$$\frac{\partial N^{ie}}{\partial t}(\mathbf{k}) = \frac{1}{V}\sum_{s,s'} w_s^{s'}(\mathbf{k}) N^{ie}(\mathbf{k})[f(s) - f(s')] \tag{A.22}$$

Again taking the classical limit, we obtain for the sum of coherent and incoherent emission, (see Melrose [1968] for details)

$$\frac{\partial P}{\partial t}(\mathbf{k}) = \sum_{\nu} \int d^3p\,[(1 + (1/2)D_\nu)\,w(\mathbf{k})_{p_\parallel,n,\nu}\,P(\mathbf{k})]\,D_\nu f(\mathbf{p}) + \frac{\partial P^{se}}{\partial t} = \gamma(\mathbf{k})P(\mathbf{k}) + \alpha(\mathbf{k}) \tag{A.23}$$

where

$$D_\nu = \hbar\left[\frac{\nu\omega_c m}{p_\perp}\frac{\partial}{\partial p_\perp} + k_\parallel\frac{\partial}{p_\parallel}\right]$$

A Taylor expansion of $f(s')$ has been used in deriving (A.23). The expression for the growth rate $\gamma(\mathbf{k})$ can now be found from (A.23) for D_ν under the assumption that $f(\mathbf{p})$ is gyrotropic, the quantum correction $(1/2)D_\nu$ is negligible, and $w(\mathbf{k})$ is given by (A.16). The final result is Equation (2.1).

Under many conditions one can also show [Kennel, 1966; Melrose, 1968; Hasegawa, 1975]

$$\gamma(\mathbf{k}) = Im[\Lambda(\mathbf{k},\omega)] \,/\, \{\partial Re[\Lambda(\mathbf{k},\omega)]/\partial\omega\} \tag{A.24}$$

10

MAGNETOSPHERIC MODELS

T. W. Hill, A. J. Dessler, and C. K. Goertz

Theoretical ideas concerning Jovian magnetospheric phenomena are at least as diverse as the phenomena themselves, and there presently exists no single comprehensive model that encompasses all known phenomena within a unified theoretical framework. We identify here a number of important theoretical concepts, some subset of which (together with perhaps others yet unidentified) will ultimately provide the elements of such a comprehensive model. A number of ideas have been advanced to account for the copious plasma source associated with Io, but none of these has yet accounted satisfactorily for both the magnitude and the morphology of the inferred source. Nevertheless, given the observed fact that Io supplies the bulk of the magnetospheric plasma mass, and the corollary that the net plasma transport is predominantly outward, it follows that the rotational energy of Jupiter is an important if not dominant source of energy for magnetospheric phenomena. This rotational energy is expended in a variety of phenomena, including the electrodynamic Io–Jupiter interaction and associated radio and auroral emissions, the acceleration of charged particles to MeV energies, and the generation of a wide variety of spin-periodic phenomena as observed both remotely and in situ. The spin periodicities observed within the magnetosphere can be explained for the most part as resulting from the diurnal wobble of the magnetospheric current sheet caused by the offset between Jupiter's magnetic dipole axis and its spin axis. However, remotely observed spin periodicities (the "pulsar" phenomena) apparently require the existence of an intrinsic longitudinal asymmetry in the Jovian magnetosphere that corotates with Jupiter.

10.1. Introduction

Many celestial bodies have magnetospheres, that is, surrounding regions within which the motion of charged particles is influenced by the magnetic field of the central body. In addition to the terrestrial magnetosphere, which has been studied in increasing detail over the past three decades, the magnetospheres of Mercury, Jupiter, and Saturn have now been explored in situ. The Sun has a magnetosphere of sorts (the heliosphere), and there is evidence that pulsars, accreting binary star systems, and certain radio galaxies also have magnetospheres. Of the planetary magnetospheres that have been explored, Jupiter's is by far the largest in terms of both absolute size and size relative to the planetary body. It is also a magnetosphere largely dominated by rotational effects; as such, it offers unique insight to the study of inaccessible pulsar magnetospheres.

The present state of knowledge of Jupiter's magnetosphere is reminiscent of the state of knowledge of Earth's magnetosphere in the early 1960s – the observational data are sufficient to inspire a variety of theoretical developments but not sufficient in most cases to dictate a clear choice among them. Future observations will probably verify some of the theoretical concepts described below, and will probably disprove others. We shall concentrate here on those theoretical concepts that we believe to be consistent with available observations as described elsewhere in this book, and we shall explicitly point out areas of divergent views or inadequate study.

Our data base is relatively incomplete in coverage (local time, latitude, time, etc.), compared to the terrestrial magnetospheric data base, but there is a tendency to suppose that we can learn more now from a limited data base by drawing on several years'

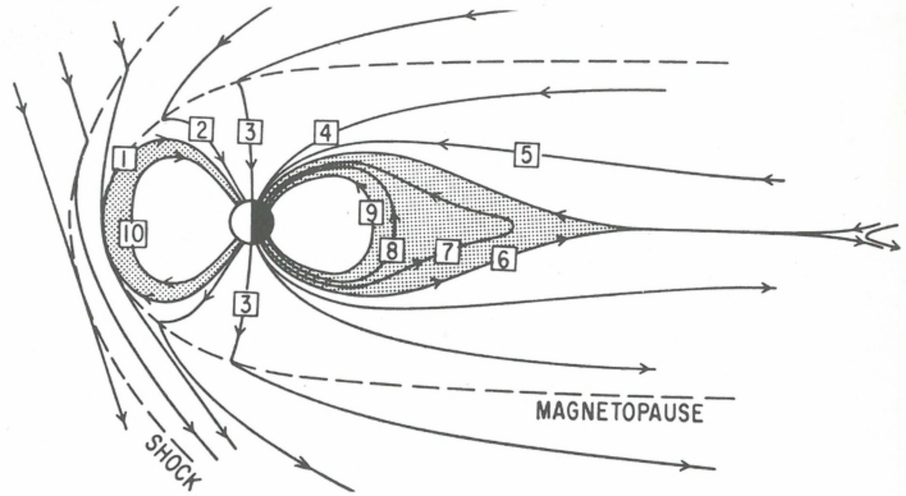

Fig. 10.1. The open model of Earth's magnetosphere [after Axford, 1969] in which, according to conventional wisdom, the solar-wind magnetic field becomes interconnected with the geomagnetic field on the dayside magnetopause (e.g., the field line labeled "1"), and the solar-wind motional electric field is transmitted to the polar cap to drive antisunward convection in the high-latitude magnetosphere (labels "2" through "5"). Conservation of total geomagnetic flux then requires a return sunward flow at lower latitudes (positions 6–10). Simple scaling arguments (see text) indicate that the Jovian polar cap formed in this manner would be small and the strength of the solar-wind-induced convection system would be correspondingly weak (in comparison with the rotational flow).

experience in studying Earth's magnetosphere. This is undoubtedly true in some important respects (for example, with respect to radiation-belt physics (Chaps. 4 and 5) or the generation of plasma waves (Chaps. 8 and 9). However, many Jovian magnetospheric phenomena have no apparent analogs in the terrestrial magnetosphere, and the fundamental differences can generally be attributed to the fact that the primary sources of plasma and energy are external in the case of Earth's magnetosphere but internal in the case of Jupiter's.

Perhaps the surest and most fundamental conclusions that have emerged from recent observational and theoretical work are that (1) the satellite Io is the primary source of Jovian magnetospheric plasma (Sec. 10.3), and that (2) the rotation of Jupiter is the primary source of energy for its magnetosphere (Sec. 10.4). These internal plasma and energy sources generate a wealth of phenomena that are subjects of active and continuing research, including the electrodynamic Io-Jupiter interaction (Sec. 10.5), the rapid acceleration of charged particles (Sec. 10.6), and the spin-periodic ("pulsar") behavior (Sec. 10.7), as well as plasma transport through the magnetosphere and the generation of the planetary wind (Chap. 11). These internally generated magnetospheric phenomena are of particular interest from a theoretical point of view inasmuch as they form a vital link between our relatively advanced understanding of the terrestrial magnetosphere (driven externally), and our relatively speculative understanding of astrophysical magnetospheres (believed to be driven internally). In order to set the context for our discussion of the internally driven phenomena, we first provide a sketch (Sec. 10.2) of what we mean by an externally driven Earthlike magnetosphere, and show why it is of limited applicability to Jupiter's magnetosphere.

10.2. An Earthlike model

In the case of Earth's magnetosphere, the solar wind drives a system of plasma convection across the polar caps in the antisolar direction with return sunward flow occuring at lower latitudes, and the Earth spins inside this Sun-oriented flow pattern. It is widely believed that this convection system is driven by the electric field induced by solar-wind flow and mapped into the polar cap along interconnected magnetic field lines (Fig. 10.1). The magnetospheric convection electric field is typically smaller than the unperturbed solar-wind electric field by a ratio $f \sim 0.1$. This ratio is frequently referred to as the "reconnection efficiency" because it represents the rate at which solar-wind magnetic flux becomes connected to the Earth, divided by the total available EMF (the solar-wind electric field times the diameter of the magnetospheric obstacle). Although this ratio is presently not predictable, its empirical value $f \sim 0.1$ is widely employed as a "universal constant" in scaling the Earth's magnetospheric convection system to other magnetospheres.

Given this "scaling law," and the other relevant parameters that are either measured directly or scaled straightforwardly, one can estimate the strength of solar-wind-induced convection at Jupiter. For example, Kennel and Coroniti [1977a] estimate a solar-wind-induced electric potential drop $\phi \sim f \times (5\ \mathrm{MV}) \sim 0.5\ \mathrm{MV}$ and an associated energy injection rate $K \sim f \times (4 \times 10^{14}\ \mathrm{W}) \sim 4 \times 10^{13}\ \mathrm{W}$. The available power is thus comparable to our estimate (in Sec. 10.4) of the rate at which energy is extracted from Jupiter's rotation to power magnetospheric phenomena. However, the available potential from the solar wind (~ 0.5 MV) is very small compared to the corotational potential $\Omega_J R_J^2 B_J \sim 376$ MV, which indicates that most of the power available from the solar wind is probably dissipated in a very small polar cap. Alternatively, we can compare the magnitudes of the solar-wind induced convection velocity and the corotation velocity. If we assume (for order-of-magnitude purposes) that the above potential (0.5 MV) is distributed uniformly across a magnetospheric diameter of 100 R_J, then the resulting convection velocity, within a dipole magnetic-field approximation, is much less than the corotation velocity throughout at least the dayside magnetosphere.

On the basis of such an argument, Brice and Ioannidis [1970] were the first to conclude that rotational effects may dominate solar-wind induced convection in determining the dynamics of Jupiter's magnetosphere. Their argument was generalized by Vasyliunas [1975], who removed the assumptions of uniform electric field and dipole magnetic field. Spacecraft observations tend to confirm this conclusion, and theoretical models have for the most part ignored solar-wind effects (although Coroniti and Kennel [1977] have attributed long-term variability [~ 1 week] to solar-wind-induced convection effects). The solar wind may, however, have significant influence on the Jovian magnetospheric tail and the magnetically connected polar caps, regions that have barely been explored by spacecraft. The solar wind is, in any case, responsible for establishing the day–night asymmetry of the magnetosphere, and this asymmetry has important theoretical implications. For example, the day–night asymmetry is the basis of the magnetic pumping process described in Section 10.6 below, and it is the coupling of the day–night asymmetry with an intrinsic longitudinal asymmetry that produces 10-hr variability (the "clock phenomena") within the magnetic anomaly model as described in Section 10.7.

10.3. The internal plasma source

Io, the innermost of the Galilean satellites, is the principal source of plasma for the Jovian magnetosphere. Secondary or negligible sources are the solar wind, the Jovian ionosphere, and the other Galilean satellites. As we will see in Section 10.4, considerations of the energetics of both the Io plasma torus and the more distant Jovian magnetosphere require an input of at least 6×10^{29} amu/s (approximately 1 ton/s) into the torus. This is the equivalent of about 3×10^{28} sulfur and oxygen ions/s; this requirement presents a considerable theoretical problem.

The Io source

A variety of approaches have been put forth to account for the Io source. They are quite different from one another and, in general, mutually exclusive. Furthermore, in their present form, none of them seem adequate to account for both the mass ejection rate and the other phenomena associated with the Io source. The source mechanisms depend on whether the atmosphere of Io is thick or thin and whether the material is ejected by direct escape, sputtering, magnetospheric pickup, ionospheric currents, and so forth. In this section, we discuss these various mechanisms and their difficulties.

Io is the most volcanically active body known. As a result of these volcanic emissions, its surface is covered principally with elemental sulfur and SO_2 frost [e.g., Fanale et al., 1979; Sagan, 1979]. The ejection velocity from the volcanic plumes is approximately a factor of three or more below the velocity of escape from Io [Smith et al., 1979a]. Material in the volcanic plumes rises along ballistic trajectories and falls back to the surface of Io, delivering kinetic energy at a rate of approximately 10^{11} W. The area where this material falls is heated slightly (less than 0.2 K) and the energy is radiated into space. Plume material that does not stick to the surface accommodates to the temperature of the surface. The scale height of an SO_2 atmosphere at the maximum daytime temperature of 135 K is only 10 km, and the mean thermal speed of the molecules is just over 100 m/s. The temperature at the volcanic vents is, of course, higher, but the vent exhaust speed is less than 1 km/s, which is still much less than the escape speed from Io (2.6 km/s). Thus, although one sees in the literature allusions to "impulsive injections into the Io torus by volcanic events," experimental and theoretical evidence is contrary to this concept. (However, see Mekler and Eviatar [1980] and Cheng [1980], for example, for an advocacy view.)

There appears to be a major problem in accounting for both the magnitude of the mass-injection rate from Io and the directionality of neutral atomic sodium escape from Io. Sodium is a relatively minor constituent of the torus, but it provides a useful tracer of the motion of neutral gas escaping Io, by virtue of its intense *D*-line radiation that is visible from Earth. Neutral sodium atoms are observed to stream predominantly from the side of Io that faces Jupiter (see review by Trafton [1981] and references therein). If the source were evaporation (Jeans escape), the sodium atoms would escape from Io more nearly isotropically; thus they do not appear to be evaporating from the top of a thick atmosphere.

Therefore, whereas a "thick" atmosphere of Io is apparently required to account for the large mass-injection rate, a "thin" atmosphere is apparently required to account for the directionality of the neutral sodium injection. A possible resolution of this dilemma would be at hand if it could be shown that there was a sudden and marked increase in the ionization rate in the torus just beyond the orbit of Io. One might then be able to allow an isotropic escape of sodium from Io, but the atoms departing from the side facing away from Jupiter would be quickly ionized and hence would not be detected optically.

In this context, a "thick" atmosphere is defined as one in which the base of the exosphere (the exobase) is several scale heights above the surface, so the surface is not subject to direct particle bombardment, and sputtering from the surface is suppressed.

A "thin" atmosphere is defined as one in which the exobase is near or below the surface (i.e., less than one scale height above the surface), and sputtering becomes a viable means of particle injection into the torus. The dividing line between thick and thin atmospheres occurs at a surface pressure of about 10^{-11} bar, which corresponds to a surface concentration of about 10^{9} SO_2 molecules/cm^3 at a temperature of 135 K.

A useful upper limit to the surface atmospheric mass density is provided by the observed behavior of the volcanic plumes. The plumes appear to be formed by particles on ballistic (parabolic) trajectories. If the atmospheric mass density were sufficiently large, the atmospheric drag acting on dust particles in the plumes would produce noticeable distortions of the parabolic trajectories, and no such distortion is evident in the Voyager imagery, at least for the descending portion of the plumes [Cook, Shoemaker, and Smith, 1979]. For a rough estimate of this upper limit, we can set the drag force ($\rho v^2 A$) equal to the force of gravity (mg), where ρ is the atmospheric mass density, m, v, and A are the mass, velocity, and cross-sectional area of typical dust particles in the plumes, and g is the acceleration of Io's gravity. If we assume solid sulfur or SO_2 dust particles of radius 0.1 $\mu = 10^{-7}$ m [Collins, 1981] and velocity 1 km/s, we find an upper limit $\sim 10^{10}$/cm^3 for the number density of an SO_2 atmosphere. A similar but larger upper limit for the region immediately adjacent to an active plume is obtained if we reevaluate the results of Lee and Thomas [1980] using 0.1 μm particles rather than the 10 μm maximum diameter particles assumed in their analysis. This upper limit is a constraint on "thick" atmosphere models.

An entirely different limitation on the ionization rate in the immediate vicinity of Io is given by Shemansky [1980b], who derives an upper limit of 10^{27} ions/s of S^+ and O^+ ions on the grounds that any larger ionization rate would have created an ultraviolet glow around Io that would have been detected by Voyager. There are two ways around this limitation: (1) assume that the initial ionization near Io is of a molecular species (e.g., SO^+ or SO_2^+) that does not radiate at wavelengths that could be detected by Voyager, or (2) assume that material initially escapes from Io (or its atmosphere) in the form of neutral atoms, molecules, or dust, and is subsequently ionized some distance away (>1 R_J) [Johnson, Morfill, and Grün, 1980; Brown and Ip, 1981].

Some material is stripped from the atmosphere of Io by a cometary type of interaction with the plasma in the Io torus, that is, atmospheric particles are ionized by electron impact and swept downstream in the corotational flow [Cloutier et al., 1978; Ip and Axford, 1980]. An upper limit of $S_n \sim 10^{26}$ ions/s for this source is given by Cloutier et al. [1978], who assume the atmosphere of Io is sufficiently thin to allow sputtering. A different approach is taken by Goertz [1980a] who assumes a relatively thick atmosphere with a concentration at the exobase $n_0 = 10^9$/cm^3, and a temperature $T = 1100$ K, and hence a scale height of 80 km. Assuming escape from the entire surface area of Io, he derives an escape flux of about 3×10^{28} ions/s. (One should reduce this estimate by a factor of two because the actual escape area is, at most, one-half the surface area of Io; ions formed on the Jupiter-facing side of Io are accelerated toward the surface by the corotation electric field as described below.) This estimate relies on the assumption that Io's atmosphere is thick (with respect to the mean-free path of incident ionizing electrons), because a thin neutral atmosphere (a) would have an "ionization efficiency" (number of ions produced per incident ionizing electron) less than unity, and (b) would maintain good thermal contact with the surface so that the temperature (and scale height) would be a factor of 10 less than assumed. Thus, for a thin atmosphere the source estimate would be reduced to $\lesssim 10^{27}$ ions/s (basically, the estimate of Cloutier et al. [1978] corrected with more recent observations of conditions in the Io torus).

As pointed out by Haff, Watson, and Yung [1981], the mass-injection rate can be made arbitrarily large for the case of a thick atmosphere, which can be heated significantly by particle bombardment at altitudes a few scale heights above the surface [Kumar, 1980]. The exobase for a thick, hot atmosphere can be far above the surface of Io where the gravitational attraction is diminished and the perturbing effect of Jupiter's gravity becomes important. Haff et al. [1981] give as one specific example an upper atmospheric temperature $T = 1500$ K and an exobase at 2.2 R_J. They propose atmospheric sputtering, and they show that sputtering efficiencies of 10^2 are expected. The required mass-injection rates can thus be realized.

The surface sputtering hypothesis, on the other hand, requires that the atmosphere of Io be thin enough (a surface pressure $\lesssim 10^{-11}$ bar) to allow both the impacting ions to reach Io's surface and the atoms sputtered from Io's surface to pass freely through the atmosphere into the torus [Johnson et al., 1976]. The observed unidirectional escape of sodium is accounted for in the sputtering hypothesis by noting that the Jupiter-facing side of Io is the one subject to ion bombardment caused by the $-\mathbf{v} \times \mathbf{B}$ electric field associated with the motion of Io relative to Jupiter and the plasma torus [Hill et al., 1979; Neubauer, 1980]. One possible source of this bombardment flux is the 10^6 A current inferred to flow toward the Jupiter-facing side of Io [Ness et al., 1979; Kivelson et al., 1979]. If we assume a distribution of ionization states such that, on the average, each ion carries a positive charge of 1.5 e, then the total ion flux delivered to Io by this current is $S_n \sim 4 \times 10^{24}$/s. The flux of energetic particles is much smaller [e.g., Krimigis et al., 1979]. In order to generate the required escape flux of at least 3×10^{28}/s the sputtering efficiency would have to be of the order of 10^4. This presents a problem because sputtering efficiencies this large are not expected [e.g., Brown et al., 1980].

Other bombardment fluxes that could cause the required sputtering are: (a) corotating ions in the plasma torus and (b) acceleration of ions created in the plumes or in Io's atmosphere. The maximum bombardment flux for source (a) is $S_n = nvA$ where n is the plasma-torus number density, $\mathbf{v}$ is the velocity of the torus ions relative to Io, and A is the cross-sectional area of Io. For $n = 10^3$ ion/cm^3, $v = 5.7 \times 10^4$ m/s, and $A = 1 \times 10^{13}$ m^2 we obtain $S_n = 6 \times 10^{26}$ ions/s, and the sputtering efficiency need be only 10^2. If these ions have an average atomic weight of 22 amu, their average streaming energy is 360 eV. The sputtering efficiency of such low energy ions is not known. The principal difficulty with this source is that the ions would strike Io on its trailing hemisphere (relative to its orbital motion), whereas the sodium observations indicate that the source is the hemisphere facing Jupiter.

Source (b) has the advantage of being in the correct hemisphere. Ions created near Io on its Jupiter facing side will be accelerated toward Io by the electric field associated with the motion of the plasma torus past Io [Cummings et al., 1980]. The potential across Io is about 400 kV, and the resulting external electric field is in the direction to accelerate ions toward Io if they are on its Jupiter-facing side. The bombarding flux is $S_n = SA$ where S is the column production rate of ions and A is either the cross-sectional area of Io or the area covered by volcanic plumes on Io's Jupiter facing side. Cloutier et al. [1978] estimate S to be 3.5×10^{12}/m^2-s, and A is either 1×10^{13} m^2 or 4×10^{11} m^2 (the area of the plumes). Thus for this source, S_n ranges from 3×10^{25}/s to 10^{23}/s, and the required sputtering efficiency ranges from 10^3 to 10^5. On the other hand, if we adopt a larger source rate, equal to the upper limit deduced by Shemansky [1980b] from the UV observations, diminished by a factor of 4 (the ratio of surface area to cross-sectional area), the source rate would be $S_n \sim 3 \times 10^{26}$/s and the required sputtering efficiency would be $\sim 10^2$. The energy of the impacting ions would

Table 10.1. *Injection of ions into the Jovian magnetosphere*

Source	S_m(kg/s)	S_m(amu/s)	Avg atomic wt. of ions
Io	$\gtrsim 10^3$	$\geq 6 \times 10^{29}$	~ 22
Solar wind	$< 10^2$	$< 6 \times 10^{28}$	1
Jovian ionosphere	$\gtrsim 20$	$\gtrsim 10^{28}$	1
Other Galilean satellites	1	6×10^{26}	6

range from zero to the full corotational energy in Io's reference frame (540 eV for sulfur ions, 270 eV for oxygen ions).

Finally, the plasma-arc mechanism suggested by Gold [1980] merits consideration. Is it possible that the 10^6 A current flowing to and from Io could concentrate into arcs at the location of volcanic events and heat some portion of the plume sufficiently to cause direct escape into the torus? Or, could some of the dust particles in the plume become charged by this current and then be electrically accelerated to escape speed [Johnson, Morfill, and Grün, 1980]? For example, jets or "linear features" of un-ionized sodium extending outward from Io have been reported [Pilcher and Strobel, 1981] (see also Chap. 6). This is the sort of ejection that might be expected from a concentrated plasma-arc source. Also, Schaber [1980] reports that nearly all of the volcanic vents on Io are in the equatorial zone, again as expected from a current driven source [Gold, 1980]. The plasma-arc mechanism has not been pursued beyond Gold's original suggestion, except for one attempt to find the small, bright spots that might be expected at the feet of the plasma arcs. Instead of spots, more diffuse "electric-glow discharges" were observed by Cook et al. [1981], presumably at the tops of the plumes, which they refer to as auroras. A quantitative analysis of how the 10^6 A current flows into Io, whether diffuse or concentrated into spots, and whether the power associated with this current (as large as 4×10^{11} W, which is comparable to the 10^{11} W expended by the plumes) influences the structure and dynamics of the volcanic plumes, is yet to be developed.

All the above considerations and difficulties may be complicated considerably if, as has been suggested, Io has an intrinsic magnetic moment that creates a magnetosphere that would protect most of the atmosphere from charged particle bombardment [e.g., Neubauer, 1978; Southwood et al., 1980; Kivelson and Southwood, 1981]. The theoretical problem of explaining how at least 1 ton/s of Io material is delivered to the Io plasma torus awaits a solution supported by a full and careful analysis (and perhaps a mechanism or mechanisms yet to be proposed). However, that Io is the primary source of plasma for the Jovian magnetosphere is not in doubt (see Table 10.1).

The solar-wind source

It is commonly accepted that the solar wind is a primary source of plasma for Earth's magnetosphere (although recent measurements have drawn attention to the importance of Earth's ionosphere as an additional source [e.g., Johnson, 1979]). The mass flux of solar-wind plasma entering a planetary magnetosphere is $S_m = \rho_m A V_s \eta$, where ρ_m is the mass density of the solar wind, A is the cross-sectional area of the magnetosphere, V_s is the solar wind speed, and η is the fraction of incident solar-wind particles absorbed by the magnetosphere. For the Earth, η is inferred to be of the order of 10^{-3} [Hill, 1974], which yields $S_m = 5 \times 10^{-2}$ kg/s. If we assume the same value of η for Jupiter, and use a circle of 100 R_J radius for the magnetospheric cross section, we obtain $S_m = 20$ kg/s. Even if we increase η to 10^{-2}, S_m is only about 100 kg/s, which is the upper limit listed in Table 10.1. There is a theoretical expectation [e.g., Lemaire, 1977], and some evidence from measurements of the abundances of energetic particles, that solar-wind injection may be important near the front of the magnetosphere [Krimigis et al., 1979; Vogt et al., 1979]. However, this is a region in which there are relatively few particles from any source, so we conclude that the solar wind is negligible as an overall source of plasma for the Jovian magnetosphere.

The ionospheric source

It has been confidently expected, in analogy with Earth, that Jupiter's ionosphere is a source of plasma for the Jovian magnetosphere [Gledhill, 1967; Melrose, 1967; Ioannidis and Brice, 1971; Goertz, 1973; Michel and Sturrock, 1974; Hill et al., 1974; Carbary et al., 1974; Mendis and Axford, 1974; Swartz et al., 1975; Goertz, 1976b], and this expectation is supported by direct observation of energetic H_2^+ and H_3^+ ions [Hamilton et al., 1980].

One ionospheric source arises from development of a relatively hot photoelectron population (energies greater than about 10 eV) that pulls ions along as the photoelectrons escape from the ionosphere. Swartz et al. [1975] estimate that this flux amounts to about 10^{28}/s integrated over Jupiter's ionosphere. Processes such as precipitation of energetic particles [Dessler and Hill, 1975] or dissipation of energy from Birkeland currents [Dessler and Chamberlain, 1979] create additional hot electrons and enhance the escape flux from the ionosphere. Finally, the escape flux can be enhanced by heating of the ionosphere by precipitation of soft electrons [Hunten and Dessler, 1977; Dessler et al., 1981], or the heating of electrons by the precipitation of sulfur and oxygen ions with energies in the low MeV range [Thorne, 1981] (see also Chap. 12).

None of these energization mechanisms makes the mass flux from the ionosphere competitive with the Io source. Direct measurements show that the ionic composition within the magnetosphere is dominated by sulfur and oxygen, with hydrogen ions (the predominant ionospheric constituent) making up no more than 1% of the mass density or 20% of the number density in the inner magnetosphere [Sullivan and Bagenal, 1979; Krimigis et al., 1979]. However, this does not mean that the ionospheric source is unimportant in its effect on Jovian magnetospheric dynamics. One important function of ionospheric plasma is to carry the Birkeland currents that enforce (partial) corotation and link Jupiter's ionosphere with the Io torus; other important effects of ionospheric plasma are discussed in Section 10.7 and Chapter 12.

Other satellite sources

With Io being such an important source of plasma for the Jovian magnetosphere, it is natural to ask what the input might be from the other satellites, particularly the other three Galilean satellites. The significance of such plasma sources was investigated by Hill and Michel [1976] before it was recognized that Io was such an overwhelming source. The problem with getting much plasma from the other satellites (a problem that is avoided by Io) is that, once sputtering has removed the easy elements, the surface is then coated with a protective residue of material that is difficult to sputter. As an example of the severity of this problem, Lanzerotti et al. [1978] estimate that of the order of 1 km of exposed ice could be eroded from Europa over a period of 10^9 yr. (More recently, Johnson et al. [1981] have revised this erosion estimate downward by a factor of ten). It is reasonable to expect that some contaminant that is difficult to sputter, such as silicon or iron, will be concentrated on the surface as the ice is

sputtered away; such a residue layer acts to prevent further sputtering. Io alone (from which about 500 meters of material would be sputtered in 10^9 yr at the presently inferred rate) avoids this limitation by the continuous resurfacing action of its volcanoes [Johnson et al., 1979].

Additional evidence that sputtering of water ice from the other satellites is not an important plasma source is provided by the ion composition measurements that show that H^+ is a negligible ionic constituent [Sullivan and Bagenal, 1979; Bagenal and Sullivan, 1981]. If a significant number of H_2O molecules were being sputtered into the Jovian magnetosphere and subsequently dissociated and ionized, the proton population would be more evident. Finally, the most recent proposal to account for the high concentrations of sulfur on the surfaces of Europa and Ganymede tends to make those satellites sinks rather than sources of magnetospheric particles [Eviatar et al., 1981b].

Time variations

Ground-based and spacecraft data show that both the temperature and the content of the Io plasma torus vary with time (see Chap. 6). These changes tend to be slow (time periods of months), and their cause has not yet been determined. The analysis of such time variations from Earth-based observations is complicated by the fact that the optical torus exhibits a gross longitudinal asymmetry [Trafton, 1980; Pilcher and Morgan, 1980; Trauger et al., 1980], being two to five times brighter in singly ionized sulfur emissions within the "active sector" ($\lambda_{III} \approx 175°$ to $320°$; see Sec. 10.7) than at other longitudes. Some analyses in which time variations have been reported have tacitly assumed that the torus was axially symmetric and hence have attributed all brightness variations to time variations rather than to the rotation of the bright portion of the torus into and out of the field of view [e.g., Mekler and Eviatar, 1980]. Similarly, Walker and Kivelson [1981] assume axial symmetry in a comparison of V 1 inbound and P 10 inbound torus data, and they attribute the inferred difference in torus ion concentration to time variations alone. What they have reported as time variations are due, at least in part, to spatial rather than temporal variations of the torus ion concentration.

Examination of the groundbased data of Trafton [1980] and of Voyager 1 and 2 spacecraft observations of Sandel et al. [1979], together with new analysis of the Pioneer 10 solar-wind detector data by Intriligator and Miller [1981] and L. A. Frank (private communication, 1981), indicate that the plasma torus may not deviate by much more than a factor of three from its average state. This is what one might expect from Io, a satellite whose surface is continually renewed by volcanic activity.

There is, however, a considerable body of opinion supporting the proposition that the torus content and geometry can change by more than a factor of 10 within a time scale of a year or two. The principal evidence to support this view is the Pioneer 10 UV spectrometer data, which were interpreted as showing only a thin torus, incomplete in longitude [Carlson and Judge, 1974, 1975]. This is in contrast to the dense, complete torus discovered by Voyager 1 and confirmed by Voyager 2 and ground observations (see Chap. 6). Does the Io plasma torus have a weak, incomplete, quiescent state as suggested by the Pioneer UV spectrometer? If so, magnetospheric theorists face yet another formidable challenge.

10.4. The internal energy source

Because of the vast size and rapid rotation of Jupiter's magnetosphere, it is widely believed that the rotation of Jupiter provides the dominant source of energy for magnetospheric phenomena (unlike terrestrial magnetospheric phenomena, for which the

Table 10.2. *Jupiter's energy budget*

Phenomenon	Power source (sink) (W) Ionosphere	Io torus	Magnetosphere	External
Solar UV	(4×10^{12})			4×10^{12}
Particle precipitation	(10^{14})	$<< 10^{14}$	10^{14}	
Secondary electron emission	$\leq 10^{14}$	$(\leq 10^{14})$		
Photoelectron emission	2×10^{9}	$(<< 2 \times 10^{9})$	(2×10^{9})	
Enforcement of corotation:				
newly created ions	$\sim 10^{12}$	$(\sim 10^{12})$		
radially transported ions	$\geq 5 \times 10^{13}$		$(\geq 5 \times 10^{13})$	
UV aurora	10^{12}			(10^{12})
X-ray emission	8×10^{9}			(8×10^{9})
Io Alfvén waves	$(< 10^{12})$	$< 10^{12}$		
Torus UV emissions		2×10^{12}		(2×10^{12})
Particle acceleration (e.g., merging, magnetic pumping, etc.)	$\sim 10^{14}$?	(?)	$(\sim 10^{14})$	
Planetary wind			2×10^{13}	(2×10^{13})
Solar-wind-induced convection	$(\sim 2 \times 10^{13})$		$(\sim 2 \times 10^{13})$	$\sim 4 \times 10^{13}$ (?)
Total	$\sim 1.3 \times 10^{14}$	$(\leq 10^{14})$	$(\geq 5 \times 10^{13})$	$\sim 2 \times 10^{13}$

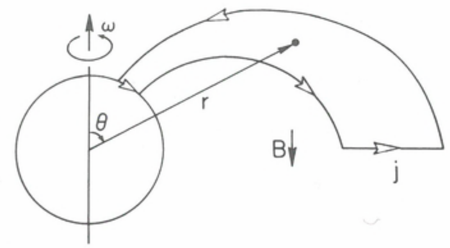

Fig. 10.2. The current system that transmits torque from Jupiter's ionosphere to plasma in the magnetosphere (e.g., in the Io torus) [Hill, 1979]. The ionospheric Pedersen current draws angular momentum from the corotating atmosphere, and the equatorial transverse current adds angular momentum to plasma as it is injected into the torus or transported outward from the torus. The ionospheric and equatorial transverse currents are linked by Birkeland (magnetic-field-aligned) currents.

dominant energy source is considered to be the solar-wind interaction). This rotational energy source is clearly responsible for enforcing (partial) corotation on plasma that is produced within the magnetosphere and transported outward. It probably also powers, directly or indirectly, various other phenomena such as auroral emissions (Chaps. 2 and 12), plasma heating (Chap. 12) and the resultant optical and UV line emissions (Chap. 6), the system of radial plasma transport in the magnetosphere (Chap. 11), and the emission of energetic electrons (Chap. 5) and radio noise (Chaps. 7 and 9). Our present estimates of the energy budget of Jupiter's magnetosphere are summarized in Table 10.2. (Altogether, these phenomena expend less than 10^{15} W, which represents an insignificant drain on Jupiter's 6×10^{34} J of rotational kinetic energy.)

The most obvious mechanism for tapping this rotational energy source consists of the Birkeland (magnetic-field-aligned) current system (Fig. 10.2) that extracts rotational energy from the Pedersen-conducting layer of Jupiter's atmosphere and invests that energy in producing and maintaining the (partial) corotation of plasma that is injected and transported outward in the magnetosphere. The local corotation energy at distance r for a particle of mass m is $W_c = m\Omega_J^2 r^2/2$, but newly injected ions generally attain an initial energy of $2W_c$ near the equatorial plane, regardless of where they are produced along the guiding field line. If the ions originate in Jupiter's ionosphere and are drawn away by hot photoelectrons as described in Section 10.3, the centrifugal slinging effect [Hill et al., 1974] produces a field-aligned streaming energy $W_{\parallel} = W_c - mM_JG/r \approx W_c$ in addition to the corotational drift energy ($= W_c$). If the ions are instead produced near the equatorial plane (e.g., by ionization of torus molecules as described in Sec. 10.3), the corotation electric field imparts a cyclotron energy $W_{\perp} = W_c - mM_JG/r \approx W_c$ in addition to the corotational drift energy. For intermediate injection points the energy will be distributed in an intermediate way between parallel and perpendicular degrees of freedom [see, e.g., Cummings et al., 1980] but the equatorial energy will generally be approximately $2W_c$. If the injection rate is S_n (ions/s), the corresponding rate of energy extraction is $2S_nW_c$.

A considerably larger investment of rotational energy is required to maintain the state of (partial) corotation as the plasma moves outward from its source [e.g., Dessler, 1980; Eviatar and Siscoe, 1980; Hill, 1981; Hill, Dessler, and Maher, 1981]. The primary source of magnetospheric plasma is the Io plasma torus at $L \approx 6$ (Sec. 10.3), and, as this plasma moves outward (probably in a rotation-driven convection system as described in Sec. 10.7 and Chap. 11), it falls through a net outward centrifugal-gravitational force field

$$g = \omega^2 r - M_JG/r^2 \qquad (10.1)$$

$$\approx \omega^2 r \; (r \gtrsim 6\, R_J)$$

where $\omega(r) < \Omega_J$ is the angular frequency of partial corotation (see Chap. 11). If plasma mass is transported outward through this effective gravity field at a rate S_m (kg/s), the rate of extraction of rotational energy can be estimated as

$$K_c = (S_m)\left[\frac{1}{2}\,\Omega_J^2(6R_J)^2 - M_J G/(6R_J) + \int_{6R_J}^{\infty} \omega^2\, r dr\right] \tag{10.2}$$

The first two terms represent the work required to accelerate the ions to corotation at Io's orbit, and the third term is the work expended in maintaining the state of (partial) corotation during the subsequent outward transport. It has been shown [Hill, 1979] that corotation is approximately enforced ($\omega \approx \Omega_J$) out to distances $r \sim R_c$ where

$$(R_c/R_J)^4 = \pi \Sigma B_J^2 R_J^2 / S_m \tag{10.3}$$

where Σ is the height-integrated Pedersen conductivity of Jupiter's atmosphere. (See the detailed discussion in Chap. 11.) Nominal values $\Sigma \sim 0.1$ mho, $S_m \sim 1.7 \times 10^3$ kg/s yield the estimate $R_c \approx 20\ R_J$ [Hill, 1980], consistent with the Voyager observations described in Chapter 3. For $r \gtrsim R_c$, $\omega \propto r^{-2}$ and the above integral can thus be approximated by

$$\begin{aligned} K_c &\approx \frac{1}{2}\, S_m \Omega_J^2 R_c^2 \qquad (10.4)\\ &= (\pi/4)^{1/2} (\Sigma S_m)^{1/2} B_J R_J^3 \Omega_J^2 \\ &\approx (5 \times 10^{13}\ \mathrm{W})\, (\Sigma_{-1} S_{m\,30})^{1/2} \end{aligned}$$

where $\Sigma_{-1} = \Sigma/(0.1$ mho) and $S_{m30} = S_m/(10^{30}$ amu/s). We have used "nominal" estimates for Σ and S_m, the actual values of which are not well determined, although their ratio is approximately determined by the Voyager observations (within the above model). Estimates of Σ range from <0.1 mho to ~ 10 mho, depending on the rate of energetic electron precipitation (Chap. 2). If, for example, Σ and S_m were both increased by a factor of 50, as suggested by Hill, Dessler, and Maher [1981], the above estimate of the energy deposition rate K_c would be increased by the same factor, while the estimate of R_c (which is constrained by the observations) would remain unchanged. The estimated energy deposition rate is at least comparable to that required to produce the observed Jovian aurora (Chap. 6). The same Birkeland current system dissipates a comparable amount of energy by Joule heating in Jupiter's atmosphere (Chap. 11), which represents an important high-latitude atmospheric heat source (Chap. 2).

The rotational energy source is evidently responsible for a variety of important effects on the structure and dynamics of Jupiter's outer magnetosphere. The centrifugal stress of the (partially) corotating plasma is partially responsible for the outward distortion of the magnetic field in a disclike structure, and hence for the overall inflation of the magnetosphere. Various theoretical models of the resulting plasma/field configuration have been developed [e.g., Goertz, 1976b; Carbary and Hill, 1978; Hill and Carbary, 1978; Vickers, 1978], and are discussed in Chapter 11.

The plasma injected by Io (and other sources interior to the magnetosphere) must ultimately escape the magnetosphere at the same average rate, and this escape is generally thought to occur in the form of a super-Alfvénic outflow called a planetary wind or a magnetospheric wind. (Other loss processes such as recombination or precipitation into Jupiter's atmosphere are probably unimportant beyond $L = 6$.) This planetary wind is sometimes decribed by analogy with axially symmetric stellar-wind models [e.g., Kennel and Coroniti, 1977a] which, however, do not really apply to Jupiter for at least two reasons: they assume a steady-state outflow and they lack the day–night asymmetry imposed by the solar wind. Because of this day–night asymmetry, Hill et al. [1974] have proposed that the planetary wind develops only on the night side of Jupiter, where the restraining solar-wind pressure is absent. Voyager data (see Chap. 4) confirm this basic geometry. A self-consistent quantitative model of a centrifugally driven planetary wind has not yet been developed (see Chap. 11).

If the rotational energy source is coupled with a corotating longitudinal asymmetry of the plasma mass distribution, as required by the magnetic-anomaly model described in Section 10.7, the result is a convective flow pattern that corotates with Jupiter [Vasyliunas, 1978; Hill, 1981; Hill, Dessler, and Maher, 1981]. This corotating convection system may provide an important radial transport mechanism (see Chap. 11). Other important rotational effects include the Io–Jupiter interaction, the acceleration of energetic particles, and the spin-periodic variations in the outer magnetosphere and interplanetary space. The remainder of this chapter is devoted to a discussion of these three effects.

10.5. The Io-Jupiter interaction

As Io moves through the corotating plasma torus, it disturbs the electric and magnetic fields as well as the particle distributions in its vicinity (see Chaps. 1, 3, 4, 5, and 6). The nature of this disturbance depends on the conductivity of Io or its ionosphere, the strength and orientation of its intrinsic magnetic field (if any), the parameters of the surrounding plasma, and the boundary conditions imposed by the Jovian ionosphere. The disturbance can be described in terms of waves ranging from zero frequency in Io's frame (i.e., a pattern carried around by Io) to very high frequencies (e.g., whistler-mode waves). Four types of models have been considered: low-frequency wave models, steady-state unipolar inductor models, acceleration models, and particle sweeping models. None of these models can be regarded as independent of the others; they all represent different aspects of the same interaction. For example, the amount of particle sweeping (Chap. 5) depends on the electric field in Io's vicinity, which in turn is related to the transverse current flowing at Io as discussed below. The transverse current is connected to Birkeland (magnetic-field aligned) currents that may be carried by low-frequency Alfvén waves. If these Birkeland currents are sufficiently large, parallel (magnetic field aligned) electric fields may occur, resulting in the direct acceleration of particles along the field lines. Although Voyager 1 passed very close to the Io flux tube, we still have insufficient data to decide which type of interaction is dominant. It may even be that the nature of the interaction changes with time in response to time-varying plasma parameters at Io's orbit.

Alfvén wave model

Independent of the exact nature of the perturbation in Io's vicinity, energy will be radiated away in the form of Alfvén waves. This is true in general for large conducting bodies moving through space [Drell et al., 1963]. This idea was originally applied to Io by Warwick [1961], Schmahl [1970], and Goertz and Deift [1973], and more recently by Neubauer [1980], Southwood et al. [1980], and Goertz [1980a].

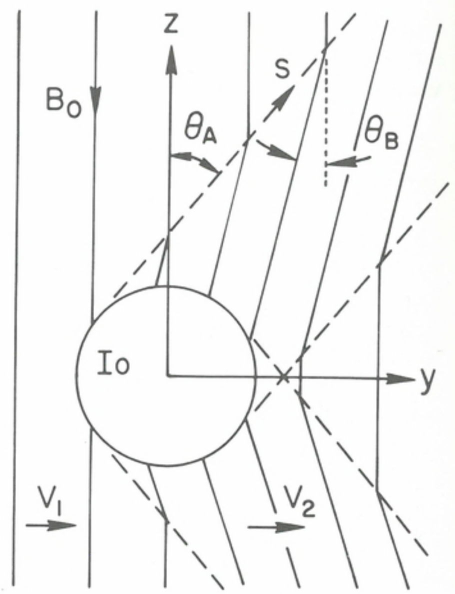

Fig. 10.3. Sketch of the magnetic-field distortion caused by Alfvén waves that are generated by the relative motion **V** between Io and the corotating magnetospheric plasma. The waves propagate along the background magnetic field $\mathbf{B}_0$ in the plasma reference frame; in the Io reference frame (shown here), the waves propagate along characteristics **s** whose angle θ_A with $\mathbf{B}_0$ is determined by the Alfvén mach number of the relative flow. Reflection from the Jovian ionosphere is neglected in this picture.

Suppose that near Io (e.g., in its ionosphere) the plasma velocity as seen in Io's frame is v_2, and that upstream from Io the plasma velocity v_1 is the local corotation velocity transformed to Io's frame: $v_1 = v_C - v_I$. The deceleration of the torus plasma from v_1 to v_2 is accomplished by the $\mathbf{J} \times \mathbf{B}$ force in the extended ionosphere of Io. The associated magnetic-field perturbations communicate the stress between Io and the torus plasma flow. These perturbations propagate along the field lines by means of Alfvén waves, while being carried downstream with the plasma. Thus, the current is confined between "Alfvén wings" which are parallel to the characteristics **s** inclined relative to the background field $\mathbf{B}_0$ by the Mach angle $\theta_A = \tan^{-1} v_1/V_A$ where $V_A = \mathbf{B}_0/(\mu_0 nm)^{1/2}$ is the Alfvén speed (Fig. 10.3). For $v_1 = 57$ km/s and $V_A \sim 400$ km/s (corresponding to $nm \sim 10^4$ amu/cm^3), $\theta_A \sim 8°$. Between the wings the field is tilted by an angle $\theta_B < \theta_A$ which depends on the amplitude of the perturbation.

Here we discuss only a simplified two-dimensional problem as illustrated in Figure 10.3, and we explicitly assume that Io has no significant magnetic field of internal origin. The Birkeland current is given by [Goertz and Boswell, 1979; Neubauer, 1980; Southwood et al., 1980; Goertz, 1980a]

$$j' = \int j_B dx = \Sigma_A B_0 (v_1 - v_2) \tag{10.5}$$

where

$$\Sigma_A = 1/(\mu_0 V_A)$$

This current is supplied by Io, whose effective conductivity Σ_I includes Pedersen, Hall, and "pick-up" conductivities as described below. The current through Io or its atmosphere is

$$j'_{Io} = \Sigma_I B_0 v_2 \tag{10.6}$$

Combining (10.5) and (10.6) gives

$$\frac{v_2}{v_1} = \frac{\Sigma_A}{\Sigma_I + \Sigma_A} \tag{10.7}$$

$$j' = B_0 v_1 \frac{\Sigma_I \Sigma_A}{\Sigma_I + \Sigma_A} \tag{10.8}$$

A three-dimensional analysis is required to find the flow pattern around Io [see, e.g., Neubauer, 1980; Goertz, 1980a]. However, the simple relations above illustrate the salient features of this local model for the interaction. The plasma velocity v_2 and hence the electric field in Io's frame depend on the ratio Σ_I/Σ_A. For small Σ_I/Σ_A the torus plasma impinges freely onto Io, and Io's low-energy plasma absorption cross section is equal to its geometrical cross section. (If Io has an intrinsic magnetic field its cross section may even be larger [Ip, 1981].) As Σ_I/Σ_A increases, the flow lines tend to avoid Io and the cross section for absorbing plasma becomes smaller. Because the amount of sweeping is proportional to this cross section, sweeping models cannot be evaluated independently of the Alfvén-wave model.

Steady-state unipolar model

Several authors [e.g., Piddington and Drake, 1968; Goldreich and Lynden-Bell, 1969; Gurnett, 1972; Shawhan et al., 1973, 1974; Shawhan, 1976; Dessler and Hill, 1979] have argued that the strength of the Io current is actually determined by the conductance Σ_J of the Jovian ionosphere, that is,

$$j' = B_0 v_1 \frac{\Sigma_I \Sigma_J}{\Sigma_I + \Sigma_J} \tag{10.9}$$

Note that Σ_J instead of Σ_A determines j' in these models (cf. (10.8) and (10.9). These nonlocal models can be viewed as extensions of the Alfvén wave model. Thus far we have treated the field lines as infinitely extended, whereas they actually terminate (insofar as Alfvén wave propagation is concerned) in the conducting ionosphere of Jupiter. When the Alfvén wave reaches the ionosphere, currents there are driven by the electric field E of the wave. The current in the ionosphere, however, is not simply the Ohmic current $\Sigma_J E$, unless that current happens to match the polarization current of the Alfvén wave (i.e., unless $\Sigma_A = \Sigma_J$). In all other cases the wave electric field will be partially reflected, and the magnitude of the reflected wave depends on the ratio Σ_J/Σ_A. (Although Σ_A is rather well determined from in situ (Voyage 1) measurements, Σ_J is very uncertain as discussed in Chap. 2.) The reflection coefficient for Alfvén waves [Scholer, 1970] is

$$R = \frac{1 - \Sigma_J/\Sigma_A}{1 + \Sigma_J/\Sigma_A} \tag{10.10}$$

The reflected wave propagates back toward Io along the distorted magnetic field and is carried along with the plasma (flowing at the reduced velocity v_2). Thus between the wings of the Alfvén waves the return wave propagates along the characteristic $\mathbf{s}'$ as indicated in Figure 10.4. Regions 1 and 2 are as above; in region 3 the velocity is $v_3 = v_2(1 + R) - v_1 R$. If the reflected wave returns to Io (as illustrated in Fig. 10.4), it will be reflected back toward the Jovian ionosphere, resulting in a further deceleration of the plasma in region 4, and so forth. The distance δ that the plasma moves downstream during one wave bounce period is given by the integrals along the characteristics **s** and **s**$'$:

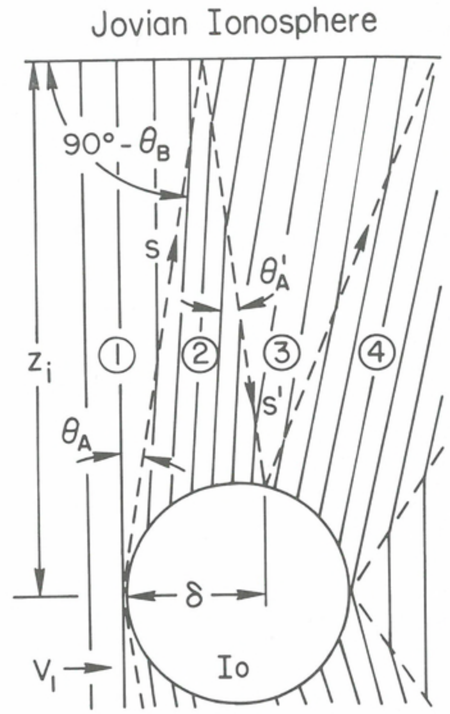

Fig. 10.4. The modification to Figure 10.3 caused by a single reflection of the Alfvén wave from Jupiter's ionosphere. The flow velocity (in Io's frame) is reduced in region 2 compared to its upstream (region 1) value, and the characteristic wavefront inclination θ_A' of the reflected wave is therefore different from that of the initial wave (θ_A). The wave is convected downstream a distance δ before returning to the equatorial plane after reflection from the ionosphere; strong Io–Jupiter coupling requires $\delta \lesssim 2\, R_I$.

$$\delta = \int_0^{z_i} \tan\theta_A\, dz - \int_0^{z_i} \tan(\theta_B - \theta_A')dz \tag{10.11}$$

The steady-state unipolar inductor model corresponds to the extreme case $\Sigma_I >> \Sigma_A$, $\Sigma_J >> \Sigma_A$, for which $v_2 \approx 0$, $R \approx -1$, $\tan\theta_B \approx \tan\theta_A = v_1/V_A$, $\tan\theta_A' \approx 0$, and $\delta \approx 0$, that is, the wave returns exactly to Io and after one round trip the current is twice the original Alfvén wave current. The process is then repeated until the current through Io is equal to $\Sigma B(v_1 - v_2)$ and a steady state is reached, which is described by Equation (10.9) [Goertz and Deift, 1973]. The condition for such a steady state is $\delta << 2\, R_I$, or

$$\int \frac{ds}{V_A} << R_I / v_2 \tag{10.12}$$

That is, in order for the return wave to hit Io, the round-trip Alfvén wave travel time must be much less than the time required for the plasma to convect past Io ($2R_I/v_2$). Before the Voyager 1 encounter, the Alfvén-wave travel time was estimated to be less than $2R_I/v_1 \sim 60$ s [Goldreich and Lynden-Bell, 1969; Goertz and Deift, 1973] and this condition was believed to be fulfilled. However, the Alfvén speed is reduced within the plasma torus, and the wave travel time is now known to be much larger (generally of the order of 1000 s) [Neubauer, 1980]. It appears that condition (10.12) is not generally satisfied, and that the currents driven by Io and the associated perturbations of electric field and plasma flow are determined largely by local plasma conditions rather than by the Jovian conductivity. (Note, however, that the time required for the plasma to convect past Io may also be increased if $\Sigma_I \gtrsim \Sigma_A$.) In this case the maximum current that Io can drive in the magnetosphere is

$$j'_{\max} = \frac{1}{2} B v_1\, \Sigma_A \sim 10^6\, A/R_I \tag{10.13}$$

Acuña (Chap. 1) has shown that the magnetic-field perturbation observed in the vicinity of Io's flux tube is compatible with this value. Likewise, the perturbations of the plasma flow near Io's flux tube are in apparent agreement with the Alfvén wave picture (Chap. 3).

Note that the Alfvén-wave travel time quoted above (~ 1000s) applies to torus parameters established by Voyager 1 inbound, and to those times when Io is deeply imbedded within the torus. When the Jovian magnetic dipole points toward or away from Io (i.e., when Io is near $\lambda_{III} = 200°$ or $20°$, respectively), the path length for Alfvén-wave propagation within the torus is less because Io is near the edge (northern or southern, respectively) of the torus. At these longitudes the wave travel time to the Jovian ionosphere (northern or southern, respectively) would be reduced to something like the pre-Voyager estimates, and a direct (unipolar-inductor) interaction might be anticipated at these longitudes if $\Sigma_I \gtrsim \Sigma_A$ (i.e., if the plasma flow past Io is significantly impeded; see Sec. 10.4).

Parallel electric fields

Several models have considered the consequences of parallel (magnetic-field-aligned) electric fields within the Io flux tube, usually within a steady state formulation (although parallel electric fields may also be expected to occur in a nonsteady interaction). Let us denote the Jovian height integrated Pedersen current by $j' = \Sigma_p \mathbf{E}'$ where $\mathbf{E}'$ is the field in the ionosphere as seen in the planet's frame, the parallel current density by j_z, the parallel potential drop between the equatorial plane and the ionosphere along a field line by ϕ, and the electric field caused by the motion of Io relative to the magnetosphere, suitably mapped to the planet's surface, by $\mathbf{E}'_s$. Then the current continuity equation reads

$$\partial j'_y / \partial y = -j_z \tag{10.14}$$

with the coordinate system as defined in Figure 10.5. The condition of steady state ($\nabla \times \mathbf{E} = 0$) implies

$$\int (\nabla \times \mathbf{E})_x\, dz = \frac{j'_y}{\Sigma_p} - E'_{sy} - \frac{\partial\phi}{\partial y} = 0 \tag{10.15}$$

Combining Equations (10.14) and (10.15) and assuming that the field $\mathbf{E}'_s$ is constant inside the Io flux tube, we obtain

$$\frac{\partial^2\phi}{\partial y^2} + \frac{j_z(y)}{\Sigma_p} = 0 \tag{10.16}$$

with the boundary condition

$$\partial\phi / \partial y = -E_{sy} \tag{10.17}$$

at the edge of the flux tube. Once a constituting relation between j_z and ϕ is formulated one can solve for $\phi(y)$. We see that if $j_z \neq 0$ and $\mathbf{E}_s \neq 0$, a potential drop must occur.

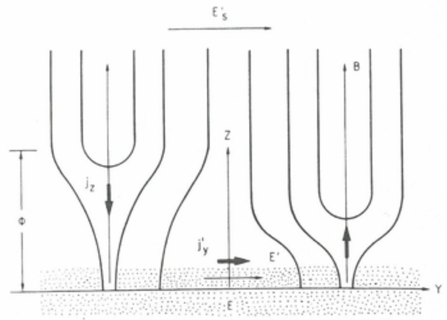

Fig. 10.5. Illustration of equipotential contours (heavy lines) associated with a field-aligned potential drop, and the coordinate system used in the text (Sec. 10.5) to relate j' to ϕ.

Various relations between ϕ and j_z have been proposed. Goldreich and Lynden-Bell [1969] used the approximation

$$j_z = -ne\left(\frac{2e|\phi|}{m}\right)^{1/2} \phi/|\phi| \tag{10.18}$$

which is valid if $e\phi << kT_e$, the electron thermal energy. Gurnett [1972] used the approximation

$$j_z = -j_e\,\phi/|\phi| \tag{10.19}$$

where J_e is the electron thermal current, which is valid in the opposite limit. Smith and Goertz [1978] give a similar but somewhat more complicated form. If the density of upward current at the inner edge of the Io flux tube exceeds the thermal current of Jovian ionospheric ions, then the current must be supplied by precipitating magnetospheric electrons, in which case the magnetic mirror force becomes significant in the determination of $j_z(\phi)$. For this case Knight [1973] has derived a complicated expression $j_z(\phi)$ that may be approximated by $j_z \approx -Mj_e(e\phi/kT_e)$ for a wide range of $e\phi/kT_e$, where M is the magnetic mirror ratio.

In any case, the parallel potential drop ϕ can be easily obtained as a function of y once the relation $j_z(\phi)$ is given. Smith and Goertz [1978] show that in all the above cases the maximum potential drop occurs at the edge of the flux tube and that under special conditions the parallel potential drop on one side of the flux tube may approach the total potential across the satellite, which in the case of Io exceeds 400 kV. Such a potential could produce large numbers of 400 keV charged particles [Gurnett, 1972], as have apparently been observed [see, e.g., Fillius, 1976].

The conductivity of Io

The character of the Io interaction depends on the conductivity of the satellite, either its bulk and surface conductivity or that of its ionosphere. Pioneer 10 data [Kliore et al., 1974, 1975] indicate that Io possesses an ionosphere. If the atmosphere is sufficiently thick, the currents may flow through the ionosphere of Io rather than through the surface and body of the satellite. If Io's atmosphere and ionosphere are maintained directly by volcanic outgassing [Kumar, 1979], then one might assume that the ionosphere is as variable as the volcanic activity. There is evidence for a variation of volcanic activity (compare, e.g., Voyager 1 and Voyager 2 images), and the role of the ionosphere as the conducting medium might thus be variable (see the discussion below). On the other hand, if a thick atmosphere is maintained by surface sublimation [Kumar and Hunten, 1981], then the ionospheric conductivity would be less variable. If the atmosphere is thin enough to allow sputtering (see Sec. 10.3), then the atmosphere is not an important conductor in any case.

Cloutier et al. [1978] have argued that an Earth-like gravitationally-bound ionosphere would be blown away by the ram force of the corotating Jovian magnetospheric plasma (see also Ip and Axford [1980]). That conclusion was strengthened by the Voyager discovery of the dense plasma torus (Cloutier et al. calculated the ram force on the basis of an assumed plasma density of 50 protons/cm^3; for a sulfur ion concentration of 1000/cm^3 the ram force is 640 times larger). Note, however, that if the atmosphere proves to be thick, then the above analysis is invalid; a sufficiently dense atmosphere can resist the corotating torus plasma, as pointed out by Herbert and Lichtenstein [1980].

Cloutier et al. suggest that the ionosphere of Io resembles that of a comet [see also Goertz, 1980a]. The corotating torus plasma causes ionization by electron impact. The ions thus created are swept past Io and the structure of the ionosphere is determined by a balance between electron-impact ionization and the loss of ionization by convection past Io. The loss rate scales with the plasma velocity relative to Io, which in turn is determined by the electric field in Io's ionosphere. Cloutier et al. show that the observed structure of the ionosphere can be explained satisfactorily if the velocity is reduced to approximately one-fifth of the corotational value. They invoke the critical velocity phenomenon proposed by Alfvén [1954] to explain this reduction. Alfvén proposed that a tenuous but un-ionized cloud of gas cannot pass through a magnetized plasma if the kinetic energy per atom of the neutral gas relative to the plasma is greater than the ionization potential of the un-ionized gas. The physics of this phenomenon is not well understood, although it has been demonstrated in laboratory plasmas [Daniellsson, 1970] and in space plasmas [Lindeman et al., 1974].

Goertz [1980a] does not invoke the critical-velocity phenomenon but points out that after the new ions are created (at the rate S/m^{3}s), they are accelerated by the electric field in the atmosphere and displaced by approximately one "cyclotron radius" $\mathbf{R}_i$ in the direction of the electric field. This displacement represents a motion of charge and hence a "pickup" current

$$\mathbf{j}_{pu} = q_i S \mathbf{R}_i \tag{10.20}$$

where the effective cyclotron radius $\mathbf{R}_i$ is given by [Goertz, 1980a; Cummings et al., 1980]

$$\mathbf{R}_i = \frac{m_i}{q_i B^2}\mathbf{E} \tag{10.21}$$

Combining (10.20) and (10.21) yields

$$\mathbf{j}_{pu} = \frac{m_i S}{B^2}\mathbf{E} \equiv \sigma_{pu}\mathbf{E} \tag{10.22}$$

The pick-up conductance $\Sigma_{pu} = \int \sigma_{pu}\,dz$ can be calculated once the rate of ionization is known. Electron impact ionization by the torus electrons is faster than photoionization, and we will consider only electron impact ionization. Scudder et al. [1981] have demonstrated that the torus electron distribution is not in thermal equilibrium but combines a cold and hot component; they report values for the concentrations and temperatures of these components not at Io's orbit but at 7.8 R_J and 5.5 R_J. Apparently, the hot component in the warm torus has a concentration of about 1–3/cm^3 and a temperature of 1 keV. The cold component has a maximum concentration of 2 × 10^3/cm^3 and a temperature of about 6 eV. Further analysis of the PLS data is needed to establish these numbers more precisely at Io's orbit. Using relations provided by Book [1980], we calculate the ionization rate for a combination of cold electrons (T_c = 6 eV, $n_c = 2 \times 10^3$/cm^3) and hot electrons (T_h = 1 keV, n_h = 2/cm^3) to be

$$S_{O^+} = 3 \times 10^{-6}\, n_O [\mathrm{cm^{-3}\,s^{-1}}]$$

$$S_{S^+} = 8 \times 10^{-6}\, n_S [\mathrm{cm^{-3}\,s^{-1}}]$$

where n_O and n_S are the concentrations of neutral oxygen and sulfur, respectively.

As noted in Section 10.3, the neutral concentration of Io's atmosphere is not well known. If, for example, we assume a thick neutral atmosphere with an exospheric temperature $T \sim 1100$ K and exobase concentration $n_{SO_2} \approx 10^9$/cm^3 [Ip and Axford, 1980; Kumar, 1980; Goertz, 1980a], then the scale height is $H \sim 80$ km, the pick-up conductivity is $\sigma_{pu} \sim 1.6 \times 10^{-4}$ mho/m, and the total pick-up conductance $\Sigma_{pu} \sim 12$ mho. This is only an order-of-magnitude estimate but it is larger than the usual Pedersen conductance estimated on the basis of ion-neutral collisions for the same atmospheric model. On the other hand, if the atmosphere is thin and therefore in thermal contact with the surface (see Sec. 10.3), the temperature is no greater than 135 K, the scale height is reduced by an order of magnitude, and the ionization rate is reduced by a factor depending on the thinness of the atmosphere. In this case the estimate of Σ_{pu} is reduced by at least an order of magnitude. (The Pedersen conductivity is also reduced by a similar factor.)

It can be shown [see, e.g., Goertz, 1980a; Southwood et al., 1980] that the electric field in the vicinity of Io is reduced (because of the shorting effect of Io's ionosphere) from its corotational value E_0 to the value

$$E = E_0 \frac{\Sigma_A}{\Sigma_I + \Sigma_A} \tag{10.23}$$

where Σ_I is the effective conductivity of Io's atmosphere (including both Pedersen and pick-up conductivities). For the thick atmosphere model with $\Sigma_I = \Sigma_{pu} \sim 12$ mho and $\Sigma_A \sim 4$ mho we find that the electric field in Io's ionosphere is reduced by a factor of 4, which is close to the value suggested by Cloutier et al. [1978]. On the other hand, the thin atmosphere model with $\Sigma_{pu} \lesssim 1$ mho produces a more modest (~20%) reduction of the electric field. It should be noted that this reduction of the electric field owing to the pick-up effect could be avoided altogether if the corotating plasma were magnetically deflected around Io, that is, if Io had its own intrinsic magnetic field as suggested by Neubauer [1978], Kivelson et al. [1979], and Southwood et al. [1980].

For the thick-atmosphere model, the total ionization rate is 2×10^{28} O^+ ions and 3×10^{28} S^+ ions per second; for a thin atmosphere the total ionization rate would be $\lesssim 10^{27}$/s. It is not presently known whether Io's atmosphere is thick or thin (see Sec. 10.3), so we cannot presently assess the importance of Io's atmosphere in the Io–Jupiter interacton.

10.6. Particle acceleration

We have discussed in Section 10.4 how the injection of ions into Jupiter's magnetosphere results in their initial acceleration up to twice the local corotation energy (namely, 1/2 $m\Omega_J^2 r^2$ in rotational energy and another 1/2 $m\Omega_J^2 r^2$ either in field-aligned streaming energy, for ions slung out from Jupiter's ionosphere, or in cyclotron energy, for ions injected near the equatorial plane). Because these centrifugal accelerations are mass-independent (producing a common velocity independent of mass), the resulting energies are significant for ions but not for electrons. The energies produced are of the order of (60 eV)$(r/6\,R_J)^2$ (m/m_p). We now turn our attention to mechanisms for the acceleration of particles to energies much larger than the local corotation energy.

We shall classify the various acceleration mechanisms according to the degree to which they violate the three adiabatic invariants of particle motion in a dipolelike field: the first (magnetic moment) invariant, the second (bounce integral) invariant, and the third (magnetic flux shell) invariant (for definitions of these invariants see, for example, Northrop [1963]). We shall use the term *adiabatic* to describe processes that involve inward transport through violation of the third invariant to produce adiabatic compression through conservation of the first and second invariants. We shall describe as *quasiadiabatic* those processes that involve repeating cycles of adiabatic compression alternating with nonadiabatic scattering. We shall call *nonadiabatic* those processes in which the first or second invariants are violated as a necessary condition of the acceleration process itself. (These rather specialized definitions are introduced as a convenient shorthand; they should not be confused with the conventional thermodynamic definition of adiabaticity.)

Adiabatic processes

The classical mechanism of magnetospheric particle acceleration is adiabatic compression wherein particles are transported radially inward by violation of the third invariant. Conservation of the first invariant implies a betatron acceleration ($w_\perp \propto B$) and conservation of the second invariant implies a Fermi acceleration ($w_\parallel \propto \ell^{-2}$ where ℓ is the distance between mirror points measured along the guiding field line). Thus, in a dipole field, $w_\perp \propto r^{-3}$ while $w_\parallel \propto r^{-2}$, and the inward-moving particles tend toward a pancake pitch-angle distribution with $w_\perp > w_\parallel$ on the average. On the other hand, if pitch-angle scattering is sufficiently rapid to maintain isotropy during the inward motion, the total particle energy then increases as $w \propto r^{-8/3} \propto V^{-2/3}$ where V is the flux-tube volume, and we have a precise analogy with the adiabatic compression of an ideal monatomic gas.

The inward transport may be provided either by a systematic convection system of the type described in Section 10.7, or by "radial diffusion," which, in this context, means a stochastic system of radial convective motions (see Chap. 11). The timescale for this radial transport is not accurately known, but it is inferred to be much greater than the 10-hr Jovian rotation period (see Chap. 5).

Before the in situ observations by Pioneer 10, it was widely held that adiabatic compression through inward diffusion of solar-wind particles was the principal means of powering the Jovian radiation belts (whose properties were inferred from the synchrotron radio emissions) [e.g., Coroniti, 1974]. We now know that simple adiabatic compression of solar-wind particles is inadequate to produce the observed radiation belts (compare Fig. 10.6 with the results in Chaps. 4 and 5). We also now know that a principal source, if not the dominant source, of energetic particles lies in the inner magnetosphere (at Io's orbit), and these particles are instead subject to adiabatic expan-