovian magnetosphere at 10–13 R_J and transient auroral features observed in the northern polar region of Jupiter. Also, results from the joint campaign have provided strong evidence that compressions of the magnetosphere caused by interplanetary shocks triggered intensified hectometric and UV emissions in the aurora (Gurnett *et al.* 2002). This complicates the question of the analogy between injection events at Earth (powered, ultimately, by the flow of the solar wind) and at Jupiter (whose dominant energy source is believed to be the rotation of the planet itself).

25.3.3 ULF Waves in Jupiter's Magnetosphere

Waves communicate stresses between various regions of the magnetosphere–ionosphere space. Studies from the Earth's magnetosphere (see Samson 1991 for a review) show that, as for most magnetospheric processes, the energy for the MHD waves is ultimately derived from the solar wind. In the Earth's magnetosphere, the waves are classified as continuous if they are regular in appearance and are further subdivided into bands (Pc1 through Pc5) depending on the period of the waves (starting at 0.2–5 s for Pc1 through 150–600 s for Pc5). The irregular impulsive type of pulsations are designated by the title Pi and are further subdivided into two categories, Pi1 (1–40 s) and Pi2 (40–150 s). This purely morphological classification lends itself nicely to understanding the waves with regard to their sources. For example, it is found that the impulsive pulsations are excited by many transient phenomena such as sudden impulses, flux transfer events, and changes in magnetospheric convection. On the other hand, the continuous pulsations in the high-frequency wave band are generally caused by ion cyclotron instabilities in the magnetosphere. In the middle band, the continuous pulsations are associated with ion cyclotron instabilities in the solar wind, and in the lowest frequency band the waves are excited mainly by the drift-mirror instability (which derives its energy from the pitch angle anisotropy of particle distributions) and the Kelvin-Helmholtz instability (caused by shear flows). One of the earliest studies of ULF waves in Jupiter's magnetosphere (Kivelson 1976) showed that the wave power reached its maximum just inside the dayside magnetopause and during current sheet crossings. Khurana and Kivelson (1989) extended these results and showed that, in the middle magnetosphere, magnetic and thermal pressure perturbations were anticorrelated and the growth of the compressional waves occurred mainly because of the drift-mirror instability similar to the situation at the Earth. They also showed that the amplitude A of the transverse component reached its maximum in the current sheet because of two factors – symmetry of the wave mode along the field line implies an antinode near the magnetic equator, and conservation of energy flux (A^2V_p) enhances the wave amplitude at the center of the current sheet where the group velocity of the wave is minimum. Glassmeier (1995) has suggested that the ultimate source of power for waves in Jupiter's magnetosphere is the rotational energy of the planet. Io's torus, because of its low Alfvén velocity, acts as a wave-guide in which the waves become trapped (Glassmeier *et al.* 1989). In addition, the toroidal and poloidal components of the waves are decoupled, allowing the radial and azimuthal components of the field perturbation to have different frequencies and amplitudes (Glassmeier *et al.* 1989). Tsurutani *et al.* (1993) summarized the wave observations in magnetic field data during the *Ulysses* flyby in 1992, and Krupp *et al.* (1996) found five-minute waves in magnetic field and particle observations caused most probably by the resonant ion beam instability.

Two investigations of the MHD waves exploited the magnetic field measurements from *Galileo* in detail. Wilson and Dougherty (2000) have extended the analysis of Khurana and Kivelson (1989) to the nightside and showed that waves on the nightside have characteristics similar to those found on the dayside, suggesting that the ULF waves are a global phenomenon. Russell *et al.* (2001) have analyzed the effects of ULF waves on the diffusion of plasma by studying the pitch angle scattering of ions in the inner and middle magnetosphere. They showed that the amplitude of the transverse magnetic perturbations normalized to the magnetic field strength increases monotonically with the radial distance. As a result, the pitch angle diffusion coefficient increases from a value of $10^{-6}\mathrm{rad}^2\mathrm{s}^{-1}$ near 10 R_J to $5 \times 10^{-3}\mathrm{rad}^2\ \mathrm{s}^{-1}$ near 25 R_J. Thus, the time for particles to diffuse into the loss cone is about 1 month in the inner magnetosphere and falls to a value of a few hours in the middle magnetosphere. Russell *et al.* (2001) argue, however, that because of the extremely large lengths of the flux tubes and the relatively large outflow rates, most of the plasma in Jupiter's magnetosphere remains stably trapped and is close to the strong diffusion limit.

Jupiter's magnetosphere shows interesting phenomena on all different scales. The magnetic field measurements of the *Galileo* spacecraft contain, for example, on top of the large-scale background magnetic field, small-scale features with amplitudes of a few nT on timescales of minutes and tens of minutes. Saur *et al.* (2003) interpreted these fluctuations in Jupiter's middle magnetosphere as weak MHD turbulence and found for the power spectrum of the fluctuations parallel to the background field a spectral index of minus two in agreement with theoretical predictions by Galtier *et al.* (2000). These small-scale fluctuations might play an important role for transport processes in the magnetosphere. For example, Joule dissipation of these fluctuations at the presence of a net background electric current system (Hill 1979, 2001, Cowley and Bunce 2001) leads to parallel electric fields that can accelerate electrons to produce Jupiter's main auroral oval.

25.3.4 40- to 80-Minute Periodicities

During the *Ulysses* encounter with Jupiter in 1992 impulsive and sometimes quasi-periodic increases in electron intensity throughout the dusk side magnetosphere were observed (Simpson *et al.* 1992). Some of them were correlated with hot plasma bursts and radio emissions. The electron bursts show an outward directed anisotropy and are more intense in energies above a few MeV. The energy spectrum hardens considerably during the bursts. In a statistical analysis of *Ulysses* high-energy electron data, over a hundred bursts lasting longer than one minute were found on the outbound pass of *Ulysses*, when the spacecraft passed through high-latitude field lines in the southern hemisphere. From the rapid onset of the bursts the authors concluded that they were produced by quasi-periodic explosive magnetic merging processes. *Galileo* particle and field data have now confirmed that 40-min fluctuations are also present in the equatorial plane (Wilson and Dougherty 2000) and are not restricted to the dusk side. These periodicities have been observed throughout the magnetosphere in magnetic field, particle and wave data. Relativistic electrons have been observed maintaining a 40-minute intensity variation over nearly half a jovian rotation in the high-latitude dusk region of the jovian magnetosphere, suggesting that a global resonance phenomenon may be involved (McKibben *et al.* 1993). Periodic 40 and 60-minute variations in electron intensity were measured onboard *Cassini* and *Galileo* when both spacecraft were close to the dusk magnetopause (see below), indicative of a global phenomenon. It has been reported that the source of the 40-minute radio bursts is in the polar region of the magnetosphere (MacDowall *et al.* 1993). One possible emission mechanism is the electron cyclotron maser instability (for details see Wu and Lee (1979)). It is therefore possible that 40-min variations observed in the magnetosphere and close to the magnetopause are related to radio phenomena (MacDowall *et al.* 1993, Kaiser *et al.* 2001), magnetic field variations, solar wind velocity, and possibly also to X-ray emissions inside the northern auroral oval observed by Chandra (Gladstone *et al.* 2002). Furthermore, Anagnostopoulos *et al.* (1998) found that even energetic ion events upstream of the jovian bow shock (see below) showed this periodicity. Hence, 40 minutes appears to be an important period in the jovian magnetosphere, but what produces this period is not yet established.

25.4 LONG-TERM VARIATIONS

In addition to these rather short-term variations and fluctuations in the jovian system, longer periodicities in various magnetospheric parameters have been detected. They range from spin-periodic variations of ≈5 and 10 hours to periods of days or longer.

25.4.1 Phenomena at the Planetary Spin Period

A particularly intriguing aspect of Jupiter's magnetosphere is its pulsar-like behaviour, the rotational modulation of various magnetospheric emissions. Modulation at the spin period of the central object (≈10 hours in the case of Jupiter) is the defining property of a pulsar in the astrophysical sense (Hill and Dessler 1995). This variability of the jovian system was first detected in ground-based observations of jovian radio emissions. It was found that the plane of linear polarization of decametric emissions rocks sinusoidally by about ± 10° as the planet rotates and that their intensity varies with the same period. These observations provided in fact the first determination both of the true rotation period of the planet (System III, as distinct from the rotation periods of various cloud structures) and of the tilt angle between the rotation axis and the magnetic dipole moment. Other modulated emissions have since been observed in the ultraviolet, infrared, and optical wavelength ranges. Most of them originate in the Io torus, and their properties (including time variations more complex than simple System III periodic modulation) are described in Chapter 23. Relativistic electrons ejected from Jupiter's magnetosphere and observed in interplanetary space also exhibit a modulation at Jupiter's rotation period, as discussed below.

There are two basic mechanisms of spin modulation by a rotating object. One is the "rotating-beacon" type, where an azimuthally asymmetric structure fixed to the object sweeps past the observer; the modulation is at the rotation period relative to the observer's frame of reference (and would disappear in a corotating frame). The other is the "flashing-light" type, where there is an intrinsic (frame-independent) temporal variation which can only arise from an interaction between an azimuthally asymmetric rotating object and an azimuthally asymmetric fixed structure.

At Jupiter, the 9.6° tilt between the magnetic dipole and the rotation axis is the source of the azimuthal asymmetry that produces the "rotating-beacon" modulation. Geometrically, the near-equatorial current sheet is attached to the tilted dipole and wobbles as the dipole rotates. As long as the associated plasmasheet corotates rigidly with the planet, the wobble is rigid. Beyond ≈20 R_J, where the plasma flow is subcorotational, the plasma/current sheet oscillates about the rotational equator as a surface wave that propagates outward in a spiral pattern. The effective propagation speed was initially estimated as 840 km s^{-1} or 43 R_J hr^{-1} (Kivelson *et al.* 1978); more recent estimates, based on *Galileo* observations, are described in Chapter 24, together with other properties of the current sheet configuration. The expected periodicity and phase depend on the location of the observer. In the rotational equator, the center of the plasma-sheet crosses over the observer twice per rotation, at equidistant time intervals. With increasing vertical distance, the two crossings per rotation occur closer and closer together, merging finally into one crossing and then disappearing altogether as the observer moves beyond the amplitude of the wavy motion. The phase delay relative to rigid corotation increases with increasing radial distance.

Most of the periodic variations in the jovian magnetosphere of quantities measured in situ, such as plasma, energetic particle intensity, and magnetic field, are explained by the wobble and the wavy motion of the plasma and current sheet, due account being taken of the dependence on spacecraft location as described above. Maxima in plasma and energetic particle intensities and reversals of the radial and azimuthal magnetic field components occur as the center of the plasmasheet is crossed; minima of the particle intensities are observed at high latitudes, far away from the

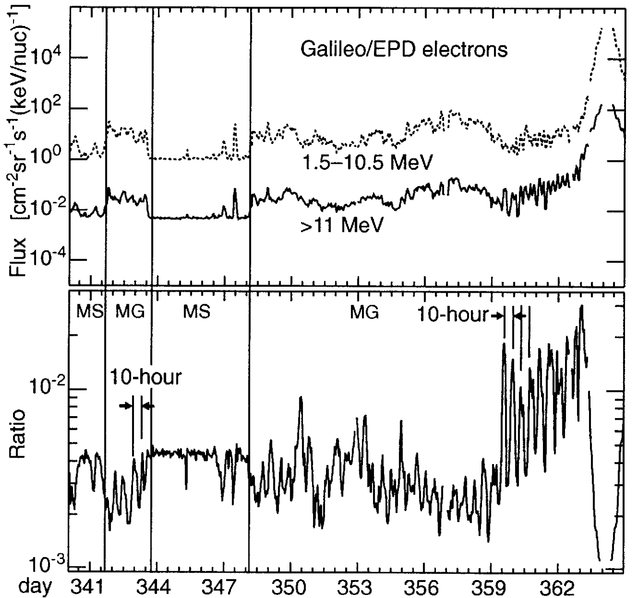

Figure 25.8. Intensities of electrons in two energy bands (1.5–10.5 MeV and >11 MeV) (top) and their ratio (bottom panel) measured on *Galileo* orbit G28 in 2000 through the dusk jovian magnetosphere. Solid lines: bow shock and magnetopause crossings (with magnetosheath, MS, between). Note the pronounced 10-hour modulation of the ratio inside the magnetosphere (MG).

center; energy spectra of energetic ions and electrons are also modulated, in association with the intensity changes.

Jupiter's rotation can also produce "flashing-light" modulation through interaction with the outermost regions of the magnetosphere which are strongly asymmetric relative to the (fixed) solar-wind flow direction. Direct evidence for such modulation was provided by relativistic electrons ejected from the magnetosphere of Jupiter but observed far away in interplanetary space, where both their intensity and their energy spectrum are modulated at the jovian rotation period (Simpson 1974, McKibben and Simpson 1974, Chenette *et al.* 1974, Simpson *et al.* 1992, and references therein) which moreover has been shown (from comparison of observations taken several years apart) to be the synodic period (rotation relative to the Sun–Jupiter line) and not the sidereal period (relative to the "fixed" stars). Minimum intensity together with maximum spectral index occurs once per rotation at a fixed phase, which led to the concept of "clock modulation" or "jovian clock:" the injection of relativistic electrons into interplanetary space (as well as possibly, by extension, their acceleration in the outer magnetosphere) may be most efficient when the rotating tilted dipole (like the hand of a clock) is at a particular position relative to the solar wind. The 10-hour "clock" modulation is observed both outside and inside the magnetosphere, and sometimes continues smoothly across the magnetopause. An example from *Galileo* observations is shown in Figure 25.8.

There is at present no well-established theory for the mechanism of the "clock" (and there is some ambiguity in deciding whether 10-hour modulations within the outer magnetosphere are of the flashing-light; i.e., "clock" type, or merely "rotating-beacon" effects far from the center of the plasmasheet). Observations of the modulated relativistic electrons in interplanetary space led directly, however, to the concept of the "active sector" (Vasyliūnas 1975), identified as that range of longitudes that faced toward the jovian magnetotail (where injection is most plausible) at the time of maximum intensity, and to the development of the magnetic anomaly model (see Hill *et al.* 1983, and references therein).

25.4.2 Plasmasheet Dynamics

Large-scale dynamical processes in Jupiter's magnetosphere are evident from the changing motion of the equatorial jovian plasmasheet (inferred from observed timing of crossings, as described in the previous section) at various timescales, as well as from directly observed changes of fields and particles. As an example, Figure 25.9 shows measurements of magnetic field, plasma, and energetic particles on *Galileo*'s orbit G8 (see, e.g., Russell 2001).

Regular changes in the sign of the radial component of the magnetic field indicate crossings of the wavy tilted current sheet. At times during this orbit, however, these regular crossings disappear for several planetary rotations. This suggests long-lasting large-scale displacements of the current sheet from its nominal position centered around the rotational equator, or from its nominal oscillation amplitude, or both. Similar arguments, using plasmasheet crossings deduced from observed keV electron intensities in the jovian magnetotail, were used by Vasyliūnas *et al.* (1997) to infer quasi-periodic plasma sheet displacements on timescales of 5–7 days. Such variations could possibly reflect changes in the solar wind, e.g., dynamic pressure or flow direction, or they could arise from internal changes such as changes in the volcanic activity or the particle source at Io (see Spencer and Schneider (1996) and references therein), or they may be related to global reconfiguration events described below. Other oscillations which can be interpreted as the result of plasmasheet distortions caused by a "flapping" or "warping" motion (Figure 25.10) have been investigated by Lachin (1997), using magnetic field measurements from the *Ulysses* Jupiter flyby in 1992.

In addition to inferences about the changing geometry of the plasmasheet, dynamic events can also be observed directly as changes of particles and field parameters on timescales of days. They seem to be present in large parts of Jupiter's magnetosphere and are often referred to as global reconfiguration events. Examples can be seen in Figure 25.9. Around day 160, the total magnetic field increases rapidly to field strengths higher than in the lobe regions far away from the current sheet, an example of events interpreted by Russell *et al.* (1998) and Russell *et al.* (2000) as large-scale magnetic reconnection events. Also, protons which normally move azimuthally now sporadically change their direction of motion quasi-periodically to radial instead of azimuthal. Global reconfiguration events have been observed predominantly in the magnetodisk regions and beyond. Characteristic of these reconfiguration processes are strong radial flow anisotropies and changes in the energy spectra of energetic particles, polarity changes in the magnetic field north–south component, and associated radio and plasma wave emissions. Figure 25.11 shows examples of quasi-periodic flow bursts (Krupp *et al.* 1998, "radially outward directed

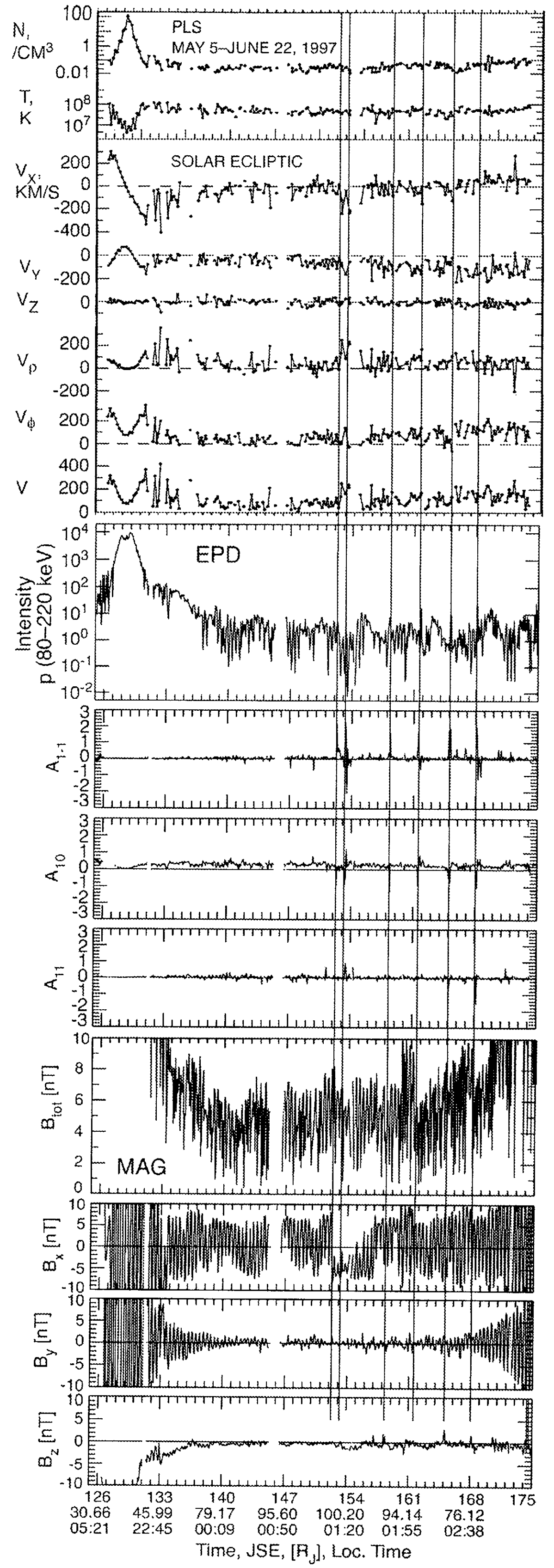

Figure 25.9. Plasma, magnetic field, and energetic particle parameters (80–220 keV) measured during *Galileo*'s orbit G8 in 1997. Magnetic field and plasma measurements adapted from Russell *et al.* (2001) and Frank *et al.* (2002).

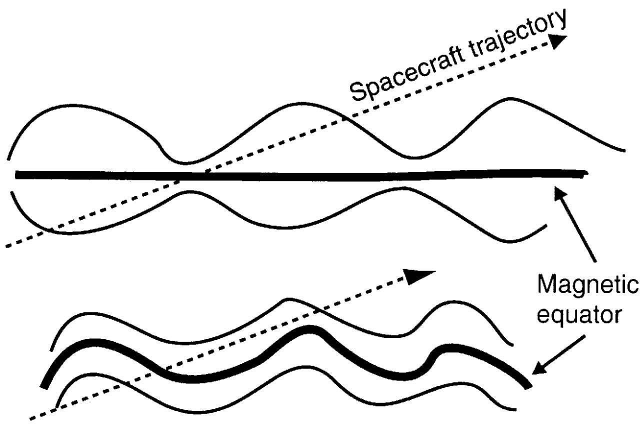

Figure 25.10. Configuration of the jovian plasmasheet proposed by Lachin (1997) to explain some observed field and particle variations.

anisotropies suggesting strongly collimated radial outflowing ion beams") occurring every 2.5–3 days (Woch *et al.* 1998, Krupp *et al.* 1998) in the pre-dawn jovian magnetotail.

Louarn *et al.* (1998, 2000) and Woch *et al.* (1999) demonstrated that the energetic particle bursts are correlated with a variety of radio emission variations, including (a) increases in intensity of hectometric radio emissions which are generated on auroral field lines most likely coupled to the middle magnetosphere (Ladreiter and Leblanc 1989), (b) initiation of a series of narrowband kilometric radiation bursts which originate on the outer edge of the Io torus ($\approx$ 10 R_J) (Kaiser and Desch 1980, Reiner *et al.* 1993), and (c) substantial variations in the low-frequency cut-off of trapped continuum radiation (Gurnett *et al.* 1980) in the intermediate magnetotail, suggestive of a thinning of the plasmasheet. They termed these "energetic magnetospheric events," as encompassing vast expanses of the magnetosphere.

These events are evidence of a major reconfiguration of the jovian magnetotail, possibly related to some not yet fully understood, internally-driven processes within the jovian magnetosphere. Louarn *et al.* (2000) offer a partial interpretation of the energetic magnetospheric events as corresponding to periods of enhanced energy releases by which the magnetosphere redistributes iogenic plasma to the outer magnetosphere: the events commence when the plasmasheet is thin, the density and the thickness of the sheet increase again after a few hours, and the magnetodisc is evacuated back to an unloaded state after a few tens of hours. Woch *et al.* (1998) suggested more specifically that the events are a result of an instability driven by plasma loading of the magnetosphere: as shown in Figure 25.12, there may be two basic states of Jupiter's magnetotail, a stretching phase with plasmasheet thinning and plasmoid release (several days) followed by a dipolarization phase ($\approx$1 to several days). The expansion phase is characterized by a thin plasmasheet with low particle intensities and soft energy spectra, and the dipolarization phase can be described by a thicker plasmasheet, harder spectra and nearly corotational flow of particles.

Reconnection of magnetic field lines in Jupiter's magnetotail (Vasyliunas 1983, Nishida 1983, Russell *et al.* 1998) is at least one of the possible mechanisms to explain the

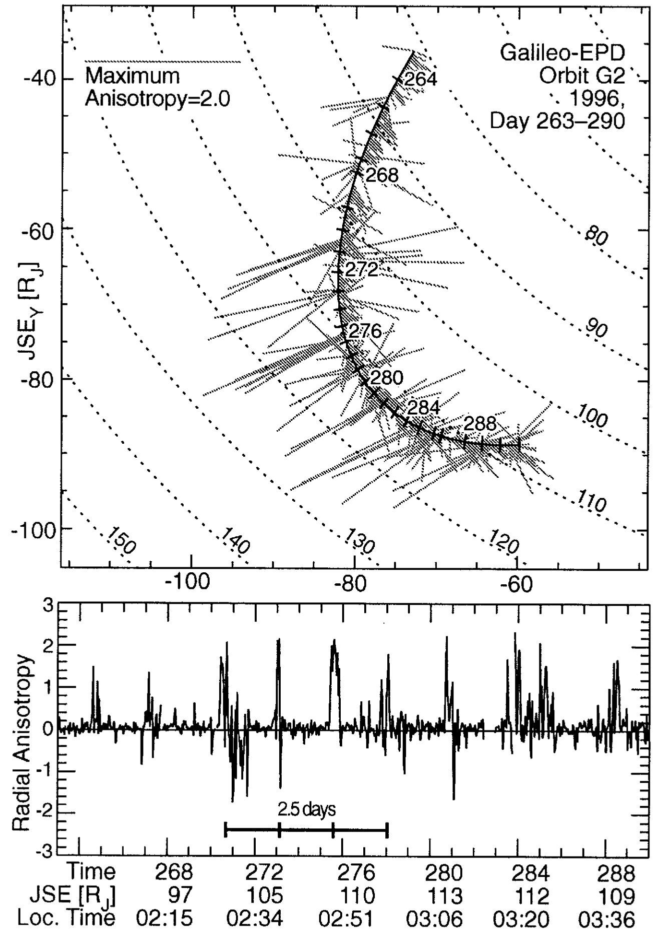

Figure 25.11. First order anisotropy vectors of protons (80–220 keV). Top: Anisotropy vector projected on to Jupiter's equatorial plane (adapted from Krupp *et al.* 1998). The vectors are plotted along the *Galileo* trajectory of orbit G2 in 1996 (days 263–290) in the pre-dawn section of the jovian magnetosphere. Bottom: Radial anisotropy component as a function of time for the same interval shown in the top panel. The 2.5–3-day modulation is very obvious.

observations. In Figure 25.13 three different phases in the magnetic topology during a reconfiguration event are drawn. Planetward of the newly formed x-line the field is pointing in north–south direction; tailward, the situation is reversed and the field points northward. Both situations have been observed during *Galileo*'s orbit G8 (Russell *et al.* 1998). It is obvious that a plasmoid can only be observed directly if the spacecraft is tailward from the x-line location. Similar periodicities of a few days in particle energy spectra and intensities have, however, been observed (Woch *et al.* 1998, Vasyliūnas *et al.* 1997) also without an accompanying flow burst. Whether this indicates thickness changes or displacements of the plasmasheet observed far away from the actual event or, instead, solar wind influence or other external cause of some of the long-term variations unrelated to the events cannot be definitively decided at present.

The two-stage process described above is reminiscent of a magnetospheric substorm at Earth, with its growth (stretching) phase and expansion (dipolarization) phase (Hones 1979, Baker *et al.* 1999), where, however, the plasmoid release is associated with the dipolarization phase, and

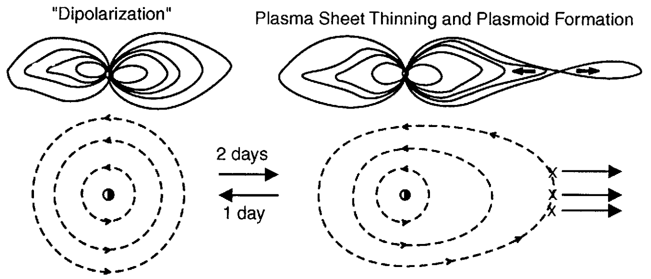

Figure 25.12. Plasma loading in the jovian magnetotail (adapted from Woch *et al.* (1998) from a more dipolar configuration state (left) to a stretched configuration (right)). Top: Field lines in the noon–midnight plane; bottom: Flow pattern in the equatorial plane.

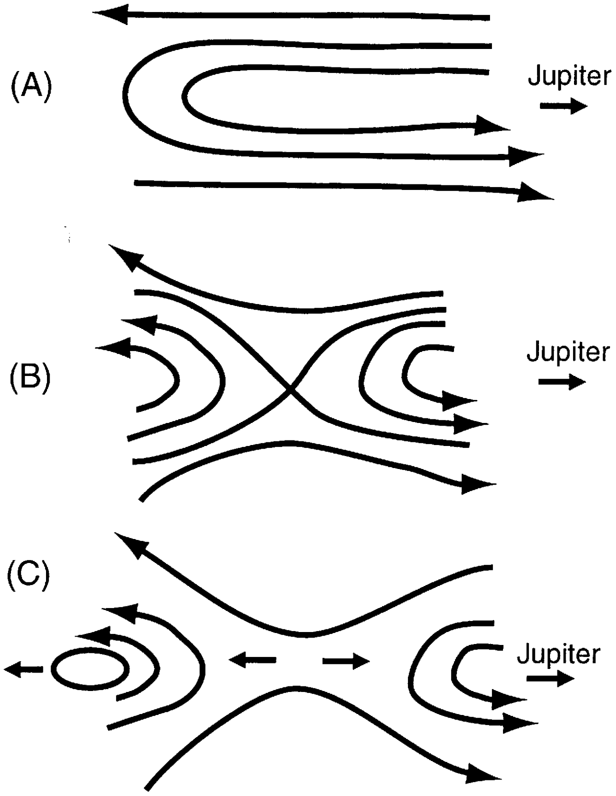

Figure 25.13. Sketch of three phases of the magnetic field topology during a global reconfiguration event: (a) plasmasheet; (b) beginning of plasmoid formation; (c) plasmoid release.

the whole process is strongly influenced by the solar wind and in particular by the north–south component of the interplanetary magnetic field. Louarn *et al.* (1998, 2000), Krupp *et al.* (1998) have drawn analogies between the jovian energetic magnetospheric events and the terrestrial substorms, explaining the instability as one intimately tied to internal processes but not ruling out the possibility that the solar wind plays a role, such as a trigger. Sorting out the influence of the solar wind in these events is difficult because of a lack of a convenient solar wind monitor near Jupiter while *Galileo* is embedded in the magnetosphere. Extrapolation of solar wind conditions from 1 AU is possible but unreliable. Previous studies have shown significant correlations between intensity of jovian radio emissions and solar wind input (Zarka and Genova 1983, Barrow *et al.* 1988, Kaiser 1993, Desch and Barrow 1984, Barrow and Desch 1989, Ladreiter and Leblanc 1989, Barrow *et al.* 1986). A statistical survey of jovian radio emissions indicates that hectometric and low-frequency decametric emissions are more intense and occur more frequently in the midnight sector of the magnetosphere (Menietti *et al.* 1999). Remotely sensed jovian magnetospheric activity is likely to occur in conjunction with solar wind pressure decreases (Southwood and Kivelson 2001). Compressions change the current systems of the magnetosphere and heat the magnetospheric plasma substantially. As a consequence the plasmasheet, at least in the outer and middle magnetosphere, can change its global configuration, as described in Chapter 24. Those regions of the disturbed plasma disk that map into the aurora are also affected, due to changes in the ionosphere–magnetosphere current systems, with the result of intensified radio and ultraviolet auroral emissions (Cowley and Bunce 2001). Gurnett *et al.* (2002) took advantage of *Cassini*'s flyby of Jupiter in late 2000 to show that the solar wind could, indeed, trigger radio emission characteristics such as those reported by Louarn *et al.* (1998, 2000). Furthermore, Gurnett *et al.* (2002) showed that at least during one brightening, the ultraviolet aurora and the integrated intensity of auroral radio emissions were correlated. Such evidence of a solar wind trigger does not preclude strong internal processes as being important, and the jovian energetic magnetospheric events may very well be the result of some complex intermingling of solar wind and internal magnetospheric influences.

Possibly related are the so-called "null fields" that have been observed in magnetic field measurements (Southwood *et al.* 1995, Haynes *et al.* 1994, Leamon *et al.* 1995). These events, characterized by brief sharp decreases in field magnitude, have been explained as detached "blobs" of plasma from the outer edge of the plasmasheet. These blobs could be the result of the internally triggered substorm-like events described above, or else the direct response to a rapid expansion of the magnetosphere due to changes in the solar wind dynamic pressure.

A statistical survey shows that the burst events (defined for this purpose as 30% or more enhancement in magnitude and at least 30° deviation from the average direction), representing 15% of all the flow estimates, are concentrated in the post-midnight tail region (Woch *et al.* 2002). Inward-directed bursts dominate closer to the planet, outward-directed bursts further away from the planet. The transition from mainly inward-directed to mainly outward-directed bursts may be taken as defining a kind of near-Jupiter neutral line at roughly 70 R_J in the pre-dawn region and at 120 R_J around local midnight. Important information on the physical nature of the burst events can be derived from their spatial distribution. Figure 25.14 shows a sketch for characteristic burst locations in the vicinity of an x-line in the jovian magnetotail. Dotted circles represent corotational flow. The bursts are interpreted as deviations from a nominal flow of particles. They are more or less radially outward in the region tailward of an x-line and predominantly towards the planet inside the x-line; the x-line extends from pre-dawn to post-dusk and is located roughly between 70 and 110 R_J.

A clear transition from mainly inward to predominantly outward bursts, embedded in the "normal" corotating flow pattern, occurs at a specific distance. Furthermore, burst events do not seem to be of importance at dusk, at least not at the distances visited by *Galileo*.

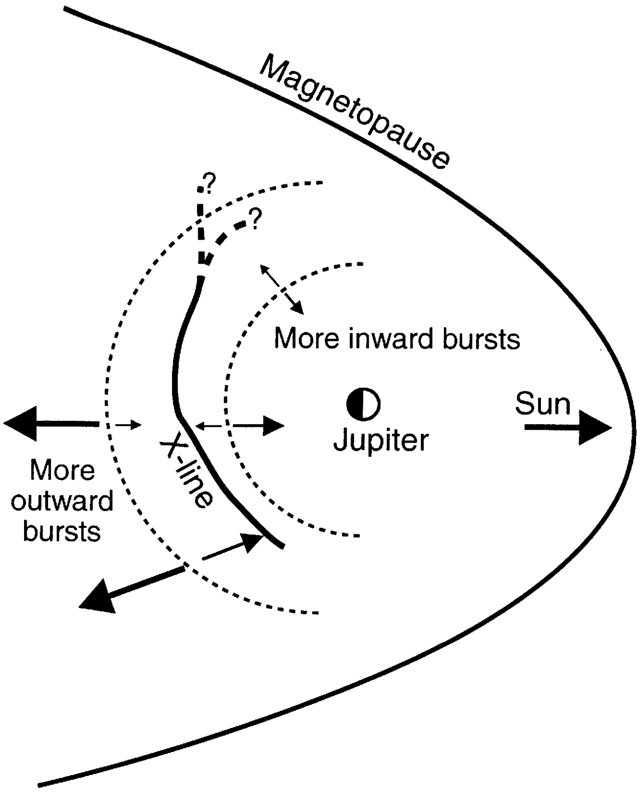

Figure 25.14. Sketch of the location of more frequent radially outward bursts and radially inward bursts in the vicinity of an x-line in the jovian magnetotail. (Adapted from Vasyliunas 1983.)

The above survey suggests that the particle flow burst events may be related to the source process of the auroral dawn storms and auroral flares, observed with the Hubble Space Telescope (Clarke *et al.* 1998, Waite *et al.* 2001). The location of these auroral events is magnetically connected to the dawn sector of the outer magnetosphere at distances larger than 30 R_J. Thus they are closely conjugated to the inward flow burst region. The energy density carried by the inward beams of accelerated particle is too low, however, to account for auroral emissions of the reported extreme intensity, and thus these beams cannot be the direct source of the emissions. However, the dipolarization of the magnetic field in the tail associated with the bursts implies a disruption of the cross-tail current, the current being partly diverted into the ionosphere and, by analogy with auroral substorms at Earth, able to drive intense auroral events. In addition to its fundamental importance for the dynamics of the jovian magnetosphere, this process is a straightforward mechanism to accelerate particles and release them into interplanetary space, constituting a very efficient impulsive source of interplanetary jovian particles.

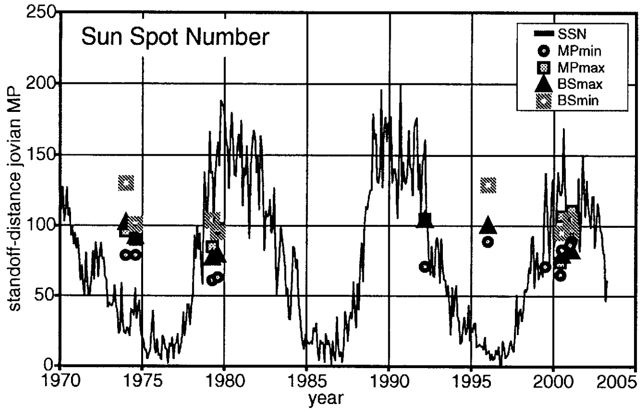

Figure 25.15. Number of sunspots and stand-off distances of the jovian bow shock and magnetopause during the time periods of all missions to Jupiter as a function of time (courtesy Steve Joy, UCLA).

25.5 BOUNDARY PHENOMENA

25.5.1 Variability of Boundaries

One of the ways in which the highly dynamical nature of the jovian magnetosphere is made apparent is through large variations of size. The location of the magnetospheric boundary, the magnetopause, in the subsolar region has been observed to vary extensively and rapidly between 40 and 100 R_J (Russell 2001), and the general variability of the distances to the boundaries are well documented (Huddleston *et al.* 1997, 1998). Table 25.1 summarizes the observed magnetopause and bow shock locations at various local times as determined from in situ measurements on all missions to Jupiter. The calculated stand-off distances (see Joy *et al.* 2002, for detail) are also added. These missions occurred at different phases of the solar cycle, as indicated in Figure 25.15.

Pioneer 10 and *11* encountered the jovian magnetosphere during solar minimum, *Voyager 1* and *2* close to solar maximum, *Ulysses* during the declining phase, *Galileo* covered an entire ascending phase from minimum to maximum, and *Cassini* flew by the planet during solar maximum. In general, the magnetosphere tends to be more expanded during solar minimum and compressed during solar maximum, as expected. There are, however, very significant departures from the trend; in particular, at the time of the *Ulysses* flyby the magnetosphere was very large compared to its size during the *Voyager* flybys.

The stand-off distance of the magnetopause is determined mainly by the balance between solar wind plasma pressure and internal (magnetic and plasma) pressure, and hence variations in the magnetopause location reflect the impact of changing solar wind conditions on the jovian magnetosphere. Rotational stresses in the jovian magnetosphere additionally stretch the magnetic field, adding to the internal pressure and thus increasing the size. Also, Io as a variable source in the inner magnetosphere influences the radial transport and can affect the size and shape of the magnetosphere. Magnetohydrodynamic (MHD) simulations indicate that, besides the solar wind dynamic pressure, the direction of the interplanetary magnetic field (IMF) also plays an important role in the configuration of the dayside jovian magnetosphere (Walker *et al.* 2001). High pressure means compression and more dipole-like magnetic field morphology, low pressure produces an extended and tail-like configuration. For northward IMF the boundaries move planetward but the field becomes more tail-like, for southward IMF the boundaries move away from the planet with more dipole-like magnetic field. Simulations also show the magnetopause extending farther from Jupiter on the dawn flank than on the dusk side, the result of interaction between the rotating and outflowing plasma and the solar wind. Such local time asymmetries have actually been observed, both at the boundaries and throughout the magnetosphere, e.g., in auroral emissions, ion flow velocities, Io-torus emissions, etc. and are discussed in detail in Chapter 24 and other chapters.

Joy *et al.* (2002) have considered the statistics of observed magnetopause locations. They found that the distribution of magnetopause stand-off distances (at local noon) at Jupiter is strongly bimodal, with two preferred locations corresponding to a compressed (dayside magnetopause at $\approx$ 63 R_J) and a relaxed state (dayside magnetopause at $\approx$ 92 R_J) of the magnetosphere. The mean bow shock stand-off distance is 84 R_J. They suggest that these preferred locations in part result from the distribution of solar wind dynamic pressure changes associated with the occurrence of corotating interaction regions (CIRs) in the interplanetary medium, but internal pressure changes are also required to explain them.

In January 2001, the two spacecraft *Galileo* and *Cassini*, at completely different locations and distances from the planet (but both on the dusk flank), crossed the magnetopause of Jupiter nearly simultaneously (Kurth *et al.* 2002, Krupp *et al.* 2002), implying a configuration of the magnetopause that cannot be reconciled with steady state MHD model simulations (cf. Ogino *et al.* 1998, Miyoshi and Kusano 1997, Walker *et al.* 2001). Kurth *et al.* (2002) and Krupp *et al.* (2002) argued that, during these joint observations, the magnetosphere was in a state of transition (in response to an increase of solar wind pressure) from an unusually large state to one which was large but not unusually so. Such transitional states have been suggested previously on the basis of radial motions of the magnetopause and bow shock inferred from single-point measurements by the *Pioneer*, *Voyager*, and *Ulysses* spacecraft Smith *et al.* (1978), Ness *et al.* (1979a,b), Bridge *et al.* (1979b,a), Lepping *et al.* (1981), Acũna *et al.* (1983), Slavin *et al.* (1985), but the joint *Cassini–Galileo* observations provide the first confirmation from two-point measurements.

The variable size of Jupiter's magnetosphere has a significant effect on its energetics. Southwood and Kivelson (2001) and Cowley and Bunce (2001) propose that a compression of the magnetosphere brings magnetospheric plasma closer to rigid corotation, simply by bringing the plasma inward with conservation of angular momentum, and hence substantially reduces the corotation-enforcement currents which flow through the ionosphere–magnetosphere system. An expansion of the magnetosphere, on the other hand, brings the plasma outward, reduces the corotational flow and hence enhances the currents. As a result, the intensity of auroral and radio wave emissions is expected to decrease when the solar wind dynamic pressure is enhanced, and to increase when the pressure is reduced (a somewhat surprising result, opposite to the usual expectation of heating/cooling of mag-

Table 25.1. Distances of bow shock (BS) and magnetopause (MP) crossings from Jupiter, observed at different local times in planetary radii (R_J) from in situ measurements onboard spacecraft (S/C). The stand-off distances (distance Jupiter–MP/BS at 12:00 local time) are calculated by Steve Joy from University of California Los Angeles (Joy *et al.* 2002).

S/C	Year	Local Time	Distance BS (R_J)	Stand-off BS (R_J)	Distance MP (R_J)	Stand-off MP (R_J)
P 10	1973	1000	108.9	102–130	96.4–50	80–96
		0600	124–189		98–150	
P 11	1974	1000	109.7–79.5	92–100	97–64.5	80–90
		1200	90.8–95		56.6–80	
VG 1	1979	1000	85.7–55.7	77–103	67.1–46.7	62–85
		0400	199.2–258		158.3–165.4	
VG 2	1979	1000	98.8–66.5	79–95	71.7–61.9	70–101
		0300	282.3–283.3		169.1–279.4	
ULS	1992	1000	113	85–104	110–87	72–104
		1800	109–149		83–124	
GLL	1995	0600	130–214	100–130	120	90
	2000	1750			107–149	84–107
		1920	130–133	82–105	120–150	88–98
	2001	1625	108–125	82–96	102	90
CAS	2001	1900	>450		204	111

netospheric plasma by compression/expansion). Whether this expectation is confirmed or contradicted by observations is not yet settled.

25.5.2 Boundary Layers

Radio wave observations onboard *Voyager* used the so-called low-frequency cut-off of trapped continuum radiation as an indicator of the electron plasma frequency

$$\omega_{\mathrm{pe}} = \sqrt{\frac{4\pi n_{\mathrm{e}} e^2}{m_{\mathrm{e}}}} \qquad (25.8)$$

where m_e and n_e are the electron mass and density, respectively. With $\omega = 2\pi\nu$ it follows

$$\nu_{\mathrm{pe}} = 8980\sqrt{n_{\mathrm{e}}} \qquad (25.9)$$

where ν_{pe} is in Hz and n_e is in cm^{-3}. They identified a region beyond 100 R_J where traversals into the low-density magnetospheric lobes ceased and termed this a boundary layer (Gurnett *et al.* 1980). This layer has densities characteristic of the plasmasheet. They point out that the *Voyager* trajectories in this region traversed a total of about 20° in magnetic latitude and, therefore, could not determine the latitudinal extent of this region. They found no evidence of such a layer on the dayside. Recently, observations by *Galileo* suggest a much narrower and perhaps different kind of boundary layer just inside the dusk magnetopause. Kurth *et al.* (2002) show an example of the electron density, again from the low-frequency cut-off of continuum radiation, which shows only minor gradients at the magnetopause as determined by the magnetometer. Only after an hour-long traversal of a region with slowly decreasing electron density does the spacecraft finally cross a steep gradient into a region with densities characteristic of the plasmasheet. They suggest that this layer of intermediate density is analogous to the low-latitude boundary layer at Earth. Such a boundary layer is not always seen and may not be restricted to the dusk side; the relative motion of the magnetopause and spacecraft and the thickness of any boundary layer obviously determine the time it takes to transit such a region, in general. Further, it appears that this magnetopause boundary layer is different from that discussed by Gurnett *et al.* (1980), primarily because of its magnetosheath-like density (versus the plasma sheet-like densities reported by Gurnett *et al.*) and its apparently much smaller thickness. It is not clear whether these differences represent two different types of boundary layers, or variations of a similar region due primarily to local time differences. Boundary layers are also dinstinct features in energetic particle measurements. Phillips *et al.* (1993) and Galvin *et al.* (1993) used the plasma ion composition to identify the boundary layer/magnetosheath regions offering the capability to investigate the solar wind input into the magnetosphere. The timings are also used to determine the thickness and motion of the boundary layer.

25.5.3 Boundary Fluctuations

The analysis of surface fluctuations at the magnetopause is a powerful tool to investigate the interaction of the interplanetary medium and the magnetosphere. Oscillations can be described as periodic displacements of large portions of the boundary or as surface waves where ripples propagate along the boundary (Kivelson and Chen 1995). Directional discontinuities in the magnetic field measurements from *Voyager 1* showed that the jovian magnetopause location fluctuated periodically. The observation was explained by a simple semi-global radial breathing mode of the magnetopause with a period of 66 min (Collier and Lepping 1996). Periods of about 40 and 60 min have also been reported in energetic particle measurements during the *Galileo–Cassini* rendezvous period in late December 2000/January 2001 when both spacecraft were in the dusk side magnetosphere and crossed the magnetopause nearly simultaneously (Krupp *et al.* 2002). As mentioned above these 40-min energetic particle intensity variations observed in the magnetosphere and close to the magnetopause strongly suggest that they might be correlated with the radio phenomena (MacDowall *et al.* 1993, Kaiser *et al.* 2001), magnetic field variations, solar wind velocity and possibly also with the Chandra X-ray observations inside the northern auroral oval (Gladstone *et al.* 2002).

Other fluctuations close to magnetospheric boundaries are mirror mode waves (see, i.e., Southwood and Kivelson (1993) and references therein) resulting in the imbalance between particle and magnetic field pressure in high β-plasma environments (β being the ratio of plasma to magnetic pressures). They have been found in Jupiter's magnetosheath on minute timescales (Balogh *et al.* 1992, Tsurutani *et al.* 1993) and are used to identify different regimes. André *et al.* (2002) have analyzed magnetic field data from *Cassini* and found mirror mode waves whenever the spacecraft was in the jovian magnetosheath.

25.5.4 Injection of Particles into Interplanetary Space

Since the *Pioneer* era it is well known that particles from Jupiter escape from the jovian magnetosphere and are observed in the interplanetary space hundreds of R_J away from the planet. Simpson (1974), Chenette *et al.* (1974), for example observed a series of high-intensity electron events with energies between 3 and 30 MeV in association with large-amplitude hydromagnetic waves (Smith *et al.* 1976) in the interplanetary magnetic field at a distance of $1\text{AU} = 2100\ R_J$ away from Jupiter (Simpson and McKibben 1976). Whenever the magnetic field lines connect the magnetosphere and the spacecraft these relativistic electrons can escape (e.g., Hill and Dessler 1976). It also turned out that their energy spectrum varies with the rotation period of the planet, and their spatial distribution is highly anisotropic (Simpson and McKibben 1976). Later *Voyager* (e.g., Krimigis *et al.* 1981, Zwickl *et al.* 1981, 1980), and *Ulysses* measurements (Haggerty and Armstrong 1999, Anagnostopoulos *et al.* 2001b, Marhavilas *et al.* 2001, Anagnostopoulos *et al.* 2001a, Chaizy *et al.* 1993, Moldwin *et al.* 1993) were then used to analyse these upstream particles in more detail and at higher magnetic latitudes. *Galileo* and *Cassini* data confirmed and extended those findings. Krupp *et al.* (2002) reported sharp increases of MeV electrons when *Cassini* skimmed along the dusk magnetosheath at distances between 250 and 950 R_J, providing evidence for leakage of magnetospheric particles at those distances. At the same time, low energy electrons have been observed onboard *Galileo*. Figure 25.16 shows the energetic particle measurements onboard both spacecraft in January 2001.

In addition, energetic neutral atoms (ENA) leaving the jovian system were observed for the first time directly onboard *Cassini*. These energetic atoms mostly result from charge exchange between energetic (hot) ions and neutrals. Recently it was found that most of the ENA's come from a region just outside the orbit of the moon Europa (Mauk *et al.* 2003). Escaping neutrals are subject to photoionization and are "picked up" by the solar wind electric field. Those singly charged ions (O^+, S^+, and SO_2^+) with clearly jovian origin could be identified as far out as hundreds of R_J (Krimigis *et al.* 2002).

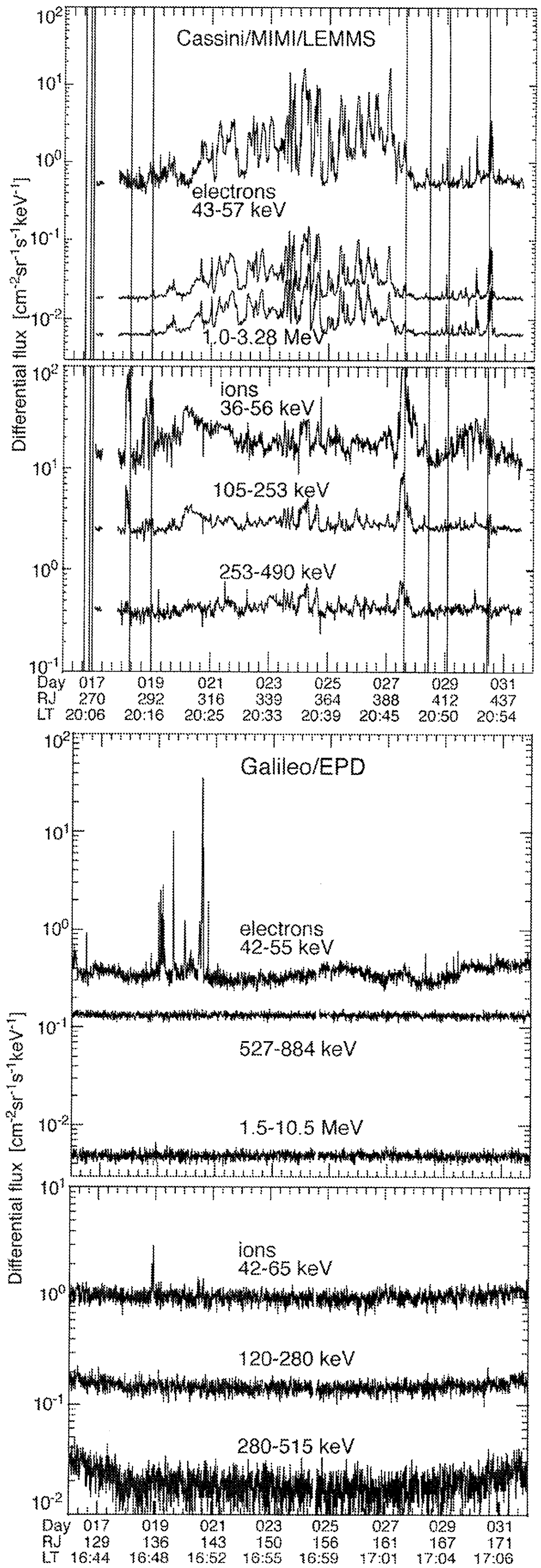

Figure 25.16. Upstream events as observed by *Galileo*/EPD and *Cassini*/MIMI/LEMMS in the jovian dusk magnetosphere.

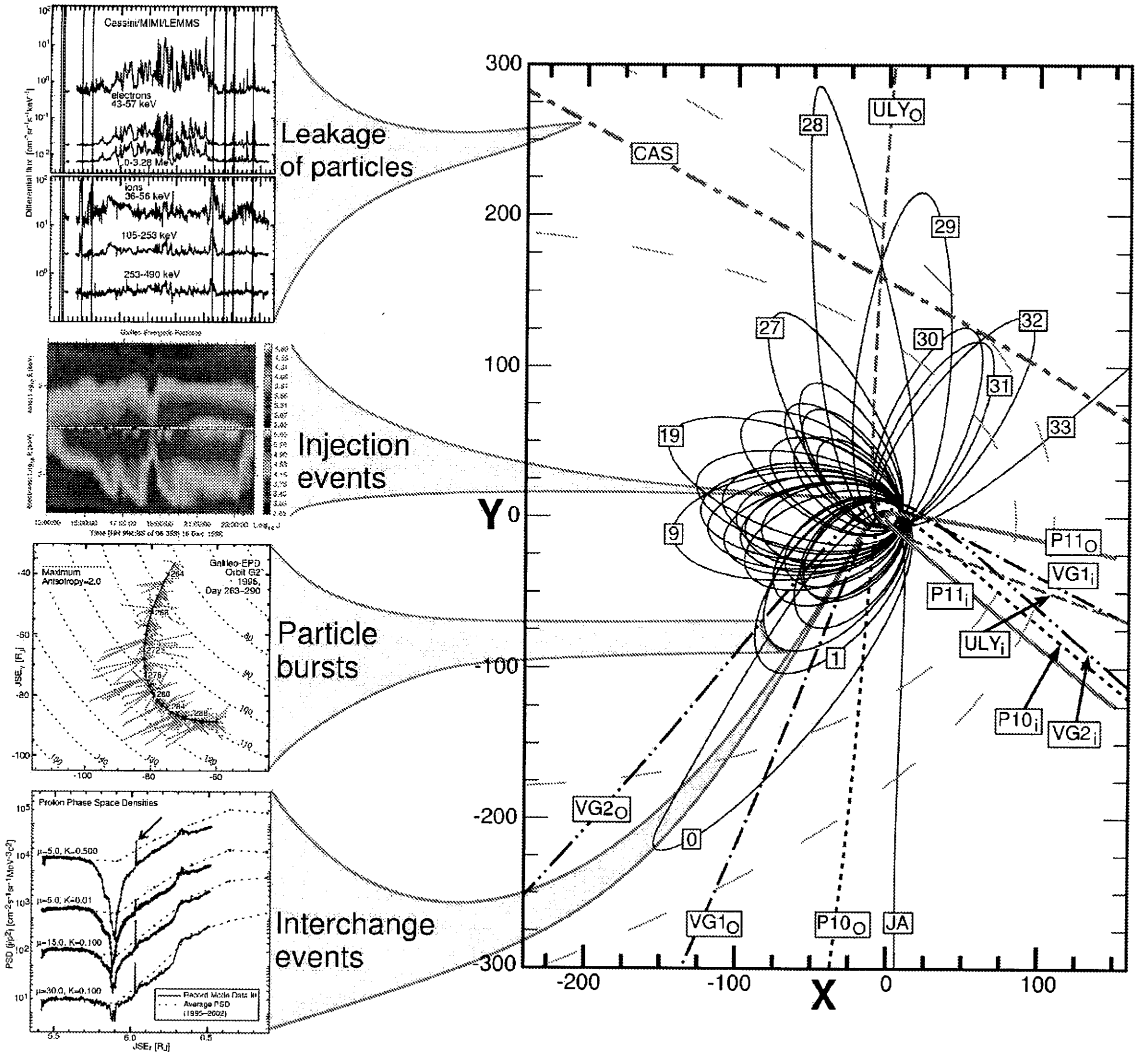

Figure 25.17. Summary of dynamic events in Jupiter's magnetosphere (adapted from Joy *et al.* 2002). (See accompanying CD for color version.)

25.6 SUMMARY AND OUTSTANDING QUESTIONS

Figure 25.17 gives a summary of the new findings in terms of dynamics in the jovian magnetosphere, especially in the light of results from the *Galileo* and *Cassini* spacecraft.

Galileo, the first orbiting spacecraft in an outer planet's magnetosphere, dramatically increased the understanding of the dynamics of the jovian magnetosphere. Timescales of several days which could not be observed with a single flyby revealed the existence of quasi-periodic particle bursts which are part of globally present reconfiguration processes. There is evidence that in turn these events are part of short-term so-called injection events in the inner magnetosphere. These injection events which were identified for the first time at Jupiter offered the possibility to apply concepts developed for the Earth's magnetosphere at Jupiter. The *Galileo* mission with its in situ particle and field observations and the auroral imaging by the HST and other Earth-based telescopes have significantly improved our knowledge of the jovian magnetosphere and its dynamics. However, in spite of the progress achieved, we are still far from a comprehensive and conclusive understanding of the jovian magnetosphere.

The most critical and fundamental open question is the role of the solar wind and the interplanetary magnetic field in shaping the topology of the magnetosphere and driving its dynamics. We have established that the solar wind pressure dramatically influences the size of the magnetosphere. However, do these changes in the outer magnetosphere affect the mid and inner part of the magnetosphere and if so, how? Magnetic reconnection of interplanetary and magnetospheric field lines certainly takes place. However, does it play a role in the overall energy and mass budget of the jovian system with its strong internal sources? Is it possible that at least temporarily and/or in certain regions of the magnetosphere the coupling of solar wind energy and mass becomes so efficient that it influences or even drives the magnetospheric convection?

It was observed that, like at Earth, the jovian magnetotail becomes unstable at times, the rotationally driven plasma flow breaks down and the tail configuration changes globally. At least conceptually, the efficient internal mass sources and the rapid rotation of the plasma provide a means to account for the onset of the instability. However, so far, we cannot exclude the possibility that, in analogy to substorms at Earth, the solar wind drives the instability and/or changes in the interplanetary medium trigger its onset.

A major break-through in understanding the Earth's magnetospheric system was achieved through the possibility to monitor continuously and globally the auroral emissions, simultaneously with the solar wind input parameters. Advanced magnetic field models allowed establishing the links between auroral features and magnetospheric key regions and processes within those. At Jupiter we are only at the very beginning of taking this major step. Auroral images have impressively demonstrated the existence of a great variety of auroral phenomena at Jupiter. Many of those by far exceed the Earth's aurorae in intensity. We know that the jovian magnetosphere has a complex structure and hosts a number of interesting transient processes. However, we yet have to conclusively establish the relation between the magnetospheric plasma regimes and the auroral features. It was demonstrated that the energetic electron population in the inner magnetosphere could possibly directly account for the diffusive, less energetic, type of aurora. But what is the source population or source process for the spectacular discrete auroral arcs? It seems that the magnetospheric energetic particle population cannot provide sufficient energy flux to directly cause either the continuous emissions making up the main auroral oval or the even more intensive emissions of transient nature, like the so-called auroral dawn storms. Other mechanisms have to be invoked, like huge potential drops above the jovian ionosphere established by field-aligned currents possibly flowing in regions where the plasma corotation breaks down (Hill 2001, Hill and Vasyliunas 2002, Cowley and Bunce 2001, Chapter 26).

A further, largely unresolved problem of fundamental nature regards the jovian magnetosphere as an efficient particle accelerator. We know Io constitutes an important plasma source. However, how is the Io plasma accelerated from basically a few eV to energies in the 100 keV to MeV range? Furthermore, what mechanism releases these particles into interplanetary space, where they are frequently observed even as particles penetrating into the Earth's magnetosphere? The mid to deep tail regions of the jovian magnetosphere remain vastly unexplored. Besides the snapshots provided by the *Voyager* spacecraft we have to rely primarily on theoretical considerations and simulation work in a region which we know from the Earth's case is a highly interesting one and of major importance for the overall dynamics of the magnetosphere.

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