Driving mechanisms of magnetospheric dynamics of planets and satellites

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Abstract

We review basic mechanisms of magnetospheric dynamics taking the cases of Ganymede, Mercury, and Jupiter. The topics include; (1) Whether or not possible effect of the intrinsic time variability of the reconnection rate can be seen in Ganymede’s magnetosphere which is embedded in an almost fixed magnetic field of Jupiter. (2) How well the occurrence of reconnection is observationally founded for Mercury’s magnetosphere. (3) In what ways various types of Jovian aurora are related to specific features of magnetospheric dynamics. (4) By what mechanisms solar wind influences the activity of the Jovian magnetosphere. (5) How the energetic particles are supplied to the boundary region of the Jovian magnetosphere and escape to the interplanetary space keeping high energies.

Keywords: Magnetospheric dynamics of planets and satellites; Driving mechanisms; Reconnection rate

1. Introduction

Magnetospheric dynamics is driven by energy of solar wind and planetary rotation. For the Earth’s magnetosphere the solar wind is the predominant source of energy, but for the giant and rapidly rotating magnetosphere of Jupiter the planetary rotation is the basic driver of its dynamics.

The energy derived from these sources gives rise to a variety of phenomena, such as convection and acceleration, electric current and magnetic disturbance, auroral emissions and plasma waves. Generation processes of these phenomena in the magnetospheres have much in common among the planets but there are also characteristic differences that reflect specific properties of individual planets. This applies also to the magnetosphere of Jupiter’s satellite Ganymede which has an intrinsic magnetic dipole.

This paper is a brief overview of driving mechanisms of magnetospheric dynamics. We address the magnetospheres of Ganymede, Mercury and Jupiter, and discuss manifestations of such basic processes as reconnection, field-aligned electric current and associated potential drop, and diffusion and acceleration of energetic particles.

2. Reconnection at Ganymedes magnetosphere

Jupiter’s satellite Ganymede has an intrinsic magnetic field whose dipole moment has an equatorial field magnitude of 719 nT and is directed southward (Kivelson et al., 2002). The magnetic field of this dipole is strong enough to stand off the Jovian magnetic field and plasma at an equatorial distance of roughly 2R_G, where R_G (Ganymede’s radius) is 2634 km, and a magnetosphere is formed (Kivelson et al., 1998). The plasma flow speed toward the magnetosphere is sub-Alfvenic (about 150 km/s) (Williams et al., 1998) so that it is mainly the magnetic pressure that produces Ganymede’s magnetosphere.

The presence of the closed field lines in this tiny magnetosphere is manifested by the observation of the field line resonance. The fundamental frequency of 0.06 Hz of resonant waves corresponds to an equatorial
plasma density of about 2 amu/cm³. These waves last for many cycles from which it can be inferred that the ionospheric conductivity is either larger than 1 s or smaller than 10⁻³ s. The latter is consistent with the available information plus some reasonable guess (Volwerk et al., 1999).

The magnetic field in the equatorial region of Ganymede's magnetosphere is directed northward and is opposite to that of the Jovian magnetosphere in which it is embedded. Hence reconnection occurs between magnetic fields of Ganymede and Jupiter and produces open field lines that are connected with Ganymede's ionosphere on one end and with the Jovian ionosphere on the other end. This open field line topology is consistent with observations of the pitch angle anisotropy of energetic electrons (Fig. 1) where there is a clear loss cone signature in energetic electrons coming from the direction of Ganymede (Williams et al., 1998). A loss cone is seen also in high-energy (304–527 keV) component of electrons that are reflected from the direction of Jupiter, but, due to scattering, much less so in reflected low-energy component (15–29 keV).

The unique feature of this reconnection is that the upstream condition is almost fixed except for the very slow variation with the period of Jupiter’s rotation. The field orientation in the upstream flow never reverses. Little energy would be stored in open field lines as an extended tail is probably not formed. This makes one wonder if reconnection occurs almost steadily or it still operates sporadically due to intrinsic bursty nature of the reconnection process, etc.

The fraction of the field lines of the Jovian magnetic field that is reconnected can be estimated by comparing the flow speed in the upstream region with that on the

Fig. 1. Pitch angle distributions of electrons observed at Galileo paths across Ganymede's open field lines (adapted from Williams et al., 1998). Top: pitch angle distributions of electrons, and bottom: positions of the electron observations shown in the top panel relative to the field line configuration inferred from magnetic field observations.
open field lines taking account of the difference in magnetic field strength in these two regions. The result shows that the fraction is very large – almost at the upper limit of 1 (Kivelson et al., 1998) which is very much larger than the corresponding ratio of about 0.1 observed for the Earth’s magnetosphere.

The rate of reconnection should be reflected in intensity and spectrum of particles that are injected from the nightside reconnection line into the closed region of the magnetosphere. However, this may be difficult to see since the injected particles are spatially dispersed depending upon their energy. It may be thought that intensity of auroral emissions also reflects the reconnection rate. In Ganymede’s atmosphere OI emissions are observed in the polar region extending 40–50° toward the equator and are interpreted to be due to electron impact dissociative excitation of oxygen molecules (Hall et al., 1998). They are longitudinally nonuniform and time-varying, but the north-south intensity ratio is also variable (Feldman et al., 2000). The last feature makes it uncertain if the emissions are caused by particles injected onto closed field lines. It may be relevant to note that a pronounced field-aligned potential drop would not be produced in the Ganymede’s magnetosphere–ionosphere system since the mirror ratio is very small – about two orders of magnitude lower than in the Earth’s.

3. Substorms in the Herman magnetosphere

Some 30 years ago Mariner 10 discovered that Mercury has extended magnetic field lines that should originate from its intrinsic magnetic field (Ness et al., 1975). The estimated strength of the equatorial magnetic field ranges from 150 to 350 nT, the ambiguity being due to limitation of the data collected by two flybys only (e.g., Giampieri and Balogh, 2001).

The Hermean magnetotail is very active, and several events of energetic electron bursts have been observed during ~17 min of the tail traversal at the Encounter I. Electron and magnetic field data for some of the burst events are shown in Fig. 2. Energies of these electrons are quite high: >35 keV if due to pulse pile up and >170 keV otherwise (Christon, 1987). Onset rise times range from <0.4 to 1.7 s and decay times are 6 to 9 s (Eraker and Simpson, 1986).

For the burst event B the increase in the counts is accompanied by a sharp increase in $B_z$ of the magnetic field. This is similar to the observation in the Earth’s magnetotail where “dipolarization” of the magnetic field is accompanied by increase in energetic particle flux. The dipolarization can be due to magnetic reconnection that occurs further downtail of the observing site. Although bursts are observed with much shorter intervals (a few minutes) in the Hermean magnetotail than in the Earth’s tail (a few hours), this is consistent with shortness of the cycle time of magnetic flux in the Hermean tail. The transition from quiet to active state during the Encounter I can be attributed to the change in the IMF polarity from northward to southward in the meantime (Siscoe et al., 1975).

Thus it seems possible to interpret the activity observed in the Hermean magnetotail in terms of magnetospheric convection driven by reconnection: southward turning of IMF intensifies the magnetospheric convection and leads to magnetic reconnection and associated particle acceleration in the magnetotail. Flux transfer

Fig. 2. Electron counts and magnetic field at burst events observed in the Hermean tail (adapted from Eraker and Simpson, 1986). CA and MP mean closest approach and magnetopause, respectively.
events (FTEs) which indicate the occurrence of reconnection have been observed at the Hermean magnetopause (Russell and Walker, 1985). However, information obtained by Mariner 10 on reconnection in the magnetotail was quite limited. The observed magnetic signature of the “dipolarization” is in fact not simple and clear; in the event \( C B_z \) is oscillatory, and in the event A both \( B_z \) and \( |B_x| \) increase only gradually. Even for the event B where a sharp increase is observed in \( B_z \), it is preceded by a \( \sim 1 \) s interval of almost entirely duskward magnetic field \( (B_x \approx 0, B_z \approx 0 \text{ and } B_y > 0) \). This means that neutral sheet expands and field-aligned current develops before the “dipolarization”. How such a current is generated and closed in spite of presumably low conductivity in the ionosphere has to be understood in parallel to the interpretation of \( B_z \) increase in terms of the dipolarization due to reconnection. (A case of field-aligned current unrelated to burst events has also been observed (Slavin et al., 1997).) Moreover, since observations did not cover the distant tail the essential nature of magnetic reconnection, that is, tailward acceleration of plasma beyond the neutral line, has not been confirmed.

Unfortunately, the plasma that constitutes the bulk of energy and pressure of the Hermean plasma sheet was not measured by Mariner 10. There were no ion data, and there was a substantial gap (from 688 eV to 170 keV) in the energy coverage of electron measurements. Acceleration of electrons to a few hundred of keV is not easy. Strong inductive electric fields could accompany sharp changes in the magnetic field that occur in a few seconds, but particles have to move a distance of several (a few) thousand km under such electric field in order to attain an energy of 500 (100) keV (Baker et al., 1986). The fraction of particles that could take part in such a process should be limited and these particles could not be taken as truly representative of the plasma population in the Hermean plasma sheet, although their acceleration process is no doubt extremely interesting. It is hoped that Messenger and BeppiColombo missions to Mercury will open really new grounds for clarifying the physics of the Hermean magnetosphere.

4. Jupiters rotating magnetosphere

The planet Jupiter rotates with a period of about 10 h while its magnetosphere is about one hundred times larger than the Earth’s, due primarily to higher dipole moment (with the coefficient \( g_0^1 \text{ of } 4.2 \times 10^5 \text{ nT according to Connerney et al. (1998)} \) and reduced solar wind dynamic pressure (due mainly to inverse square decrease of the solar wind density with the distance from the sun). The plasma in the Jovian magnetosphere rotates with the planet and in the outermost region the rotational speed is comparable to that of the solar wind. The rotational motion is the basic driver of the magnetospheric dynamics at Jupiter. Fig. 3 shows the average pattern of the ion flow that is derived from Galileo observations of ion anisotropy averaged over 30 min (Woch et al., 2002).

In fact the rotational motion is not fully corotational since the plasma never reaches dynamical equilibrium with the planet The bulk of plasma in the Jovian magnetosphere originates from the atmosphere of Io, and diffuses radially across magnetic field lines. For the plasma that diffuses outward its azimuthal velocity decreases with distance because of conservation of the angular momentum. Hence the azimuthal velocity of plasma in the outer magnetosphere is bound to be less than the local velocity of the exactly corotational motion. The amount of this lag is determined by the rate of the plasma outflow from Io and the electric conductivity in the Jovian ionosphere (Hill, 1979). The magnetospheric plasma is driven toward corotation by the force that acts on the electric current that flows radially outward in the plasma sheet, and this current is supplied from the ionosphere by a pair of field-aligned currents.

![Fig. 3. Averaged pattern of the ion flow in the equatorial region of the Jovian magnetosphere (adapted from Woch et al., 2002).](image-url)
that is upward (relative to the ionosphere) at the inner edge and downward at the outer edge.

Cowley and Bunce (2001) have used an empirical model of the field and flow in the middle magnetosphere to estimate the intensity and spatial distribution of field-aligned currents and have obtained an upward field-aligned current density of about 1 μA/m². This current is confined to circumpolar annular rings of latitudinal width of about 1° (1000 km) centered near 16° dipole colatitude. Thus the ionospheric footprint of the upward current compares rather well with the observed location of the main oval of Jovian aurora (Fig. 4) which is at the projection along field lines from the radial distances of 12–30 RJ (Connerney and Satoh, 2000).

The upward current is carried predominantly by electrons which stream down along magnetic field lines from the magnetosphere to the ionosphere. In order to make their way to the ionosphere and carry the inferred current density, these electrons have to overcome repulsion by the magnetic mirror force. This can be accomplished by acceleration by field-aligned electric field as known to work in the Earth’s magnetosphere (Knight, 1973). Applying this theory Bunce and Cowley (2001) have estimated that a field-aligned voltage of order 100 kV is produced at altitudes of 3–4 RJ along the Jovian polar field lines and that the peak values 0.1–1 W/m² of the precipitating electron energy flux are sufficient to produce the brightest of the observed auroras in the range of 1–10 MR. The field-aligned potential difference can develop more readily in the Jovian magnetosphere where the mirror force acting on precipitating electrons is about an order of magnitude stronger than for the case of the Earth.

While the above mechanism accelerates electrons downward only, Frank and Paterson (2002) have observed that electrons in the range of several keV to tens of keV flow both parallel and antiparallel to the magnetic field at radial distances of 20–30 RJ. The energy flux extends up to 1 W/m² when projected to the ionosphere. The origin of this bistreaming beam is a challenging issue.

Returning to the plasma flow, the observed ion flow shows bursty enhancements with time scales shorter than 30 min. Directions of such enhancements depend characteristically on local time and radial distance. In Fig. 5 (Woch et al., 2002) the left panel delineates regions where different signatures of flow bursts are seen, and the right panel gives expanded data plots at representative locations. In the pre-dawn region at 100 RJ (at the point 1) bursty flows are often directed antisunward. In the postmidnight region they are predominantly in the anti-sunward direction at 125 RJ (point 3) and in the sunward direction at 95 RJ (point 4). In the postdusk region at 100 RJ (point 2) the bursts are rather infrequent.

The above observations agree well with the model proposed by Vasyliunas (1983) where magnetic reconnection is supposed to take place on the nightside of the Jovian magnetosphere. Fig. 6 illustrates (left) the flow pattern and (right) the field line configuration that is expected to occur as the rotation carries magnetic field lines from the duskside to the dawnside. (1) In the late afternoon sector they are stretched anti-sunward due to centrifugal force and pressure since their extent is no longer constrained by the magnetopause. (2) Then magnetic reconnection takes place at the neutral sheet of the extended field lines and (3) their tip is blown away in the form of a plasmoid. Fig. 6 also assumes that not only the closed field lines are rotated from the duskside to the dawnside but also the open field lines are transported across the polar cap and (4) become reconnected in the neutral sheet adjacent to the dawnside magnetosphere.

![Fig. 4. Auroral images and field line projections in the polar region of Jupiter (adapted from Connerney and Satoh, 2000). IFT means the projection of the flux tube passing the satellite Io.](image-url)
sphere. Comparing Figs. 5 and 6, we can see that the demarcation that is observed in directions of the bursty flow corresponds to the X-type neutral line where reconnection takes place.

Injections of energetic electrons to the inner magnetosphere have been detected at ~10–13 RJ and corresponding auroral patch has been identified (Mauk et al., 2002). These injections are accompanied by low-frequency magnetic oscillations and narrowband kilometric radiation (n-KOM) (Louarn et al., 2001). Reconnection is the likely cause of these events, while Louarn et al. (2001) have invoked an instability in the external part of the Io torus or in the magnetodisc.

Observations of energetic ions in the nightside magnetosphere throughout the 20–80 RJ range suggest that the occurrence of reconnection is clustered and repeats quasi-periodically with a period of about 3 days (Woch et al., 1998). There are two basic states in ion observations. One of the states is characterized by a thick plasma sheet with high intensities of energetic particles having a spectral index typical of the inner magnetosphere. The plasma flow is essentially in the corotation direction. The other is a thin plasma sheet with low intensity of energetic particles where plasma flow direction deviates from the corotational direction and is tailward on the pre-midnight side and sunward at post-midnight. This suggests that the accumulation of the rotating plasma on closed field lines modulates the reconnection rate with a periodicity of ~3 days. It is also tempting to speculate that the auroral dawn storm (Fig. 7, left)
where the auroral brightness close to the dawnside main oval grows to a level (several mega-Rayleighs) many times higher than the other features (Clarke et al., 1998) occurs when the state of the enhanced sunward flow has been established in the dawn sector. The upward current density from the ionosphere would be higher and aurora would be brighter when there is a greater influx of plasma into the dawnside magnetosphere.

Signatures of magnetic reconnection in the dawnside magnetotail have been observed in an earlier survey of the Jovian magnetosphere by Voyager 2 (Nishida, 1983). As reproduced in the left panel of Fig. 8, northward inclination of the magnetic field (third panel from top) and tailward directed anisotropy of energetic ions (fourth panel) are observed together in the plasma sheet (magnetodisc) at the distance of 150 $R_J$. Statistically it is seen in the right panel of Fig. 8, that the magnetic inclination in the magnetodisc is always southward (types A and B) up to the distance of about 80 $R_J$ but it involves (type C), or is overwhelmed by (type D), northward spikes at the crossings beyond this distance. This means that magnetic reconnection tended to take place at the distance of about 80 $R_J$ when Voyager 2 traversed the dawnside magnetotail of Jupiter.

There is another feature of the Jovian aurora that can be compared with magnetospheric dynamics. Brightness of the infrared aurora in the polar cap (that is, in the region poleward of the main oval) varies with local time and has been shown statistically to be brighter at dusk (Satoh et al., 1996) (see Fig. 7, right panel, for an example seen in ultraviolet). Pallier and Prangé (2001) have suggested that this emission occurs at footprints of
closed field lines that extend to the distant magnetosphere. Indeed the closed field lines originating from the dusk sector of the polar cap are stretched tailward as envisaged in Fig. 6. This stretching is associated with intensification of the plasma sheet current that flows from dusk toward dawn and is connected to the current flowing upward from the ionosphere to the duskside boundary region of the magnetosphere. Brightening of the polar-cap aurora in the dusk sector could be due to electron acceleration associated with this upward current.

Open field lines in the Jovian magnetosphere are to be produced by reconnection between Jovian and interplanetary magnetic field lines on the magnetopause. Signatures of impulsive reconnection (FTE) have indeed been found on the magnetopause when the interplanetary magnetic field is northward as expected, but the electric fields generated by Jovian FTSs are very small in comparison with the corotation electric field (Walker and Russell, 1985). This conclusion was derived from the magnetopause observations by Pioneer 10, 11, Voyager 1 and 2 in the dawn-to-noon sector between 0900 and 1200 LT. However, it has recently been noted that in the dusk sector Galileo’s position with respect to the Jovian magnetopause and bow shock correlates with changes in the disturbed north-south reversing field seen by the Cassini spacecraft behind the shock in such a way as would be expected if the magnetopause moves inward when the magnetosheath field turns northward and reconnection occurs (Kivelson and Southwood, 2002). It seems possible that the reconnection occurs more routinely on the duskside where the solar wind and the rotational flow are parallel. In the dawn–noon sector where they are antiparallel, velocity shears of hundreds km/s are present and would act against the development of the reconnection.

Even if the reconnection takes place on the duskside magnetopause, the newly opened field lines would tend to converge to the cusp region around noon since the magnetopause is covered by field lines that pass the cusp region, so that auroral emission can be produced by particles precipitating to the ionospheric projection of the cusp as observed by Pallier and Prangé (2001).

In addition to the flows generated by corotation and by reconnection with the IMF, Laxton et al. (1997) have suggested that “viscous” input of solar-wind momentum at the magnetopause also drives flow in the Jovian magnetosphere. This is based on the observation of the sunward-directed, anti-corotational anisotropy of 1.0–1.75 MeV protons in the dusk sector by Ulysses. Hawkins et al. (1998) have also found the same anisotropy for energetic ions above 50 keV. However, the flow velocity derived from simultaneous observation of thermal electrons did not show the corresponding feature (Laxton et al., 1999). Overall, the duskside magnetosphere of Jupiter seems to be the region where very important processes await to be clarified. Fortunately Galileo has surveyed this sector during its Millennium phase and we hope that further progress of its data analysis will give new insight in the nature of such processes.

Variability in the magnetospheric activity of Jupiter was recognized well before the advent of in-situ spacecraft observations by means of Earth-bound monitoring of radio emissions. Variations in the Jovian decametric emissions consist of two components; one is correlated with the orbital position of the satellite Io but the other is not. The former is due to the dynamo action of Io as it moves across the magnetic field of Jupiter, while the latter is governed by the solar wind. Fig. 9 shows that the occurrence probability of the non-Io related emission of the types NA and NC depends clearly on the solar wind dynamic pressure that is inferred from the solar wind parameters at 1 AU by using nonlinear, one-dimensional (radial) magnetohydrodynamic equation system (Terasawa et al., 1978).

The effect of the solar wind on the Jovian hectometric radio emission and aurora has been confirmed lately by simultaneous observations using Cassini and Galileo spacecraft; a large increase is observed in the intensity of the hectometric emission following arrival of interplanetary shock and is accompanied by enhancement of the extreme ultraviolet intensity of aurora (Gurnett et al., 2002). Correlation with the solar wind dynamic pressure has also been indicated by ground-based observation of the auroral infrared emission (Baron et al., 1996). The reason why the dynamic pressure of the solar wind controls the magnetospheric activity at Jupiter is not obvious, but it could rather be the magnetic field strength that plays the key role in the correlation since solar wind and IMF are correlated. If this is the case, the above correlation can be manifestations of the energy input by reconnection between Jovian and interplanetary magnetic field lines.

Fig. 9. Occurrence frequency of Jovian radio emission and solar-wind dynamic pressure (adapted from Terasawa et al., 1978).
The size of the Jovian magnetosphere varies over a wide range. When the size varies the plasma inside moves radially inward or outward, and its rotational speed should change due conservation of angular momentum. This leads to changes in the intensity of the corotation enforcement current and in the rate of its energy dissipation. Hence it can be expected that compression and expansion of the magnetosphere can activate the magnetosphere through modulating the energy provided by the corotation enforcement current (Nishida and Watanabe, 1981). This effect, which would be stronger for the expansion events (Southwood and Kivelson, 2001), remains to be confirmed.

The Jovian magnetosphere has an intense belt of trapped particles. While their inward diffusion is accompanied by adiabatic acceleration (Cheng et al., 1985), substantial extra energization is needed to produce the observed spectrum. Reconnection that operates in the nightside magnetosphere is most likely to contribute to the energization. In addition to this, Galileo has found evidence that ions are accelerated to MeV nucleon\(^{-1}\) energies in the middle magnetosphere near 25 \(R_J\) (Cohen et al., 2001). The composition of these particles shows that solar material dominates.

A bistreaming anisotropy of energetic electrons also seems to be an important feature that has been observed over a wide range of distances (from the magnetopause to \(\sim 10 R_J\)) in the magnetosphere of Jupiter. Van Allen et al. (1974) have found such an anisotropy for the MeV electrons when Pioneer 10 traversed the Jovian magnetosphere in noon and dawn sectors.

As a possible cause of energization and bistreaming we have proposed a recirculation model (Fig. 10). This model involves four stages: (1) Radial diffusion that occurs across the entire length of field lines. This stage that conserves both the first and second adiabatic invariants energizes inward-diffusing particles and increases their pitch angles at the same time. (2) Particles are scattered and spread evenly along field lines while conserving energy. (3) Scattering of particles in low altitudes causes diffusion toward higher latitudes. This diffusion, which affects particles with small equatorial pitch angles, conserves the first invariant but not the second, so that it does not reduce particle energy and produces bistreaming anisotropy. (4) Pitch angle scattering reduces the pitch angle of the accelerated particle beams. When these stages are cycled particles can gain energy repeatedly (Nishida, 1976; Fujimoto and Nishida, 1990). The efficiency of this process depends critically upon the level of fluctuations in the low-altitude electric field having time scales of the bounce motion of the particles.

A layer of energetic ions (\(\sim 1\) MeV) was observed just inside the high-latitude duskside magnetopause at the outbound orbit Ulysses. The ion fluxes in this layer do not show the 10-h periodic variation due to rotation of

![Fig. 10. Four stages of diffusion involved in the recirculation model (adapted from Fujimoto and Nishida, 1990).]
the plasma disc, and there is little indication of a latitude gradient though overall the flux slowly declined with increasing distance and/or time (Cowley et al., 1996). This boundary layer has been detected also for ions and electrons having lower energies (above several tens of keV) (Seidel et al., 1997; Anagnostopoulos et al., 2001). Bursts of ions and electrons in this layer show field-aligned anisotropy. For electrons the anisotropy is outward at the onset of the bursts but relax to a strong field-aligned bi-directional anisotropy later (McKibben et al., 1993), but for ions the outward anisotropy does not relax to a bistreaming distribution (Zhang et al., 1995). It has been suggested that sources of these protons and electrons are located at a few Jovian radii above the planetary surface over the polar region. Modulations with a quasi-period of about 40 min have been recognized (McKibben et al., 1993; Karanikola et al., 2003).

If the source of energetic particles is the field-aligned electric field, potential drops as high as mega-Volts have to be generated in upward and downward directions alternately either in space or in time. Alternatively, if the fluctuating electric field in the azimuthal direction is intensified at the “source” height, trapped particles could diffuse poleward by the process (3) of Fig. 10 and provide the boundary layer with ions and electrons which are already sufficiently energetic. Electric field observations by a low-altitude polar orbiter are needed to test these hypotheses and elucidate the origin of the ion and electron beams in the Jovian magnetosphere.

Bursts of energetic electrons and protons originating from the Jovian magnetosphere have been observed in the interplanetary space (Chenette et al., 1974; Schardt et al., 1981). Energies of these particles are in the same range as those of the particles trapped in the radiation belt of Jupiter, but it is not the energy but the adiabatic invariant that particles conserve as they are transported from the inner magnetosphere to the magnetopause. If the outward diffusion is governed solely by the conventional radial diffusion of the type (1) of Fig. 10 they would have been cooled by a factor of $10^2$ to $10^3$ when they reach the magnetopause. Diffusion of the type (3) in low-altitudes is the only mechanism suggested so far that could transport particles from the radiation belt to the magnetopause without significantly losing energy. Once particles leave the magnetopause, or are loaded on the open field lines, they can stream away maintaining their energy.

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