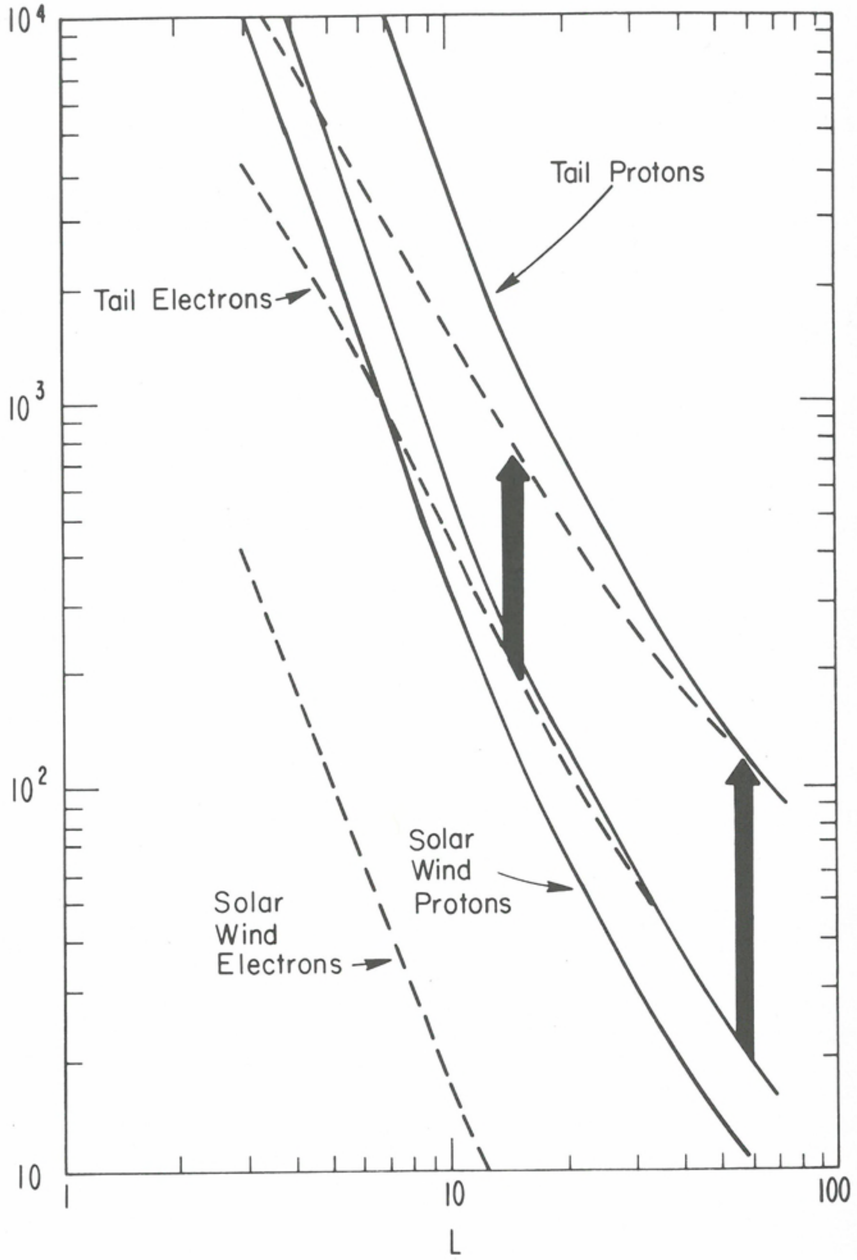

Fig. 10.6. Particle energies attainable in the Jovian magnetosphere as the result of betatron acceleration of solar-wind particles, and of particles from the magnetospheric tail having initial magnetic-moment invariants larger than solar-wind values as a result of magnetic merging in the tail [Carbary, Hill, and Dessler, 1976].

sion, and hence cooling, as they are transported outward in the magnetosphere. Moreover, the radial transport is an intrinsically slow process and cannot account for the rapid timescale (~10 hr) associated with certain acceleration processes that are inferred from the observations [Chap. 5; Fillius and Knickerbocker, 1979]. Thus we

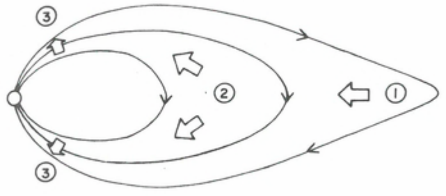

Fig. 10.7. Multiple-diffusion process proposed by Nishida [1976]. Inward radial diffusion from 1 to 2 increases $w_\perp$ by first-invariant conservation; pitch-angle scattering at 2 moves some particles to low altitudes (3) where they may diffuse across field lines (owing to atmospheric winds) without betatron deceleration, thus returning to point 1 with large field-aligned velocities.

require a faster and more powerful acceleration mechanism, although adiabatic compression remains important in determining the overall structure and energetics of the radiation belt, and particularly of the innermost synchrotron radiating region ($L \lesssim 3$).

Quasiadiabatic processes

The effect of adiabatic compression is limited by its reversibility – a particle in a dipole field, for example, gains a factor of 10^3 in perpendicular energy while moving from $L = 50$ to $L = 5$, but loses the same factor in moving back out to $L = 50$. This limitation can, however, be surmounted by alternating cycles of adiabatic compression and nonadiabatic relaxation.

A model of this type, proposed by Nishida [1976], is illustrated in Figure 10.7. Step 1, inward radial diffusion conserving the first and second invariants, is as described above; this produces a pancake pitch-angle distribution (peaked at 90°) at point 2. At this point pitch-angle scattering becomes important, as the result of cyclotron-mode waves that are amplified by the anisotropic distribution itself (see Chap. 12). The pitch-angle scattering allows some particles to mirror at low altitudes (3) where they are subject to meridional diffusion as a result of upper-atmospheric dynamo winds. This meridional diffusion displaces some particles toward the pole such that they return along the field line to the outer magnetosphere (back to point 1). If most of the poleward displacement occurs at low altitudes, the particles do not suffer the betatron deceleration that would have accompanied the equivalent radial displacement in the equatorial plane. The net result is that particles return to point 1 with field-aligned energies comparable to the cyclotron energy they gained in moving from point 1 to point 2. (Because the process is diffusive in nature, the opposite result is also possible: some particles will be displaced from 1 to 2 without benefit of any betatron acceleration.)

Sentman, Van Allen, and Goertz [1975] have added an additional pitch-angle scattering process at point 1 so that the field-aligned energy there is partially converted to cyclotron energy. (A plausible mechanism for such scattering has been discussed by Barbosa [1981].) Particles can then, in principle, repeat the cycle an arbitrary number of times and hence gain arbitrarily high energies. Sentman et al. recognized, however, that this recirculation process is inefficient because of its diffusive nature – during each cycle a particle is as likely to lose energy as gain energy, so that arbitrarily high energies are attainable only for an arbitrarily small fraction of the initial population. The process is also slow as it consists of multiple cycles of inward radial diffusion, itself a slow process. The process may, however, provide an explanation for the "dumbbell" (field-aligned) pitch-angle distributions of energetic particles observed by Pioneers 10 and 11 within the inner magnetosphere [cf., Sentman, Van Allen, and Goertz, 1974, 1978].

Another quasiadiabatic acceleration process was proposed by Goertz [1978], utilizing the day-night asymmetry of the magnetospheric field. Because the night-side magnetic field is weaker at a given distance than the day-side field, a corotating particle is subject to a small degree of betatron acceleration in drifting from midnight to noon, and a corresponding degree of betatron deceleration in drifting from noon to midnight. Without scattering the process is reversible and results in no net energy gain. However, if pitch-angle scattering occurs preferentially at the extreme points of the drift orbit (noon and midnight), then some of the perpendicular energy gained in the midnight-to-noon half of the orbit can be "stored" in the parallel component at noon and thus escape the corresponding betatron deceleration during the noon-to-midnight half, then returned to the perpendicular component at midnight, resulting in a net increase of the first invariant and of the total energy. (The parallel-energy component is also subject to adiabatic gain and loss through second-invariant conservation, but to a lesser degree than the perpendicular component – see above.) In the absence of scattering, the pitch-angle distribution would tend toward pancake anisotropy at noon and dumbbell anisotropy at midnight – it is the relaxation of these anisotropies through scattering that allows a systematic energy gain after a full rotation. Possible mechanisms for such scattering have been discussed by Northrop and Schardt [1980].

This mechanism is a close analog of the general magnetic pumping process first proposed by Alfvén [1949] to account for the acceleration of galactic cosmic rays. Because it systematically increases the average particle energy, it is more efficient than the recirculation process described above. It is also faster, requiring n rotations for a factor of 2^n increase in energy according to the estimate of Goertz [1978]. Thus, magnetic pumping may account for the bulk acceleration of particles ejected into interplanetary space – some observations of interplanetary electrons of Jovian origin apparently require an energy *e*-folding time in the magnetosphere of about 10 hr (Chap. 5). Even so, the magnetic pumping process is too slow to account for particle acceleration and loss on timescales $\lesssim 10$ hr as seems to be required by some observations [e.g., Simpson et al., 1974b (Fig. 3); Fillius and Knickerbocker, 1979; Chap. 5 (Figs. 5.7, 5.12, 5.13, 5.17)].

Nonadiabatic processes

Three non-adiabatic processes – magnetic merging, parallel (magnetic-field-aligned) electric fields, and plasma wave heating – are possible candidates for producing the transient acceleration events (timescales $\lesssim 10$ hr) in the outer magnetosphere.

Magnetic merging (or "field annihilation," or "reconnection") is a general process for converting magnetic-field energy into particle energy (bulk flow energy and/or thermal energy) in a region of magnetic-field reversal. An extensive theoretical literature has been reviewed by Vasyliunas [1975] – see also Hill [1975]. Likely regions of merging in Jupiter's magnetosphere include the magnetodisc current sheet (especially its extension into the magnetospheric tail) and perhaps the magnetosphere of Io, should one exist [e.g., Southwood et al., 1980].

In steady state models, the merging process generally accelerates particles (mostly ions) to an average energy corresponding to the magnetic energy density just outside the current sheet divided by the particle density within the current sheet, that is, $B^2/(\mu_0 n)$ [see Alfvén, 1968; Vasyliunas, 1975; Hill, 1975]. (Such an average energy is required to balance the pressure of the opposing magnetic fields on either side of the field reversal.) If we take $B \sim 10$ nT and $n \sim 0.1/\text{cm}^3$ as representative values (see Chaps. 1, 3, and 4), the average energy per particle is about 5 keV. Individual particles may gain energy increments larger than $B^2/(\mu_0 n)$ (limited ultimately by the total EMF across the system), but only insofar as their initial energy exceeds $B^2/(\mu_0 n)$ [Hill, 1975].

Thus, steady state merging by itself does not produce MeV particles in the outer magnetosphere, although it constitutes an important input to the adiabatic compression cycle described above, providing a factor-of-ten enhancement of the initial value of the first invariant $w_\perp/B$ compared to simple injection of solar-wind particles [Coroniti, 1974; Carbary et al., 1976].

The total average EMF associated with magnetic merging cannot presently be estimated because it depends on the (unknown) strength of the magnetospheric convection/planetary wind system. Whatever its average value may be, the EMF may be dramatically enhanced by "sporadic" merging associated with rapid changes in the magnetic-field configuration, either the relaxation of a highly stressed field toward a more dipolelike configuration or the formation of magnetic "bubbles" (closed loops) in the disc current sheet. This latter case may be appropriate to the production of energetic ion fluxes that have been observed streaming away from the equatorial current sheet (Chap. 5). The sporadic merging phenomenon has not been satisfactorily modeled theoretically, but observations in the Earth's magnetospheric tail [e.g., Sarris, Krimigis, and Armstrong, 1976] suggest that particle energies far in excess of that corresponding to the average EMF can be expected to accompany rapid reconfigurations of the disc magnetic field.

Carbary, Hill, and Dessler [1976] have proposed that rapid merging in the magnetospheric tail occurs with a 10-hr periodicity, peaking after each rotation through the tail of the active sector of the magnetic-anomaly model (see Sec. 10.7). Thus, they propose to account simultaneously for the 10-hr periodicities in both particle flux and energy spectral index observed outside and inside the magnetosphere.

Particle acceleration by parallel electric fields is evidently important in the auroral regions of the Earth's magnetosphere, and, by analogy, it is expected to be important wherever sufficiently intense Birkeland currents flow. In particular, parallel electric fields have been discussed in connection with the Io–Jupiter interaction (see Sec. 10.5). The field-aligned potential drop may be largely confined to small "double-layer" regions imbedded in the Io flux tube [see Smith and Goertz, 1978].

The observation of enhanced fluxes of electrons of several hundred keV energy near the Io flux tube (Chap. 5) tends to confirm the importance of field-aligned electric fields in the Io–Jupiter interaction. The total particle energy is, however, limited by the total EMF of the Io–Jupiter circuit, which is the potential across Io generated by the flow of torus plasma past Io:

$$\phi = (6\Omega_J R_J - V_I)\, B_I\, (2R_I) \sim 400\ \text{kV} \tag{10.24}$$

Particles accelerated near Io are subject to betatron deceleration (adiabatic expansion) as they move radially outward, and thus they do not contribute directly to the energetic particle population of the outer magnetosphere.

A potentially more powerful source of field-aligned electric fields would be the differential rotation of different parts of the same magnetic flux tube in the outer magnetosphere, as might occur if there were insufficient plasma to carry the Birkeland currents needed to enforce corotation; this phenomenon might be important if and when the (partial) corotation becomes super-Alfvénic. This possibility was mentioned by Fillius and McIlwain [1974] but has not yet been explored theoretically. The electric potential associated with corotation in the equatorial plane is $\phi = \Omega_J B_J R_J^2/\text{L} \sim (376\ \text{MV})/L$, and if any significant fraction of this potential were to appear along the field lines, a powerful linear accelerator would be produced. The direction of the corotation electric field is such that if the equatorial portion of a flux tube were to rotate more slowly than the near-Jupiter part (the expected sense), the field aligned electric field

Table 10.3. *Jupiter's pulsar behavior*

Phenomenon or property	Jupiter	Pulsar
1. Time variation of electromagnetic emission	Tied to planetary spin period	Neutron-star spin period
2. Release of energetic particles	(a) Jupiter is source of heliospheric cosmic-ray electrons with $E < 30$ MeV. (b) Outflow of relativistic electrons is modulated at planetary spin period.	(a) Crab pulsar is source of relativistic electrons in Crab Nebula. (b) Not known.
3. Source of energy	Kinetic energy of rotation of planet, i.e., solar wind unimportant.	Kinetic energy of rotation of neutron star, i.e., external sources unimportant.
4. Source of magnetospheric plasma	Internal to magnetosphere (principally Io and ionosphere), i.e., solar wind unimportant.	Internal to magnetosphere, i.e., external sources unimportant.
5. Magnetic moment	1.5×10^{20} T-m^3 (for equatorial surface field 4.2×10^{-4} T).	1.0×10^{20} T-m^3 (for surface field 10^8 T).
6. Fit to empirical power-loss relationship for pulsars $P \propto M^2\Omega^n$.	Extrapolates to Crab pulsar if $n = 3.1$	$n = 3.5 \pm 0.5$

would be directed toward Jupiter so as to accelerate electrons toward the equatorial plane. This hypothetical differential rotation should not be confused with the partial corotation discussed in Section 10.4 and in Chapter 11, in which entire flux tubes rotate at a common angular velocity which is, however, less than that of the neutral atmosphere.

Particle acceleration by plasma waves (especially by cyclotron resonant interactions) is another nonadiabatic mechanism of potential importance which has not been adequately explored either observationally or theoretically (See Chap. 12). Ion cyclotron waves, for example, are thought to be responsible for accelerating the upward beams of O^+ ions observed over the Earth's auroral zones [e.g., Ashour-Abdalla et al., 1981], and such waves may also be important in the acceleration of heavy ions in Jupiter's magnetosphere, especially in the vicinity of the Io torus where the wave propagation speed, and hence the minimum resonant particle energy, are drastically reduced. (Plasma waves, of course, do not provide an energy source, but rather a mechanism for tapping a given source of free energy to provide plasma heating.)

In summary, the three nonadiabatic processes mentioned here (and possibly others) are not well developed theoretically, but they presently hold the greatest promise for explaining the rapid acceleration that seems to occur at times in the outer magnetospheric radiation belt ($\gtrsim 25\ R_J$) on a timescale less than one Jovian rotation period.

10.7. Spin periodicity

In almost every phenomenon with which it is associated, Jupiter exhibits evidence of modulation at its spin period. No other planet shows such a variety of spin-dependent behavior, although Saturn shows an interesting spin modulation of its radio emissions [e.g., Warwick et al., 1981]. In this respect, Jupiter is more like a pulsar than a planet (see Table 10.3), a suggestion made when pulsars were first discovered (e.g., Dowden [1968]). The only certain knowledge we have about pulsars is that they emit electromagnetic radiation with a well-regulated, time-varying intensity. The remainder of pulsar theory, for example, the hypothesis that the pulsation period is tied to the spin period of a rapidly rotating central object (commonly supposed to be a neutron star), is founded solely on logical inference and theoretical modeling. The Pioneer and Voyager encounters with Jupiter have enabled us to make in situ measurements of a body that exhibits weak but genuine pulsar behavior. Application of our understanding of the physics of the Jovian magnetosphere to pulsars is already forthcoming [e.g., Michel and Dessler, 1981; Michel, 1982]. However, the reader should be aware that there is, as usual, a contrary view; for example, Douglas-Hamilton [1968] and Kennel and Coroniti [1975] have considered the question of whether Jupiter's magnetosphere is like a pulsar's, and they have concluded it is not. Nevertheless, we concentrate on the spin periodic phenomena because they offer the most definitive challenge to magnetospheric modelers. One could feel some confidence in a model that could quantitatively describe the various spin-periodic phenomena that have been observed. The few magnetospheric phenomena that show no dependence on either Jupiter's spin phase angle or Io's orbital position should be fully contained within the time-dependent models.

Spin-periodic phenomena

The strongest variation of any observed magnetospheric quantity such as plasma density, temperature, particle flux, magnetic field strength, optical emission, synchrotron radiation, and so forth, is its variation with latitude. For example, the Io torus density and associated optical emissions vary by two orders of magnitude over a latitude

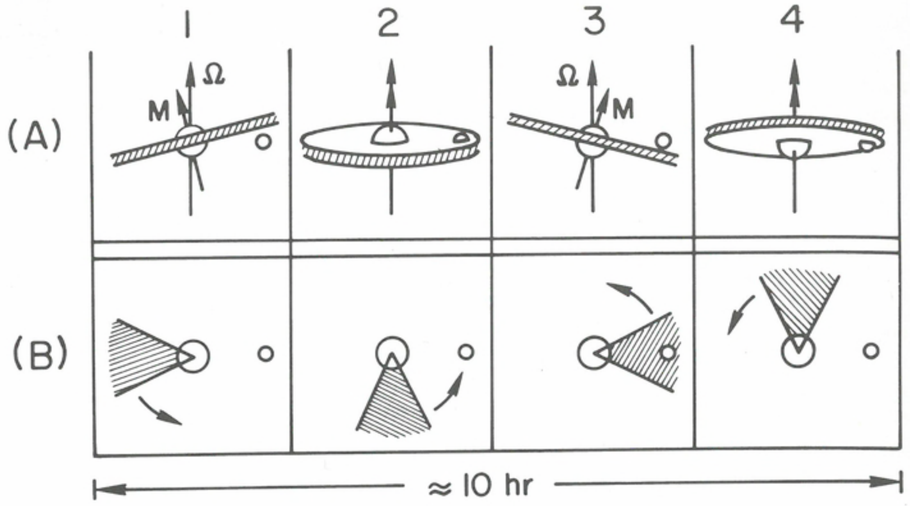

Fig. 10.8. Sketch illustrating the primary manifestations of the two basic magnetospheric models that have been put forth to account for certain of Jupiter's spin periodicities [after Hill, 1981]. Strip (*a*) shows the tilted dipole or disc model, and strip (*b*) shows the corotating active-sector or magnetic-anomaly model. The observer is at 0, and the time sequence is from left to right. Steps 1 through 4 represent one rotation of Jupiter, which requires approximately 10 hr. The most striking difference between the two models is that, for an observer near the spin equatorial plane, there are generally two events per planetary rotation for the disc model (*a*), but only one event per rotation for the magnetic-anomaly model (*b*).

range of 10° but only by a factor of, at most, 5 with longitude. This latitudinal confinement varies with distance and local time, but is observed throughout the explored portion of the magnetosphere. A smaller, but nevertheless quite important effect is the longitudinal modulation of these parameters. The effects of latitudinal confinement and longitudinal modulation, taken separately, are illustrated in Figure 10.8. It has become customary to associate the latitudinal confinement effects with the "disc model" and the effects of longitudinal variation with the "magnetic anomaly model," although many observed spin-periodic phenomena require both latitudinal and longitudinal effects for a complete explanation.

The models are described in the next subsection. The various phemonena known as of this writing are listed in Table 10.4 and are described briefly below. These are among the phenomena that a comprehensive theoretical model of the Jovian magnetosphere would be expected to explain.

a. Decametric radio emission. Before the discovery of the Io plasma torus, it was thought that the decametric radio emission that was independent of the position of Io in its orbit around Jupiter was somehow a separate phenomenon from the radio emission that occurred only when the angle between Io, Jupiter, and the observer was in one of two specific ranges (see Table 7.4 and the attendant discussion in Chap. 7). However, now, particularly with the information obtained with Voyager, it appears that the Io-dependent and Io-independent emissions are basically the same phenomenon, but that the emission is simply enhanced when Io has the preferred phase angle relative to the observer. Nearly all of the decametric radio emissions appear to come from a fixed sector of Jovian longitude with most of the emission coming from the northern hemisphere, but with specific important contributions originating in the southern hemisphere (see Fig. 10 of Alexander et al. [1981] for a graphical representation of the single northern-hemisphere source and Chap. 7 for a general discussion). The radio emission arises from the region where downward Birkeland currents, that is, upward moving electrons, are expected to flow because of a longitudinal asymmetry in the Io plasma torus that is discussed below (item c) [Dessler, 1980a].

Table 10.4. *Spin-periodic phenomena*

Phenomenon	Comments
a. Decametric radio emission (i) Io-unrelated (ii) Io-related (Chap. 7)	a(i) and a(ii) appear to be the same phenomenon except presence of Io at proper Jovian longitude and phase angle relative to observer causes emission intensity to increase. Primarily a longitudinal effect.
b. Modulated injection of relativistic electrons into interplanetary space (Chap. 5)	Seen primarily in modulation of spectral index, which is a minimum when active sector faces tail. Primarily a longitudinal effect.
c. Longitudinal asymmetry of Io plasma torus (Chaps. 6 and 11)	Seen only in emission from singly ionized sulfur. Torus brightest in active sector. Primarily a longitudinal effect.
d. Hydrogen bulge (Chap. 2)	Corotating bulge of atomic hydrogen north of spin equator and opposite active sector. Primarily a longitudinal effect.
e. Longitudinal asymmetry in radial extent of torus plasma	Outward motion of singly ionized sulfur from torus in active sector. Primarily a longitudinal effect.
f. Longitudinal asymmetry of plasma temperature in outer magnetosphere.	Higher proton temperature at active-sector current-sheet crossing. Primarily a longitudinal effect.
g. Modulation of magnetospheric plasma, energetic particles, and magnetic fields. (Chaps. 1, 3, and 5)	Inconsistent with extreme version of magnetic-anomaly model. Firm evidence for existence of thin disc in predawn quadrant to 60–80 R_J. Primarily a latitudinal effect.
h. Asymmetry of longitudinal shifts in leading and trailing particle intensity maxima as seen by Voyager (Chap. 5)	Ambiguous interpretation. Possible magnetic-anomaly effect within disc, effect of magnetotail, or wave motion. A combination of latidudinal and longitudinal effects.

b. Modulated injection of relativistic electrons into interplanetary space. Jupiter is a powerful source of interplanetary electrons; essentially all heliospheric cosmic-ray electrons with energies less than about 30 MeV originate at Jupiter (see Chap. 5). From the standpoint of magnetospheric models, the most important feature of these electrons is a "clock" modulation of their spectral index. Specifically, if the energy spectrum is represented by a power law $E^{-\gamma}$ with γ the spectral index, Chenette, Conlon, and Simpson [1974] discovered that the spectral index of Jovian electrons in interplanetary space varies by about a factor of two, and the variation is synchronized with Jupiter's spin period. The spin-periodicity in spectral index is observed to occur both in interplanetary space and within the outer part of the magnetosphere [see Fig. 9 of Chenette et al., 1974; and Fig. 3 of Simpson et al., 1975]. On the outbound pass, the clock phenomenon commences as soon as the spacecraft leaves the region of disclike modulation and enters the planetary or magnetospheric-wind region [Schardt, McDonald, and Trainor, 1981].

Vasyliunas [1975] noted that the spectral index is a minimum (or the escape of the most energetic electrons into interplanetary space is a maximum) when Jupiter is oriented so that the subsolar longitude is near $\lambda_{III} = 60°$ (or when $\lambda_{III} = 240°$ faces the tail). This discovery, which was made using data from the Pioneer 10 and 11 spacecraft, has been confirmed by data from the Voyager spacecraft [Schardt, McDonald, and Trainor, 1981]. This finding was labeled by its discoverers as a magnetospheric "clock" in that the effect is seen essentially everywhere in interplanetary space (if the spacecraft is in a flux tube that passes near Jupiter) whenever a given Jovian System III longitude faces the magnetospheric tail (see Chap. 5).

From the standpoint of conceptual magnetospheric modeling, this is a significant discovery; it shows that there is some longitudinal asymmetry fixed in System III coordinates (i.e., corotating with Jupiter's internal magnetic field) that perhaps influences the magnetosphere/solar-wind interaction and certainly influences the escape of relativistic electrons into interplanetary space. The importance of this particular spin dependence must be emphasized. Something at or near the surface of Jupiter modulates the escape of relativistic electrons from the distant magnetosphere to produce a 10-hr periodicity in interplanetary space. It was the discovery of this 10-hr modulation of relativistic electrons in interplanetary space that inspired the development of the magnetic-anomaly model [Dessler and Hill, 1975] (see Sec. 10.7 and Chap. 5).

The phase of the modulation (a minimum in the spectral index when $\lambda_{III} \approx 240°$ faces away from the Sun) is not affected by interplanetary conditions, such as the orientation of the interplanetary magnetic field, sector boundary crossings, or strength of the solar wind. A compelling analysis of the connection between the surface field of Jupiter (the magnetic anomaly to be discussed in Sec. 10.7) and the System III longitude dependence of the phase of the modulation is provided by Schardt, McDonald, and Trainor [1981] (see their Fig. 18 and their attendant discussion).

The clock effect cannot be caused by the rotation of a tilted dipole because that would produce a 5-hr variation (Fig. 10.8); some sort of interconnection between the Jovian and interplanetary magnetic fields might produce a 10-hr variation, but it would also produce a shift in the phase of the modulation as the orientation of the interplanetary magnetic field changed (e.g., the phase would be expected to shift by $\approx 180°$ when a sector boundary swept past Jupiter, as illustrated in Fig. 10.13). Neither the 5-hr variation nor the 180° phase shift is observed.

c. Longitudinal asymmetry of the Io plasma torus. A series of independent, ground-based observations shows that the optical torus has a pronounced longitudinal asymmetry in the brightness of singly ionized sulfur emissions [Pilcher and Morgan, 1980; Trafton, 1980; Trauger et al., 1980]. These various observations, which extend over a period of four years, show that the maximum torus brightness usually lies near $\lambda_{III} \approx 250°$, although both the location and amplitude can vary with time. The reported range of longitudes of the maximum brightness is between 180° and 260°, and the reported asymmetry ratio of maximum to minimum brightness varies from 5 to 2. This longitudinal variation in brightness is attributed to a longitudinal variation in plasma concentration [Pilcher and Morgan, 1980; Trafton, 1980].

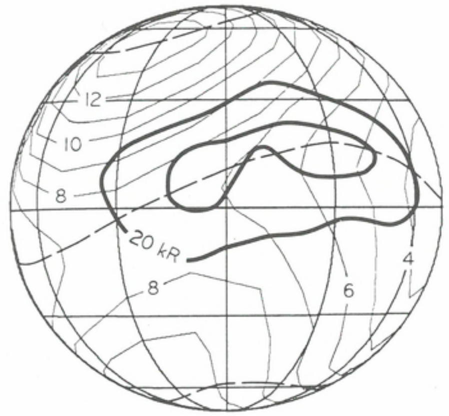

Fig. 10.9. The hydrogen bulge (a mountain of atomic hydrogen in Jupiter's upper atmosphere) as seen by Voyager 1 in resonantly scattered solar Lyman-alpha radiation [Dessler, Sandel, and Atreya, 1981]. The heavy closed curves show the 20 and the 22 kilo-Rayleigh isophotes that delineate the bulge. The view is from above the spin equator and the $\lambda_{III} = 110°$ meridian. The dashed line passing through the hydrogen bulge is the charged-particle drift equator. The lighter curves are the surface magnetic field contours in Gauss (10^{-4} T). The coincidence of the bulge with the drift equator and the corotation of the bulge with the planetary magnetic field show that the hydrogen bulge is created by the effect of charged particles on Jupiter's upper atmosphere.

This asymmetry has so far shown itself only in the [S II] emission from singly ionized sulfur. No explanation has yet been offered as to why a similar asymmetry is not seen in the emission from the more highly ionized components in the outer torus, for example, [S III] or [S IV], but data obtained with the Voyager ultraviolet spectrometer instrument, which was sensitive to only these more highly ionized states, show the torus to be axially symmetric to within about 10% [Sandel et al., 1979; Sandel and Broadfoot, 1982]. Although the symmetry of the [S III] and [S IV] emissions is a puzzle, the asymmetry in the [S II] emission is not; it is fully expected in the context of the magnetic-anomaly model [e.g., Dessler and Vasyliunas, 1979; see their Prediction 1].

d. The hydrogen bulge. Sandel, Broadfoot, and Strobel [1980], on the basis of data obtained with the Voyager Ultraviolet Spectrometer (UVS), discovered another feature that is, thus far, unique to Jupiter – the hydrogen bulge. This feature is a mountain of atomic hydrogen in Jupiter's upper atmosphere that remains fixed in System III coordinates. The hydrogen bulge is located at longitude $\lambda_{III} \approx 90°$ and a latitude 10° to 15° north of the spin equator. Its longitude is approximately 180° removed from the longitude of the maximum plasma concentration in the Io torus, and its latitude is coincident with that of the particle drift equator. The contours of the hydrogen bulge as seen in resonantly scattered solar H Lyman Alpha (Lyα) are shown in Figure 10.9. The particle drift equator is the locus of the minimum in the magnetic field strength at ionospheric levels, that is, it is the locus of energetic particles at ionospheric height having 90° equatorial pitch angles. The coincidence of the hydrogen bulge and the particle drift equator, and the fact that the neutral atomic hydrogen enhancement that constitutes the hydrogen bulge corotates with the magnetic field (System III) rather than with the clouds and underlying neutral atmosphere (System II), make it obvious that the hydrogen bulge is created by some sort of interaction between the upper atmosphere and the energetic charged particles trapped in the Jovian magnetic field.

The existence and the stability of the hydrogen bulge are established by independent observations by Clarke et al. [1980] and Clarke, Moos, and Feldman [1981]. The observations, which were obtained over a period of nearly two years, suggest that the longitude of the bulge varies by up to about 30°, and the amplitude of the bulge (the excess column content of atomic hydrogen) varies by about a factor of two.

The hydrogen bulge is explained by the magnetic-anomaly model in terms of a two-cell convection pattern that corotates with Jupiter [Dessler, Sandel, and Atreya, 1981]. The convection is driven by the asymmetrical mass-loading of the plasma torus described in the following subsection (see also Chap. 11). An alternative explanation in terms of centrifugally driven flow of atomic hydrogen from the northern auroral zone is offered by Clarke, Moos, and Feldman [1981].

e. Longitudinal asymmetry in radial extent of torus plasma. Ground-based observations of singly ionized sulfur by Pilcher et al. [1981] show transient extensions of this plasma out to 7 or 8 R_J in the same System III longitude range as the maximum in torus density described previously. In this longitude range, the transient [S II] extensions are always outward from the torus, never toward Jupiter. At longitudes removed roughly 180° from these outward extensions, the motion of the sulfur is never away from Jupiter [Pilcher et al., 1981]. These transient extensions of the torus plasma from its average position can be explained as another manifestation of corotating convection within the Jovian magnetosphere. The sporadic nature of these plasma motions, and the variability in the amplitude and location of the hydrogen bulge described in the preceding subsection, would indicate that the convection is not a steady state phenomenon.

f. Longitudinal temperature asymmetry. There is evidence that the temperature of plasma within the magnetosphere shows a longitudinal asymmetry. Specifically, the results from the Low-Energy Charged Particle Experiment, described in Chapter 4, indicate that the temperature of protons is systematically higher in one of the two equatorial crossings than the other. This experimental result is shown in Figure 4.17. The higher temperature peak is marked A, in reference to the active sector of the magnetic anomaly model. (See the following discussion for a description of this model.) Evidence of a higher temperature in the active sector is also observed closer to Jupiter. The decimetric emission, which is generated by synchrotron radiation from relativistic electrons at about 2 R_J, is observed by de Pater [1980b] to be brightest at $\lambda_{\rm III} \approx 270°$. The proton temperature maximum in Figure 4.17. appears only at $\lambda_{\rm III} \approx 300°$ because of limitations imposed by the flyby trajectory. The actual maximum might be at $\lambda_{\rm III} \approx 270°$, but the spacecraft did not cross the equator at this longitude.

The relative relationships in longitude of the phenomena described in the preceeding subsections a through f are illustrated in Figure 10.10.

g. Modulation of magnetospheric plasma, energetic particles, and magnetic fields. The most striking feature of the Jovian magnetosphere seen during the outbound trajectories of P 10, V 1, and V 2 is the confinement of magnetospheric plasma and energetic particles to a thin disc. By disc we mean a configuration that is thin in latitude compared to its extent in longitude. Although the current sheet extends inward to about $5R_J$, the field remains principally dipolar in character with the disc geometry starting at about 20 R_J and extending to at least 60 to 80 R_J in the predawn quadrant (see Chap. 1, particularly Figs. 1.20 and 1.23). Beyond that distance, with but a few exceptions, only one contact was made with the plasma and energetic particles during each planetary rotation. This behavior is discussed in some detail in Chapter 5, see particularly Figure 5.6, and by Fillius and Knickerbocker [1979]. The effect of a magnetodisc confinement is to produce, for an observer near the spin equator, two passages through the disc during each planetary rotation, as illustrated schematically in Figure 10.8a.

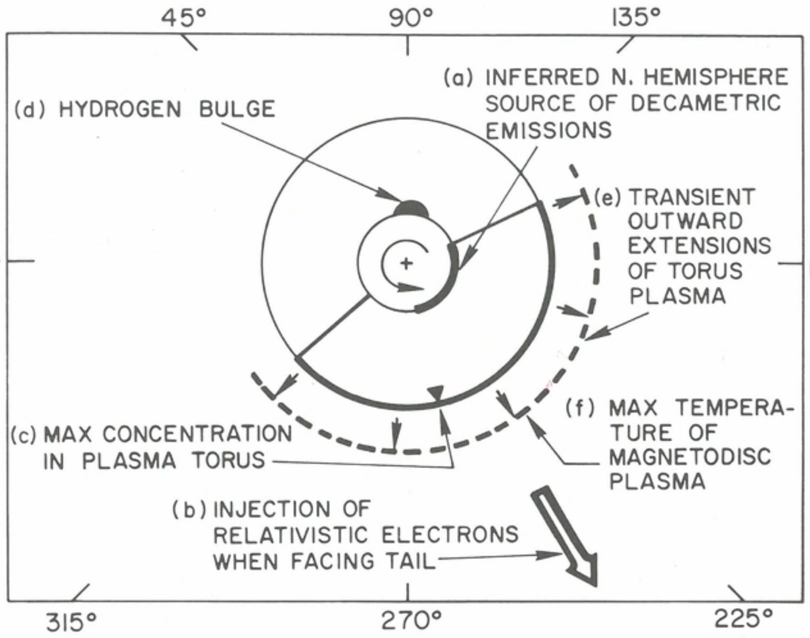

Fig. 10.10. Illustrative sketch showing various phenomena that can be explained in terms of the magnetic-anomaly model. The angular extent of each phenomenon is shown approximately to scale, but the radial distances are not.

h. Asymmetric spiraling of magnetodisc. Pioneer 10 and Voyagers 1 and 2 traversed the predawn magnetosphere at sufficiently low latitude to encounter the magnetodisc, once each planetary rotation for P 10 and twice each rotation for V 1 and V 2. It was noted, first using P 10 data, that the System III longitude at which the disc crossed the extended dipole magnetic equator increased with increasing radial distance [Northrop, Goertz, and Thomsen, 1974; Eviatar and Ershkovich, 1976; Kivelson et al., 1978; Goertz, 1981]. The most common explanation for this effect is in terms of the finite speed of propagation of the position of the rotating tilted dipole to the distant magnetodisc. If the spiraling is represented as a longitudinal shift between the expected equatorial crossing of the disc and its observed position, a curious effect was noted by the Voyager experimenters [Barbosa et al., 1979; Bridge et al., 1979a,b; Krimigis et al., 1979a,b; Vogt et al., 1979a,b]: of each pair of consecutive crossings, the two were systematically but oppositely displaced relative to the position predicted from the formula derived earlier by Kivelson et al. [1978] with the assumption of a constant radial propagation speed. That is, in the course of each planetary rotation, one of the two crossings always occurred earlier than expected, and the other always occurred later; the tightness of the spiraling appears to be a function of longitude.

Two distinct explanations have been offered to account for this effect. Vogt et al. [1979a,b] suggest that the speed of radial propagation from the rotating, tilted dipole to the disc is a function of longitude, the propagation speed being a minimum in the active sector as defined by the magnetic-anomaly model (see Secs. 5.4 and 10.7). This explanation has been further developed by Vasyliunas and Dessler [1981] who show that, with no additional assumptions, a single set of parameters can be selected that fit the P 10 as well as the V 1 and V 2 outbound observations. Adopting an alternative approach, Bridge et al. [1979b], Carbary [1980], Behannon, Burlaga, and Ness [1981], and Goertz [1981] have developed similar quantitative models in which the disc, in addition to spiraling, is hinged at about 40 R_J in the tailward sector. That is, the disc is bent away from the magnetic equator toward the spin equator, and this bending starts at about 40 R_J. In order to fit both P 10 data, which do not show evidence for hinging, and V 1 and V 2 data, which do, the hinging action is attributed to the action of the magnetospheric tail [Goertz, 1981], which is assumed to be pulled to within about 3° of the spin equator by the solar wind. There seems to be no clear test with presently available data to differentiate between these alternative explanations.

Models advanced to account for spin periodicities

There are two basic models that pertain to various of the observed spin periodicities: (a) the tilted dipole or disc model and (b) the corotating active-sector or magnetic-anomaly model. These are illustrated schematically in Figure 10.8.

Disc and magnetic-anomaly models – phenomenological distinction. With the disc model, an observer O, at or near the spin equator, sees two similar phenomena each planetary rotation, either at Frame (a)1 and (a)3 of Figure 10.8 when respectively the south and north polar caps are tipped toward the observer or at Frames (a)2 and (a)4 when the observer passes through the plane of the magnetic equator or through the plane of the disc. There are variations on this model that include spiraled, bent, warped, and wavy discs, but all have the feature that an observer near the spin equator sees two events per planetary rotation.

With the extreme version of the magnetic-anomaly model, there is only one event per rotation, either as in Frame (b)3 when the active sector points toward the observer, or, for certain phenomena, as in Frame (b)1 when the active sector points away from the observer. The magnetic-anomaly model also includes "clock" behavior wherein some phenomenon that can be propagated omnidirectionally occurs each time the active sector points in some particular direction relative to the solar wind, for example, either toward the Sun or toward the Jovian magnetospheric tail. Thus, if the solar wind were coming from the left in Figure 10.8, a particular clock-type phenomenon would occur at either Frame (b)1 or (b)3. As with the disc model, there are variations to this elementary form of the magnetic-anomaly model that involve propagation and convective effects.

Before the Voyager flybys of Jupiter, some proponents of the magnetic-anomaly model posed an "either or" case for the magnetic-anomaly model vs. the disc model [see, for example, Dessler and Vasyliunas, 1979]. It is now clear that Jupiter's magnetosphere is complex enough to involve, in one way or another, nearly all ideas that have been developed thus far. In particular, the idea of a thin disc in the predawn quadrant of the magnetosphere is fully confirmed by the Voyager flybys, but it also appears that the disc involves magnetic-anomaly effects.

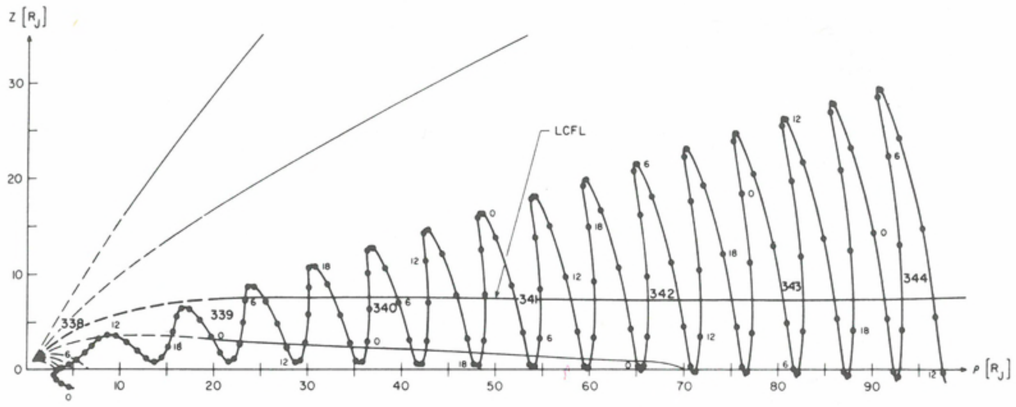

Fig. 10.11. Magnetic field lines superposed on the "wiggle-plot" trajectory of Pioneer 10 outbound, which is projected on a ρ, z plot where ρ is the axial distance from the tilted magnetic dipole and $z = 0$ is the spiraled magnetic equator. The line marked LCFL is the last closed field line above the $z = 0$ plane; the magnetodisc is presumed to be contained within that line and its mirror image below the $z = 0$ plane [after Goertz et al., 1976].

Magnetodisc models. One of the most striking features of the Jovian magnetosphere, particularly in the predawn quadrant, is the confinement of plasma and energetic particles to a narrow latitudinal range with relatively small asymmetries in longitude. That is, the latitudinal gradient in plasma concentration and energetic particle flux is large while, for many purposes, the longitudinal gradient can be neglected. The relative thinness of the disc is illustrated in Figure 10.11 (although its absolute thickness, as great as 4 to 5 R_J, is such that it could encompass the entire terrestrial magnetosphere). Liu [1982] has concluded that the thickness of the disc may be a function of both radial distance and longitude, but, for many purposes, such variations are unimportant. The day side region between about 0900 and noon local time (LT) (P 10 in, P 11 in and out, V 1 in, and V 2 in) does not exhibit the sharp latitudinal confinement that is characteristic of the night side region thus far observed between about 0300 and 0500 LT (P 10 out, V 1 out, and V 2 out). (See Fig. 5.1 for spacecraft trajectories.) However, there is enough concentration of plasma and energetic particles toward the magnetic equator to allow one to carry the concept of the magnetodisc to the day side [Jones et al., 1981], even though the term "disc" may not be strictly applicable.

Fillius and Knickerbocker [1979] have pointed out that the term "disc" may not be applicable to the day side because the energetic particles are not confined to a narrow range of latitude as they are on the night side. Specifically, Pioneer 11, which was at least 30° north of the magnetic equator during its daytime outbound passage, saw much the same time variation as other spacecraft that passed through the equator on the dayside. Moreover, the magnetic signature of the disc is less pronounced on the day side than in the predawn quadrant. Thus, although there is some concentration of plasma and energetic particles toward the magnetic equator, there is other evidence against the existence of a simple disc on the day side. It is assumed (sometimes tacitly) by proponents of the disc model that the thin disc is broadened or modified on the day side by solar-wind effects, but that disc confinement of plasma and energetic particles prevails through most of the night side magnetosphere.

There are, at present, neither direct measurements nor even qualitative theory to tell us how the plasma and energetic particle populations are confined through the rest

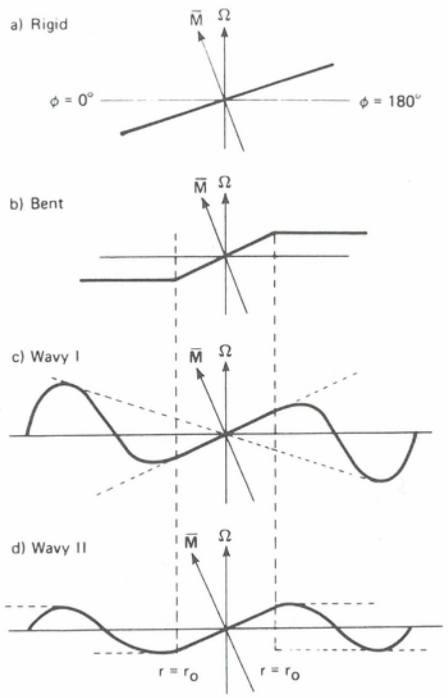

Fig. 10.12. Magnetodisc models [after Carbary, 1980]. The rigid disc (*a*) is formed by a hot plasma, the bent or hinged disc (*b*) occurs either for a plasma sufficiently cool that centrifugal force dominates the magnetic mirror force or when external stress such as that produced by a magnetotail becomes important. A wavy disc (*c*), which corresponds to (*a*), or (*d*), which corresponds to (*b*), results if propagation delays are important. All of these disc models spiral out of the meridional plane. Although the illustrations imply some degree of axial or reflection symmetry, the plasma and energetic particles on the dayside region investigated thus far do not organize themselves into such a symmetrical thin disc.

of the magnetosphere. That is, measurements within a 2-hr local-time interval in the night side magnetosphere show a well-formed disc; on the day side there is a 3-hr local-time interval in which the sharp disc appears to be broadened in latitude. Extrapolation of these results to the remaining 19 hr of local time remains uncertain pending theoretical development and future observations.

The plasma that determines the configuration of the magnetodisc is hotter than its principal source, namely the plasma in the Io torus (Chaps. 3, 4, 11, and 12). Outward transport should cool the torus plasma by simple adiabatic expansion, but this cooling tendency is overpowered by a heating mechanism yet to be identified. (A possible ionospheric heating source is discussed in Chap. 12; see also Barbosa [1981].)

Goertz [1976b] developed a quantitative model of a Jovian hot plasma disc, and showed that "hot" for the case of a magnetodisc means that the average ion cyclotron speed is significantly greater than the corotation speed at a given radial distance [see also Hill et al., 1974]. A hot plasma disc would be rigidly aligned with the magnetic equatorial plane whereas a cold disc would "hinge" toward the rotational equatorial plane because of centrifugal stress [Hill et al., 1974; Goertz, 1979]; the rigid disc model appears to be consistent with data from Pioneer 10 outbound [Goertz, 1976b]. The Pioneer 10 data alone are not unambiguous, however. Specifically, Jones et al. [1980] were able to get an acceptable fit with a hinged, spiraled disc, although their model requires the somewhat ad hoc assumption of a longitudinally confined corrugation of the disc. The difference between a rigid and a hinged or bent disc is shown schematically in Figures 10.12*a* and 10.12*b*. Analysis of detailed relationships between magnetic field magnitude and energetic proton flux led Walker et al. [1978] to conclude that "low energy (≤ 5 keV) plasma contributes less than 3% to the current-sheet energy density." These conclusions are confirmed by direct measurements by Krimigis et al. [1979a, 1979b, and Chap. 4] and indirectly by Barbosa et al. [1979], so the weight of the evidence indicates that the plasma is hot so that centrifugal force is not important in determining the morphology of the portion of the magnetodisc thus far observed.

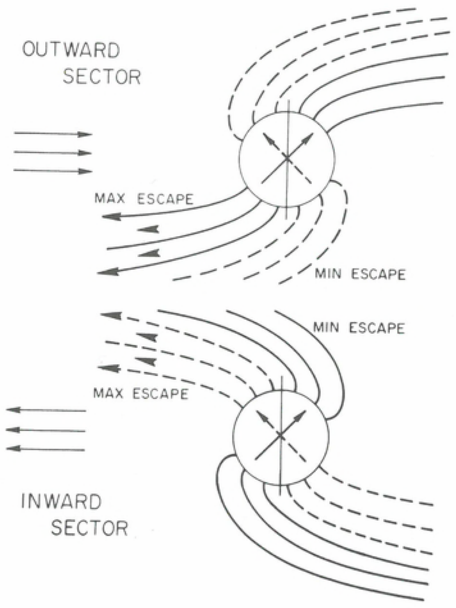

Fig. 10.13. Sketch illustrating how the phase of the clock governing the escape of energetic electrons from the Jovian magnetosphere would shift by five hours after a sector boundary crossing if the rate of escape were controlled by magnetic merging between the Jovian and interplanetary magnetic fields. The solid arrow shows the orientation of the dipole at some arbitrary time, and the dashed arrow shows the dipole five hours later. The circle represents the magnetosphere, and the dashed and solid lines external to the circle represent the interplanetary magnetic field. The phase shift expected by this model is not observed.

Although the Pioneer 10 outbound pass at about 0500 LT did not show any appreciable deflection or "hinging" of the magnetodisc from the dipole equator of Jupiter's magnetic field, the Voyager 1 and 2 outbound measurements indicated what has been interpreted as evidence for hinging, even though the plasma in the magnetodisc fulfills the criterion for a hot plasma, which should form a rigid disc. Centrifugal effects should not be important for a hot plasma, but solar-wind stress, transmitted through Jupiter's magnetotail, might be. Thus, it has been suggested by Ness et al. [1979b] that hinging has been observed because of an antisunward stress on the disc produced by the Jovian magnetic tail (see Chaps. 1 and 5). This conclusion has been challenged by Vasyliunas and Dessler [1981] and defended by Goertz [1981] and Thomsen and Goertz [1981a]. The matter is discussed further in Chapter 11. It is possible that this issue can be resolved by more detailed, quantitative analysis of existing data.

Magnetic-anomaly models. The development of the magnetic-anomaly model was initially put forth to explain the discovery by Chenette, Conlon, and Simpson [1974] of the clock modulation of the spectral index of relativistic electrons in interplanetary space (see Sec. 10.7b). To understand this phenomenon, it is necessary to find some means of relating the orientation of the internal magnetic field of Jupiter relative to the solar wind with a modulation in the escape of relativistic electrons from the Jovian magnetosphere into interplanetary space. A simple interaction between a magnetodisc and the solar wind or the magnetopause will not work because a 5-hr variation would be produced as suggested schematically in Figure 10.8a, and the observed modulation has a 10-hr periodicity. Nor will a simple connection between the Jovian magnetic field and the interplanetary magnetic field suffice. Figure 10.13 illustrates how such a scheme would lead to a 180°, or 5-hr, shift in phase whenever the direction of the interplanetary field switched by 180°, as occurs at sector boundary crossings, for example.

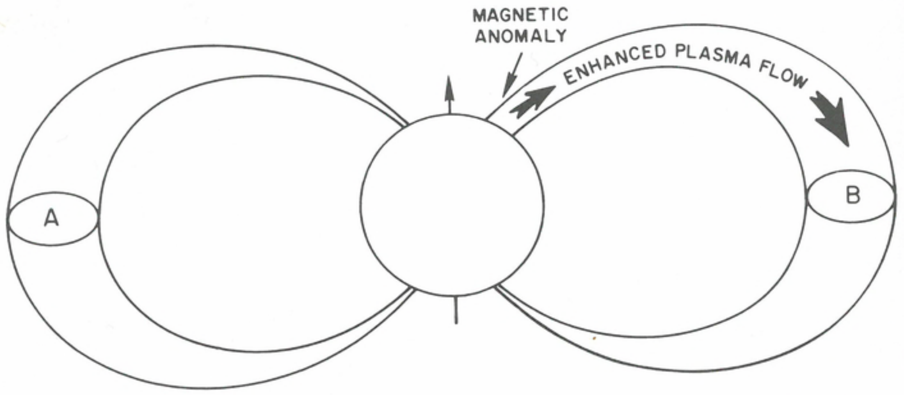

Fig. 10.14. Schematic illustration of how a magnetic anomaly enhances the flow of ionospheric plasma into the Io torus and the magnetosphere. Flux tubes A and B have the same cross-sectional area at the equator. However, flux tube B, which enters a negative magnetic anomaly (a weak-field region) in the northern hemisphere has a larger foot than either foot of flux tube A. The effect of a larger foot is that, for a given ionospheric escape flux, more ionospheric plasma will be transported to the equatorial plane by flux tube B.

Because such phase shifts are not observed, some other internal linkage must be sought. The only other idea that has thus far been developed is the magnetic-anomaly model wherein an extensive area of weak surface magnetic field is reflected to large radial distances as an enhancement in plasma concentration [Dessler and Hill, 1975].

The magnetic-anomaly model is simple in concept. The basic idea is that high-order multipoles in Jupiter's internal magnetic field produce, through one or more plasma processes, a gross longitudinal asymmetry within the magnetosphere at unexpectedly large Jovicentric distances. As can be seen by comparing the total surface field intensity with the total field intensity at 2 R_J in Figure 1.1, the direct contribution of the quadrupole and octopole moments are very small even at a distance of 2 R_J; at 6 R_J, the Jovicentric distance of the Io plasma torus, the magnetic field is completely dominated by the dipole component.

In planetary magnetism, a magnetic anomaly is defined as a deviation of the surface magnetic field from that expected from the best-fit displaced dipole. Thus, Figure 1.5 is a magnetic-anomaly map, that is, it shows the surface field minus the displaced dipole field. The magnetic anomaly of interest is the depressed field region in the northern hemisphere centered near $\lambda_{III} = 260°$. There may also be some magnetic anomaly influence from the smaller area of depressed field in the southern hemisphere around $\lambda_{III} = 45°$.

There are at least two ways a magnetic anomaly might affect the distribution of plasma within the Jovian magnetosphere so as to produce a longitudinal asymmetry. The two suggestions advanced thus far are (1) a longitudinal variation in the escape flux of plasma from the Jovian ionosphere [Dessler and Hill, 1975] and (2) a longitudinal variation of the height-integrated conductivity of the Jovian ionosphere [Dessler and Hill, 1979]. The most obvious observed manifestation of a plasma asymmetry within the magnetosphere is the longitudinal asymmetry of the Io plasma torus described above. Much of the controversy surrounding the magnetic-anomaly model centers on how much weight should be given to this asymmetry, which is seen only in the cold torus and not in the hot torus. Needless to say, proponents of the magnetic-anomaly model regard the observed cold-torus asymmetry with some reverence.

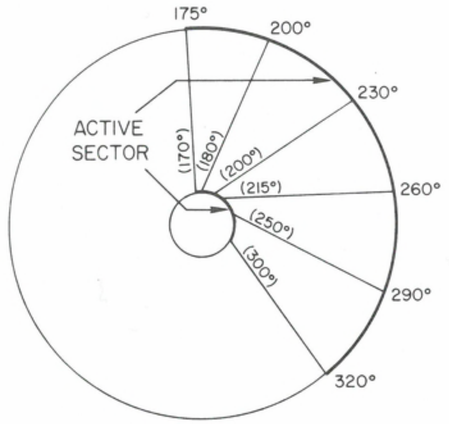

Fig. 10.15. Schematic view from above the north pole showing the longitudinal extent of the active sector. The outer circle represents the Io plasma torus and the longitude extremes of $\lambda_{III} = 175°$ and 320° are the approximate limits of the active sector within the torus. The System III longitudes of intermediate positions are marked as well as the longitudes of these positions when followed down magnetic field lines to the northern hemisphere ionosphere. These ionospheric longitudes, which are shown in parentheses, extend from $\lambda_{III} = 170°$ to 300°.

The way in which a longitudinal asymmetry in magnetospheric plasma loading from the ionosphere can be caused by a surface magnetic anomaly is illustrated in Figure 10.14. Given two magnetic flux tubes with equal equatorial cross-sectional areas and at the same equatorial distance from the displaced dipole, it is obvious that the flux tube with its foot in the magnetic anomaly has a larger cross-sectional area at ionospheric heights, and therefore it conducts a larger escape flux of ionospheric plasma to the equatorial plane.

The second mechanism is related to an enhancement of ionospheric conductivity within the magnetic-anomaly region. The conductivity enhancement is a twofold effect of the reduced magnetic field within the magnetic anomaly. First, the conductivity is increased because the Pedersen conductivity in the ionosphere is approximately inversely proportional to the magnetic field strength. Second, the ionization rate by particle bombardment within the magnetic-anomaly region should be greater because of the reduced mirror altitude and correspondingly larger loss cone for trapped particles where the surface magnetic field is weaker. Dessler and Hill [1979] estimate that the height-integrated Pedersen conductivity within the magnetic-anomaly region is increased by an order of magnitude or more over the conductivity at other longitudes.

Given these two direct consequences of a magnetic anomaly, enhanced plasma loading of the magnetosphere in the longitude range of the magnetic anomaly can be accomplished by one of a number of processes [Dessler and Hill, 1975, 1979; Dessler, Sandel, and Atreya, 1981]. The most common theme is that un-ionized gas escapes from Io, goes into Keplerian orbit around Jupiter, and is subsequently ionized, with the ionization occurring most rapidly in the magnetic-anomaly region. Some such process would account for the observed longitudinal asymmetry in the cold torus, although the question remains as to why the asymmetry is not mimicked in the hot outer torus.

The magnetic-anomaly region and the magnetically connected region of the Io torus is the active sector defined by Vasyliunas [1975b] as the System III longitude range that is associated with non-Io-related radio noise when facing the Sun and the release of relativistic electrons into interplanetary space when facing the tail (see also Sakurai [1976]). Because of the contribution of higher-order multipoles to Jupiter's magnetic field, connections between the torus and the ionosphere are not along meridional planes, as is illustrated in Figure 10.15; the longitudes of magnetically connected torus and ionospheric elements can differ by as much as 45°. The longitude range of the active sector is presently uncertain to within perhaps ±25°.

A longitudinally asymmetric loading of the magnetosphere leads immediately to a longitudinal asymmetry in the radial transport of magnetospheric plasma; specifically,

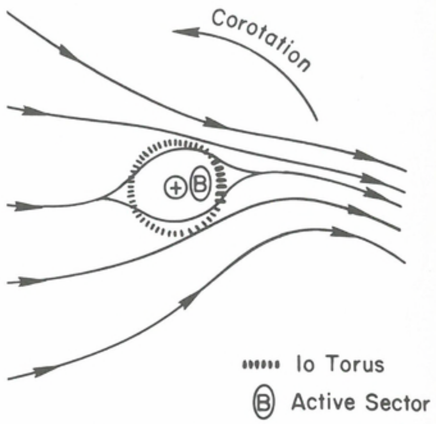

Fig. 10.16. The denser portion of the Io plasma torus moves outward because of the action of centrifugal force. This motion establishes an electric-field pattern that causes the rest of the magnetospheric plasma to move in a corotating convection pattern roughly as shown. The magnetic anomaly region corresponds to flux tube B in Figure 10.14. The convection is probably sporadic.

it has been proposed that the transport occurs in the form of a two-cell convection pattern that corotates with Jupiter [Vasyliunas, 1978; Dessler, Sandel, and Atreya, 1981; Hill, Dessler, and Maher, 1981]. The convection is outward from the active sector and inward in the conjugate sector (180° removed in longitude), as illustrated in Figure 10.16. A two-celled convection pattern is thus established that corotates with the planet.

The convection is likely to be a time-varying, if not impulsive, phenomenon. There are two reasons for this conclusion: (1) The convection period is calculated by Hill, Dessler, and Maher [1981] to be as short as 15 hr, with 30 hr being more probable. The escape of material from Io to supply the plasma torus appears to be too slow to allow such rapid convection to proceed continuously. The introduction of the concept of a duty cycle into the corotating convection model reduces the required rate of supply to an acceptable level. (2) Phenomena that are proposed to be related to or controlled by convection show an erratic, time-varying behavior. For example, the amplitude and longitude of the hydrogen bulge vary, the decametric radio emissions from Jupiter show evidence of nulling and timing jitter (in pulsar parlance), the amplitude and longitude of the maximum in the mass density in the cold torus can change appreciably on a time scale of one Jovian rotation period, and the escape of relativistic electrons into interplanetary space, while a reproducible phenomenon, is not a continuous one. The time and longitude variations in these phenomena can be understood on the basis of time variation in the pattern of corotating magnetospheric convection.

An explanation of the first five phenomena listed in Table 10.4, and graphically illustrated in Figure 10.10, follows naturally as a consequence of the corotating convection that results from the magnetic anomaly model. For example:

a. Decametric radio emission is generated principally in the active sector. The ionospheric conductivity has its maximum value there, and the most intense Birkeland currents should flow between the active sector and the density maximum in the torus. These intense Birkeland currents presumably lead to the generation of radio noise by current driven instabilities [Dessler and Hill, 1979; Dessler, 1980; see Chap. 9]. When Io is near the active sector, additional plasma injection into the torus causes the Birkeland currents to be enhanced and the radio emissions to brighten correspondingly.
b. Modulation of the energy spectrum of electrons released into interplanetary space occurs because magnetospheric plasma and energetic particles escape primarily through the Jovian magnetic tail; this flow is enhanced once each planetary rotation when the corotating convective outflow is directed tailward [Hill, Carbary, and Dessler, 1974; Hill and Dessler, 1975].

c. The longitudinal asymmetry of the Io plasma torus probably arises from an ionizing interaction between neutral particles escaping Io and the active sector. This asymmetry is more correctly regarded as a cause than a consequence of corotating convection.
d. The hydrogen bulge, presently the strongest evidence for the existence of corotating convection, is caused by inflow of hot magnetospheric plasma which dissociates CH_4 and H_2 in Jupiter's upper atmosphere [Dessler, Sandel, and Atreya, 1981].
e. The longitudinal asymmetry of the radial extent of plasma from the Io torus, as reported by Pilcher et al. [1981], can be regarded as visual evidence of the plasma flow expected from a corotating convection system.

The longitudinal asymmetry of plasma temperature (item f) might also be related to the corotating convection pattern, but the nature of this connection is not clear at present because the nature of the plasma acceleration mechanism itself is not clear. Whatever this acceleration mechanism may be, an important clue may be provided by the fact that it appears to be more effective in the active sector.

10.8. Conclusion

We have described a number of theoretical concepts that have been applied more-or-less successfully to the explanation of observed Jovian magnetospheric phenomena. The emerging picture of Jovian magnetospheric dynamics differs radically from that of the terrestrial magnetosphere, although our progress in understanding the Jovian magnetosphere is undoubtedly aided by the experience gained in several years' detailed study of the terrestrial magnetosphere. The important differences apparently result from the internal sources of plasma and energy within Jupiter's magnetosphere, giving rise to a variety of spin-periodic phenomena. These phenomena are generally attributed to the diurnal precession of Jupiter's tilted magnetic dipole (the disc model) and/or the corotation of a longitudinally asymmetric magnetospheric plasma feature (the magnetic anomaly model). Each type of model has had some success at explaining (as opposed to merely describing) some of the phenomena, although neither type of model, as presently formulated, can account for all of the observed phenomena. Moreover, the Saturnian magnetosphere exhibits spin-periodic control of low-frequency radio emissions reminiscent of that in the Jovian magnetosphere [Warwick et al., 1981], even though Saturn's intrinsic magnetic field does not exhibit the significant tilt required for modulation by a disc model. The Voyager trajectories were not adequate to detect a modest nondipole component of the type required for a magnetic anomaly model.

Further theoretical work (and perhaps acquisition of new data) are required before we will be in a position to set forth a comprehensive Jovian magnetosphere model that encompasses the known phenomenology of Jupiter's magnetosphere and elucidates the connection (or lack of connection) between spin-periodic phenomena in the Jovian, Saturnian, and pulsar magnetospheres. Such a model must address (at least) the following fundamental unanswered questions:

What is the nature of the electrodynamic Io–Jupiter interaction, and why does the strength of this interaction appear to depend on Jovian longitude?

How is material removed from Io and ionized to form the plasma torus? (This question is discussed further in Chap. 6.)

How is the Io torus plasma transported outward to form the magnetospheric current sheet and planetary wind? (This question is discussed in detail in Chap. 11.) In particular, why does a persistent longitudinal asymmetry appear in the inner, cooler torus but not in the outer, warmer, UV-emitting torus?

By what mechanism is torus plasma heated (rather than adiabatically cooled) as it moves outward in the magnetosphere?

How are ions and electrons from the torus accelerated to form the extensive radiation belt?

How do relativistic electrons escape from Jupiter's magnetosphere with evidence of modulation at the Jovian spin period?

A comprehensive model of the Jovian magnetosphere should be expected not only to address these questions individually but also to expose the physical connections among the answers to these and many subsidiary questions. We have identified a number of conceptual ingredients that may be important in formulating such a model, and a number of problem areas where additional theoretical work is called for in the context of present observational knowledge. The development of a comprehensive model will, however, probably require a much broader data base than is available now. Only then will we be in a position to apply our understanding of Jupiter's magnetosphere with confidence to other magnetospheres outside the solar system.

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11

PLASMA DISTRIBUTION AND FLOW

Vytenis M. Vasyliunas

The highly extended magnetic field-line configuration of the Jovian magnetosphere with a near-equatorial current sheet and associated plasma sheet arises from mechanical stresses in the rotating plasma balanced by magnetic stresses. The relative geometrical thinness of the current sheet permits the use of several approximations in the description of the stress balance, each with a specified regime of validity in terms of taillike vs. dipolar field and hot vs. cold plasma; these include pressure balance, a simplified tangential stress balance, and an estimate of current-sheet thickness. A number of simple but quantitative models of the magnetic field are now available, including both theoretical models based on various assumptions about the distribution and degree of corotation of the plasma and empirical models intended to represent the observations. From the empirical models, values of plasma parameters required to maintain stress balance can be estimated. To obtain agreement between the estimated and the observed mass density values, it is necessary to assume that the azimuthal velocity of the plasma decreases significantly below rigid corotation in the outer magnetosphere. The uncertainties in the magnetic field component normal to the current sheet lead to sizable discrepancies among various estimates of the density or of the current sheet thickness. Azimuthal magnetic fields over the midnight-to-dawn quadrant are nearly independent of local time, in contrast to the situation in the terrestrial magnetosphere; they imply radial currents whose closure through the ionosphere is related to partial corotation. Generalization of Parker-spiral arguments to include a finite ionospheric conductivity provides a quantitative model for the azimuthal field. To keep the angular acceleration of the plasma within the required bounds, a mass flow of at least some 10^{30} to 10^{31} amu/s must be assumed but it is not yet clear whether this is a net outflow or primarily a circulation. Dipole tilt effects on the current sheet can be quantitatively modeled within the rigid corotation region; at larger distances, only qualitative propagating-wave descriptions plus empirical fits are available. Plasma flow models so far are mostly qualitative except for the description of partial corotation. The inability of magnetic stresses to maintain centripetal acceleration of a given flux tube content of plasma beyond a limiting distance is expected to result in a radial outflow (the planetary wind) and associated changes of magnetic field topology; the implied flow pattern is very similar qualitatively to the observed magnetospheric wind.

11.1. Introduction

The role of magnetospheric plasma in determining the configuration and dynamics of the magnetosphere is considerably more important at Jupiter than it is at Earth. If we imagine a sphere centered on the planet and require that the effects of the plasma inside the sphere on the magnetic field represent no more than a fractional perturbation of the total field, then the radius of the sphere could be allowed to reach almost the distance to the subsolar magnetopause at Earth but hardly a tenth of that at Jupiter. Consistency between the magnetic field configuration and the plasma distribution and flow is thus a major constraint on the physical description of almost the entire Jovian magnetosphere, whereas in the terrestrial case it is for most purposes a significant requirement only in the outermost boundary regions and the magnetotail. The main concern of this chapter is the extent to which various aspects of Jovian magnetospheric configuration and dynamics can be understood in a unified and self-consistent fashion