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Magnetic fields and charged particles around major planets and their satellites

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Jupiter and Saturn have magnetospheres whose large-scale structure can be understood by analogy with Earth, but the ways in which the magnetospheres differ are of great interest. At Earth, large-scale processes are dominated by convective plasma flows driven by the solar wind. At Jupiter, centrifugal effects driven by planetary rotation are critical. Magnetospheric particle sources include not only the ionosphere and the solar wind (as at Earth) but also satellites and rings. The internal planetary magnetic moments that control the scale of the magnetosphere differ by orders of magnitude between Jupiter and Earth. The magnetic moments have been modelled from spacecraft data but the restricted spatial sampling biases the results and limits confidence in details of the models. Because Jupiter is the only accessible protostar, it serves as a laboratory to test how well inferences from ground-based observations accord with *in situ* measurements. The agreement in some cases examined is reassuringly good but remote observations probe less than 0.1% of the magnetospheric volume. Within that small volume, strong currents couple the moon Io with Jupiter's ionosphere. Voyager data give new insight into the Io story and suggest that Io may itself be magnetized and surrounded by an entirely unfamiliar type of magnetosphere.

1. Introduction

Planetary science rests heavily on observations and insights of past members of the Royal Society. Hooke, Halley and Rayleigh, to name but a few, would surely have shared our delight in learning more of the complexity and diversity of the planets of our Solar System. Their fundamental contributions provide the continuo that accompanies our development of themes related to their work.

The particular sub-theme of this paper is planetary magnetic fields and magnetospheres. In particular, following some introductory definitions and an examination of the features that cause one magnetosphere to differ from another, this paper focuses on four topics. The properties of Jupiter's and Saturn's internal fields are described and the uncertainty inherent in published field models is stressed. Next, the recent progress in measuring and interpreting synchrotron radiation from Jupiter is described, following which some features of Io's torus are reviewed. Both these subjects illustrate the elegant manner in which remote and *in situ* observations support and amplify one another. The confirmation of inferences drawn from remote observations has special significance for astrophysics, where our knowledge relies exclusively on such inferences. Many of Jupiter's properties, such as the modulation of its electromagnetic emissions by its rotational period, have parallels in pulsar properties; so the relations are quite direct. Finally the possibility that Io has an intrinsic magnetic field is considered (Neubauer 1978) and the properties of Io's putative magnetosphere, embedded within the Jovian magnetosphere (Kivelson *et al.* 1979), are discussed.

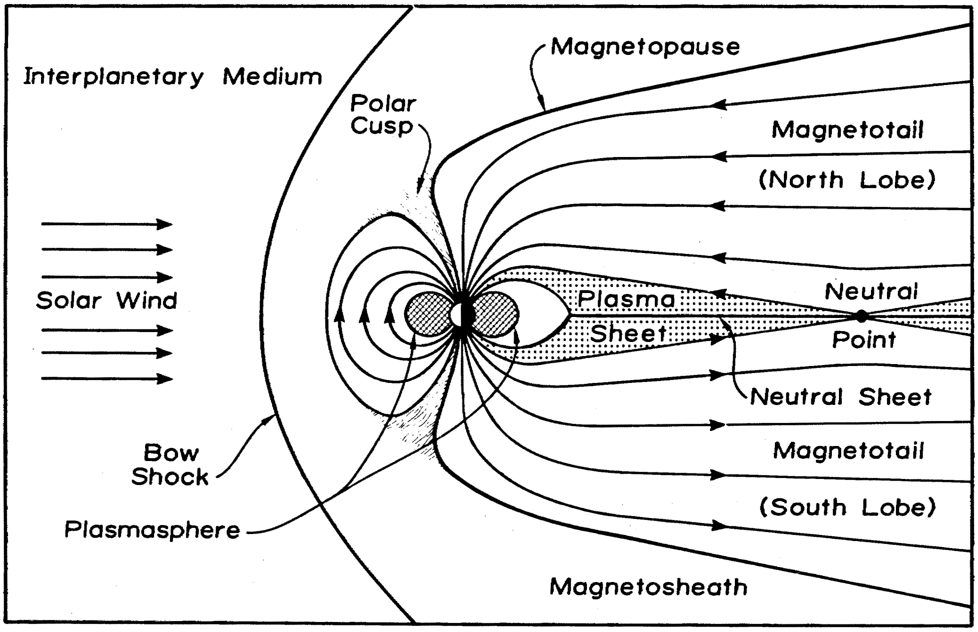


FIGURE 1. Schematic representation of the terrestrial magnetosphere.

A magnetosphere develops when a magnetized body is present in the flow of a highly conducting plasma or ionized gas. The concept was elucidated by Chapman & Ferraro (1932, 1933), whose idealized treatment contains the basic concepts that we accept today. The ionized gas flows outward from the Sun and is called the solar wind. A magnetized planet deflects the incident fluid and produces a cavity in the flow which is called a *magnetosphere*. Within the magnetosphere, the distorted planetary magnetic field largely orders the charged particle motion so that different spatial regions on average contain predictable plasma populations.

A schematic view of the organization of the terrestrial magnetosphere is given in figure 1. Because the solar wind speed exceeds the phase velocity of the pertinent magnetohydrodynamic wave modes, a *bow shock* forms upstream. The shocked solar wind is slowed and diverted in the *magnetosheath*. The *magnetopause* forms the boundary between the solar wind and the magnetosphere and only in limited regions such as the *polar cusp* or at the dawn and dusk edges of the *plasma sheet* in the *magnetotail* does solar wind plasma gain access directly into the magnetosphere. Additional plasma flows upward along magnetic flux tubes from the ionosphere and together the two plasma populations account for the presence of relatively high density regions called the *plasma sheet*, the *plasmasphere*, the *ring current* (not illustrated), etc.

Fortunately for the curious scientist, other planets have magnetospheres and here we look outward from Earth towards Jupiter and Saturn and their major satellites. We shall examine their plasma environments and shall stress how and why the magnetospheres differ from one another.

The earliest remote observations relevant to this presentation were those of Galileo, who with his low resolution telescope first identified the four major moons of Jupiter and argued that they moved in near-circular orbits around Jupiter. In this century, Jupiter was found to be a strong radio source, and the spectrum at gigahertz frequencies or decimetric wavelengths was interpreted as synchrotron emissions from relativistic electrons trapped in a planetary magnetic field (Roberts & Stanley 1959).

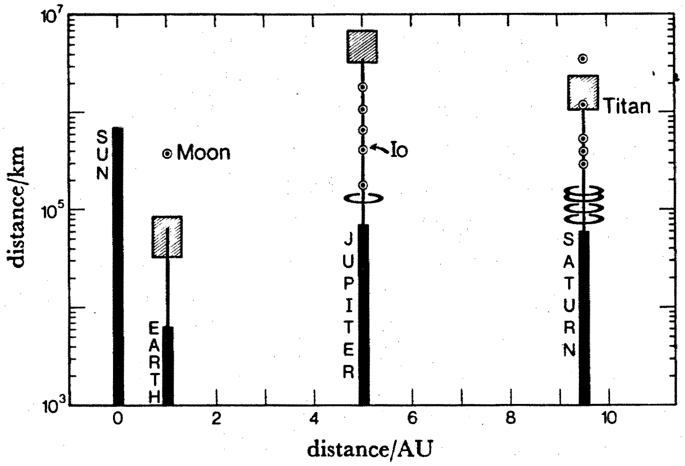


FIGURE 2. Schematic diagram of magnetospheric scale sizes. Solid black bars represent the central bodies. Lines represent the magnetospheres, while shading shows approximate range of observed dayside magnetopause locations. Major satellites are shown as ⊚ and principal known rings are indicated. (Adapted from Siscoe (1979).)

In 1964 it became clear that the radio emissions at $\leqslant$ 40MHz or at decametric wavelengths were modulated by the phase of the moon Io relative to the Earth–Jupiter line (Bigg 1964). It was soon suggested that the radio emissions cut off at the gyrofrequency of an electron at the ionospheric foot of Io's flux tube and that Io modulation implied coupling between Jupiter's ionosphere and Io. It was suggested that the coupling was provided by Alfvén waves travelling along the planetary magnetic field lines (Marshall & Libby 1967) or by field-aligned currents (Goldreich & Lynden-Bell 1969).

It was only following the flybys of the Pioneer 10 and 11 spacecraft that the actual size and complex phenomenology of the magnetospheres of Jupiter and Saturn could be fully appreciated. The scales of these magnetospheres, beside which the Sun itself shrinks, are truly imposing, as the schematic figure 2 illustrates. Indicated on the diagram on a logarithmic scale are the positions of the major moons and the planetary rings. Earth's moon moves outside the magnetosphere on the dayside and, indeed, for most of its orbit. By contrast, the Galilean moons of Jupiter and several moons of Saturn as well as the rings are present well within the magnetosphere. Titan may prove of special interest, for its orbit lies near the magnetopause which moves back and forth across Titan's orbit as solar wind conditions change. The Voyager 1 trajectory takes it some 2500 km from Titan's surface and should give the first data for Titan's immediate environment in one phase or the other.

2. WHY DO MAGNETOSPHERES DIFFER?

The magnetospheres to be considered differ markedly from one another and the challenge is to identify the controlling parameters both in the external flow and within the magnetosphere. Some are obvious from analogy with Earth. The size of the cavity, for example, is largely determined by the need to balance the dynamic pressure of the solar wind with the magnetic pressure of internal origin. The solar wind pressure decreases as the inverse square of heliocentric distance and becomes more variable. The frequently changing size of Jupiter's magnetosphere (Wolfe *et al.* 1974; Bridge *et al.* 1979*a*, *b*) can largely be attributed to the variability of the solar wind at Jupiter's orbit (Smith *et al.* 1978).

The planetary magnetic moments vary over many orders of magnitude, with Jupiter's moment more than 10^4 times that of Earth. The moments vary approximately linearly as $\rho^{\frac{1}{2}}\Omega R_c^4$, where ρ is density, Ω is angular velocity and R_c is the core radius (Russell 1979).

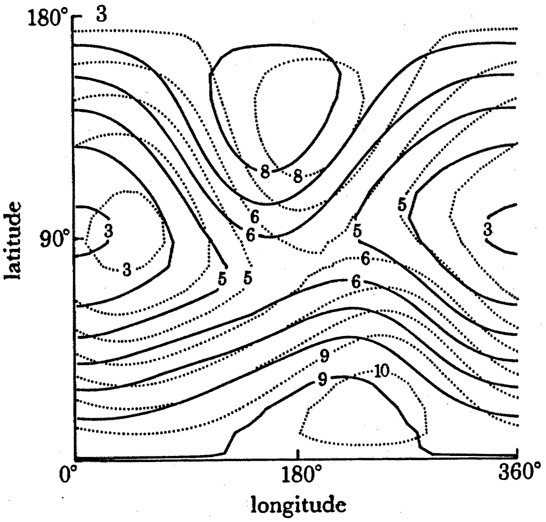
Within the magnetosphere, the macroscopic plasma dynamics depend on the relative magnitudes of certain characteristic velocities. To some extent the planet is able to impose corotation on the magnetospheric plasma, and the centrifugal forces are important when the velocity of corotation, V_{cr}, becomes comparable with the sound velocity, C_s, or the Alfvén velocity, V_A, which characterizes transverse hydromagnetic wave propagation. The corotation velocity increases with radial distance but even at Io's orbit near 6 R_J (1 R_J = radius of Jupiter = 71000 km) typical values are: $V_{cr} \approx 70$ km/s, $C_s \approx 20$ km/s and $V_A \approx 200$ km/s. Although the plasma near Io moves azimuthally at sub-Alfvénic speeds, centrifugal forces act to spin out near-equatorial plasma, and probably are partly responsible at larger distances for inflating the Jovian magnetosphere. For Earth, at 6 R_E (1 R_E = radius of Earth = 6400 km) typical values are: $V_{cr} \approx 3$ km/s, $C_s \approx 1000$ km/s and $V_A \approx 700$ km/s. So centrifugal effects do not dominate. On the other hand, the motions of the plasma in the terrestrial environment are governed quite directly by interaction with the solar wind, which imposes convective flows throughout much of the magnetosphere. At Jupiter the externally driven flows appear to be confined to regions near the boundaries and within the magnetotail (Ness *et al.* 1979; Krimigis *et al.* 1979). For Saturn the situation appears to resemble Earth's more than Jupiter's.

Finally, the diversity of internal sources and sinks of plasma must be stressed. At Earth, the ionosphere is the only significant *internal* source or sink. At Saturn, moons appear to be largely sinks (see, for example, Van Allen *et al.* 1980*a*) and the rings, which fully absorb particles in most energy ranges (see, for example, Fillius *et al.* 1980), serve as sources of very energetic protons, $E_p > 80$ MeV (Van Allen *et al.* 1980*b*).

As regards internal sources, Jupiter's case is most exceptional. Like Saturn, it has moons and rings, which tend to absorb magnetospheric plasma, but it has, as well, a moon (Io) quite pock-marked with active volcanoes (Morabito *et al.* 1979), which spew heavy ions into the inner magnetosphere. Additional planetary debris is introduced into the magnetosphere by 'sputtering' from the surfaces of the moons and possibly the ring. The moons, particularly the innermost ones, move through large fluxes of energetic charged ions whose surface impacts sputter neutral material into the magnetosphere (Brown *et al.* 1978; Lanzerotti *et al.* 1978), where it is later ionized by electron impacts. The heavy ions from Io, mainly sulphur, oxygen and sodium, form a relatively high density torus near Io's orbit, and in a later section some of the consequences of the torus are discussed.

3. INTERNAL FIELDS OF JUPITER AND SATURN

The internal magnetic fields of the outer planets have been described in terms of multipole coefficients obtained by inversion of the magnetic field measurements made inside of some arbitrary distance (usually between 5 and 10 planetary radii) within which it is assumed that no distributed currents flow (Acuña & Ness 1976; Smith *et al.* 1976, 1980). To lowest order, field properties are expressed in terms of a dipole magnitude and tilt relative to the planetary rotation axis. The magnitude can be stated in terms of the equatorial field strength at the 'surface' or cloud-top level, where Saturn's field is 2×10^{-5} T, quite similar to the field at the surface of Earth; for Jupiter the surface field is 4×10^{-4} T, more than an order of magnitude



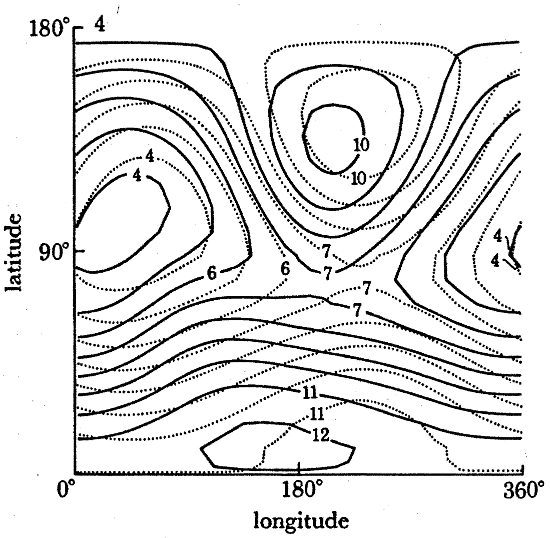


FIGURE 3. Contours of equal $|B|$, labelled in 10^{-4} T, from the Pioneer 10 (dotted lines) and 11 (solid lines) quadrupole models. This diagram is from Mullen & Walker (1980).

FIGURE 4. Contours of equal $|B|$, labelled in 10^{-4} T, from the quadrupole fits to a 2^5-pole test model field sampled along the Pioneer 10 (dotted lines) and Pioneer 11 (solid lines) trajectories. This diagram is from Mullen & Walker (1980).

larger. Perhaps more interesting are the tilts, which for Jupiter and Earth are *ca.* 10° and *ca.* 11°, respectively. Before the Pioneer 11 flyby of Saturn, experience and theory both made it tempting to suppose that a near 10° tilt was an essential feature of planetary dynamos, but Smith *et al.* (1980) find that the dipole tilt at Saturn is 'consistent with 0.0°' and more recent work (E. J. Smith, personal communication) suggests that the tilt does not exceed 1°. Future dynamo theories must be compatible with this important observation.

Higher order fits to the measurements have also been presented. Quadrupole and octupole moments are relatively larger for Jupiter than for Earth and the surface field is consequently quite irregular, as illustrated in figure 3, in which contours of equal magnetic field magnitude, $|B|$, are plotted against surface latitude and longtitude for the quadrupole models of Smith *et al.* (1976) for both the Pioneer 10 (1973) data and the Pioneer 11 (1974) data. The two sets of contours appear to be displaced from one another by about 30° and the peak field strengths differ by about 10% near the south pole. The longitudinal variation of the surface field strength at fixed latitude is thought to account for various phenomena that manifest the 10 h periodicity of planetary rotation (Vasyliunas & Dessler 1980).

Saturn's higher order multipoles are relatively small (Smith *et al.* 1980); so it is somewhat surprising to find that radiofrequency emissions in the *ca.* 200 kHz range are clearly modulated at the period of planetary rotation. The radio emissions show a periodicity of 10 h 39.4 min ± 0.15 min (Kaiser *et al.* 1980), and so far the mechanism that modulates the emission has not been identified.

The two Pioneer spacecraft obtained magnetic field measurements close to Jupiter 1 year apart in time. (Unfortunately the Voyager 1 and 2 spacecraft helped little in defining the internal field because they remained outside of 4.8 R_J.) It is tempting to compare the 1973 and 1974 models obtained from the Pioneer 10 and Pioneer 11 observations, respectively, as we have done in figure 3 to assess the temporal variation of the internal field. R. Hide (1978) has argued that it may be possible to infer the radius of the conducting core, within which dynamo action

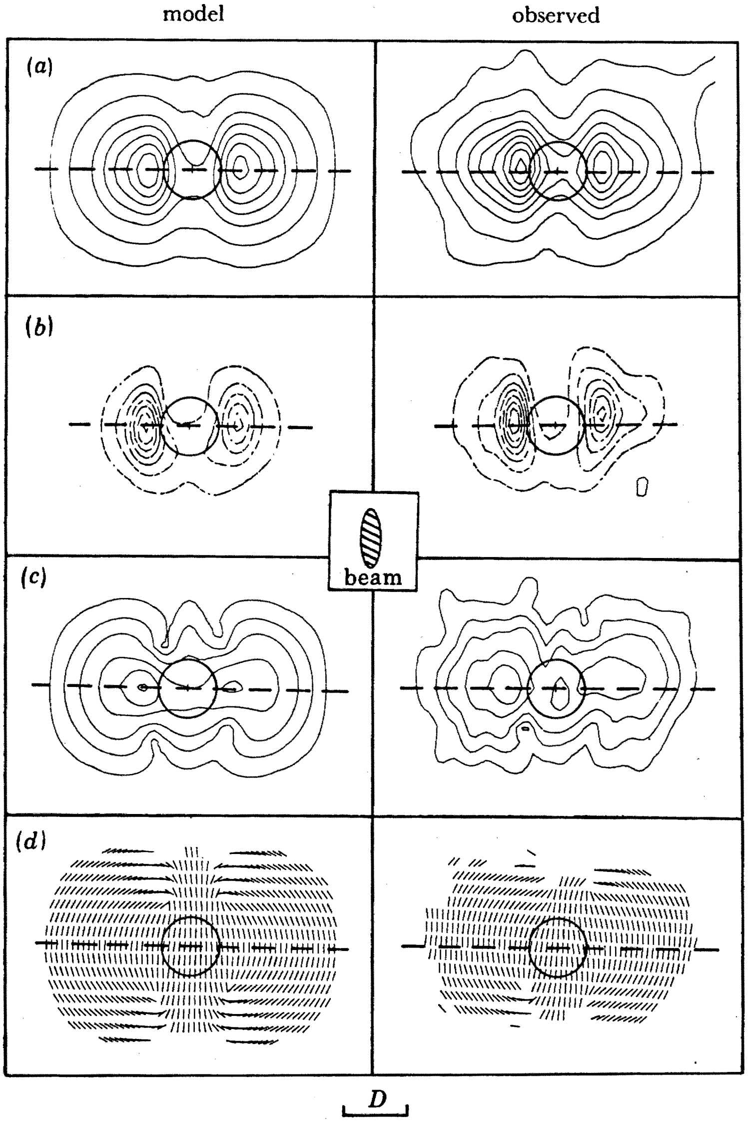


FIGURE 5. Observed and model patterns of 21 cm synchrotron radiation from the calculation of De Pater (1980). This is fig. 19 of that paper. (*a*) Total flux density; (*b*) circularly polarized flux density; (*c*) linearly polarized flux density; and (*d*) inferred magnetic field orientation (everywhere perpendicular to electric field vectors).

is confined, from knowledge of the change of the surface field in a year. The theorem relies on a demonstration that, on time scales short with respect to the diffusion time in good conductors, the core can be regarded as a perfect conductor through whose surface the magnetic flux linkage does not change. Hide & Malin (1979), although skeptical about accepting the differences between the 1973 and 1974 models as representative of secular changes, nonetheless used them in conjunction with Hide's method to determine the core radius of Jupiter. Their calculated value, 0.7 R_J, appears to be physically reasonable.

Recently Mullen & Walker (1980) at University of California, Los Angeles, have estimated the uncertainties in inferred field models that result from the restricted spatial sampling available. For example, within 5 R_J, Pioneer 10 sampled less than 80° of sub-satellite surface longitude and remained within ± 10° latitude of the rotational equator. Pioneer 11, though less restricted in both longitude and latitude, also did not sample uniformly. The consequence of this 'spatial aliasing' is demonstrated by Mullen & Walker using what they call a test model, a nominal planetary field containing up to 2^5-pole terms normalized to have equal power in each multipole at 0.7 R_J. This field is sampled without error along the actual trajectories of Pioneers 10 and 11 at points equispaced in time. The sampled fields are then fitted in the least squares sense with a quadrupole model. Figure 4 shows the constant $|B|$ contours from fits obtained for the *identical test model field* sampled along the two trajectories. The two sets of contours are displaced from one another by *ca.* 30° and some difference in maximum field strength appears at high latitudes. The differences in this test calculation appear similar to those obtained by fitting measured fields, and support strongly the view that differences between the fits to actually measured fields arise principally because of spatial aliasing. Thus, on the time scale of 1 year the data are consistent with a constant internal field. It appears that the core size cannot be meaningfully obtained from a comparison of the 1973 and 1974 field models.

4. Synchrotron emission

As already noted, Jupiter's magnetic properties were first inferred from analysis of the decimetric radio spectrum. The early interpretations have stood the test of time. It is now certain that relativistic electrons trapped and gyrating in Jupiter's magnetic field emit the observed radiation. Recently, De Pater (1980) has provided high resolution maps of the 6 and 21 cm radiation. Recognizing the considerable asymmetries of the Jovian magnetic field, she obtained separate maps for every 15° of Jovian central meridian longitude and demonstrated that the synchrotron emission also is quite asymmetric.

Next De Pater compared the radio data with a model calculation of the synchrotron radiation based on Pioneer 11 magnetic field models (Acuña & Ness 1976; Smith *et al.* 1976) to determine the high energy electron distribution in Jupiter's inner magnetosphere. The calculation considers inward radial diffusion of particles, properly includes the adiabatic variation of particle flux along a flux tube, allows for local losses by incorporating a lifetime consistent with Pioneer data, considers the sweeping effects of the moon Amalthea (near 2.6 R_J) and of Jupiter's ring (near 1.8 R_J) and allows for pitch angle scattering. The free parameters are selected to give good fits to the constraints from the radio data, including total flux density, degree of linear and circular polarization, etc., for data taken at a specific Jovian central meridian longitude. Figure 5, reproduced from De Pater (1980), indicates the success with which this procedure has reproduced the observations. The inferred electron spectrum is in reasonable agreement with the integral flux measured *in situ* (Van Allen 1976) at the same epoch but is harder than the measured spectrum. De Pater is dissatisfied with the agreement between the longitudinal asymmetries in her calculation and the observations and suggests that the magnetic field models may be deficient. It will be interesting to follow her efforts, which could give comfort to astrophysicists by supporting the conclusion that a good way to find out about Jupiter's particles and fields is to remain on the Earth.

5. Io's plasma torus

Planetary astronomers have, for the past 7 years, been aware that heavy atoms and ions are present in Jupiter's inner magnetosphere near the orbit of Io. Pioneer 10 and 11 measurements failed to locate the radiating particles, but Voyagers 1 and 2 were successful. Complementary data from several instruments give confidence in the data from which an understanding of mass and energy transport is beginning to emerge.

Pre-Pioneer discussions of the Jovian particle distributions foresaw satellite sweeping effects and predicted strong decreases of particle fluxes at the orbits of the Galilean satellites (Mead & Hess 1973). Such losses were observed (see, for example, Van Allen 1976) and no evidence for the moons as ion sources emerged from Pioneer 10 and Pioneer 11 measurements. This remained true despite the reports that a cloud of neutral sodium surrounded Io and extended far ahead of its orbital position (Brown & Chafee 1974) and that radiation from ionized sulphur was present in an extensive region centred at Io's orbit (Kupo *et al.* 1976). The only suggestion based on Pioneer 10 and 11 observations that Io served as an important source of particles was put forward by Fillius (1976), who reported that Io was a source of electrons with energies of a few hundred thousand electronvolts.

From the two Voyager passes through the Jovian magnetosphere there has emerged a new appreciation of Io as a primary source of magnetospheric plasma and of the torus of heavy ions that is located near Io's orbit. The Voyager 1 ultraviolet spectrometer detected emissions at 6850 nm and the source was modelled as a toroidal cloud of uniform density. The model cloud was centred at $5.9 \pm 0.3\ R_J$, had a cross-sectional radius of $1 \pm 0.3\ R_J$ and was centred on the magnetic equatorial plane (Broadfoot *et al.* 1979). The emissions at this frequency betoken the presence of a high temperature plasma capable of exciting SIII, SIV, and OIII.

When Voyager 1 was between 5 and 9 R_J in the region of the plasma torus, the planetary radio astronomy experiment independently confirmed the presence of dense plasma. Strong emissions were found at the electron upper hybrid frequency, from which the total electron density can be quite unambiguously determined (Warwick *et al.* 1979). The peak densities ($\geqslant 4500\ \mathrm{cm^{-3}}$) occurred close to Io's orbit and the ring was found to be bounded by steep gradients on its inner edge.

The Voyager plasma experiment also directly confirmed the presence of hot (2.5×10^5–4.9×10^5 K), dense (*ca.* 10^3–2×10^3 ions/cm^3), heavy ion (S^{2+}, O^+) plasma in the Io torus and noted that it is bounded on its inner edge by a region of cold, dense plasma (Bridge *et al.* 1979*a*). Further efforts (Bagenal & Sullivan 1980) have provided very convincing models of ion distributions in the vicinity of the Voyager 1 path through the Io torus. Along each field line the scale height distribution away from the centrifugal symmetry surface (the point on each field line furthest away from the rotational axis of the planet) is expressed in terms of reference density and temperature and the charge separation electric field is accounted for.

From the plasma distribution model, Bagenal & Sullivan obtain the column density along lines of sight perpendicular to the rotation axis, thus permitting direct comparison with Pilcher's (1980) ground-based observations of the radiation emitted at 67310 nm by S^+ ions (Pilcher 1980). Pilcher finds a fan-shaped emitting region with a sharp outer edge at $5.9\ R_J$ (beyond which he believes that the temperature may exceed 25 eV and that the sulphur may be present only as S^{2+}). The vertical extent of the fan diminishes inward and reaches a minimum near $5.1\ R_J$, quite in keeping with the calculated distribution of Bagenal & Sullivan. Further comparison of these two sets of observations could prove very useful, especially as Pilcher's ground-based observations show major changes from day to day and could provide a means of monitoring the properties of the torus plasma.

The plasma torus clearly contributes to many other observed features of the magnetosphere. For example, a diffuse aurora (Broadfoot *et al.* 1979) appears to arise from the destabilizing effect of enhanced cold plasma density on inward diffusing protons (Goertz 1980) or electrons (Thorne & Tsurutani 1979; Scarf *et al.* 1979). Sandel *et al.* (1979) argue that the u.v. auroral intensity requires some 10^{12} W of power, which is significant in terms of the inner magnetosphere's energy budget.

The significance of the plasma torus may not yet have been fully comprehended, but some appreciation of its global magnetospheric effects is beginning to emerge. The torus is found to constrain the inward penetration of energetic ring current plasma (Siscoe *et al.* 1980). Io ejecta in the torus are found to brake corotation (Hill 1979; Eviatar *et al.* 1981). Possibly Io and its torus will be found to be the features that most strongly control Jupiter's dynamical behaviour.

The satisfying agreement between the data obtained *in situ* within Jupiter's magnetosphere and expectations based on planetary astronomy supports the proposition that astrophysical inferences can be remarkably accurate. On the other hand, emission regions observed remotely fall inside of $10\,R_\mathrm{J}$ and occupy only about 0.1% of the planetary magnetosphere; so many aspects of the system can be understood only through spacecraft measurements.

6. An Ionian magnetosphere

The key to the torus properties is the small moon Io (its radius, R_Io, is 1800 km). Why is Io so special? Part of the answer may have been provided by Peale *et al.* (1979), who have proposed that tidal stresses may lead to internal melting. Their pre-Voyager speculation that Io might have volcanoes was magnificently confirmed only days after their paper appeared in *Science, N.Y.*

Not only is Io volcanic, it is also coupled to the Jovian ionosphere through field-aligned currents whose strength is approximately 10^6 A. The existence of currents at Io is not difficult to understand. The torus plasma corotates with Jupiter. Because Io moves more slowly, the torus plasma sweeps by it from behind at 57 km/s and creates a wake ahead of Io in its orbital motion. We can describe the resultant interaction in hydromagnetic terms. Outside Io, the magnetic field is frozen in flowing plasma. Near Io, viewed as an imperfect conductor, the electric field is reduced because the conductor can be polarized. The flow is correspondingly slowed. Magnetic field lines bend as they move through the conductor and produce Maxwell stresses which act both to slow the torus flow and speed up Io. The currents that communicate the stress between the conductor and the plasma flow in the moving plasma and it is these currents that ultimately reach the Jovian ionosphere and power the decametric emissions previously mentioned. The field perturbations produced by the interaction described propagate along the field with the Alfvén velocity while the plasma continues to move relative to Io as has recently been described by Neubauer (1980). The configuration that results is indicated schematically in figure 6. The perturbations are carried along 'Alfvén wings' whose angle with the field is determined by the Alfvén Mach number. The small rectangle represents the approximate region within which Voyager 1 transversed Io's flux tube and provided evidence of strong Io-associated field and particle perturbations (Ness *et al.* 1979; Krimigis *et al.* 1979), though, as is evident from the schematic diagram, the spacecraft remained upstream of the region of maximum perturbation.

If Io has an intrinsic magnetic field, as suggested by Neubauer (1978), the interaction with the flowing plasma will create a magnetospheric cavity (Kivelson *et al.* 1979). Most of the characteristic magnetospheric properties mentioned in the introduction will be present, but, as the relative flow velocity (57 km/s) is small compared with the Alfvén velocity (of order 200

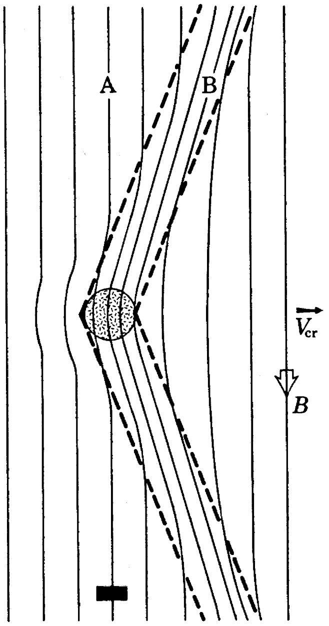


FIGURE 6. Schematic illustration of the magnetic field in an azimuthal plane through the centre of Io, assumed to be an unmagnetized conductor. Dashed lines represent boundaries of the Alfvén wings. The approximate locations of Voyager 1 as it crossed Io-associated field lines lie within the solid black rectangle.

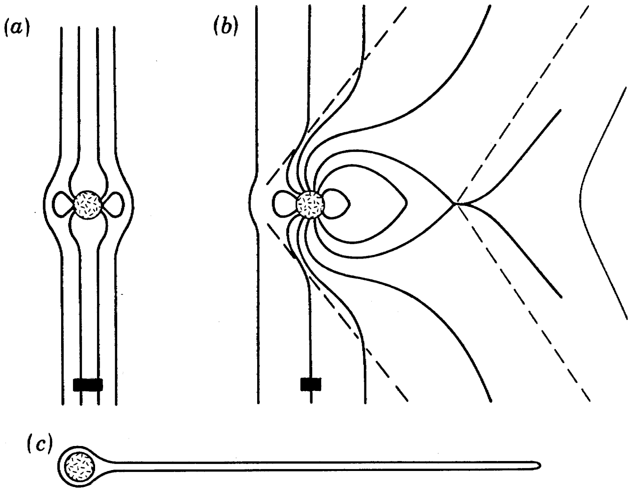


FIGURE 7. Schematic illustration of magnetic fields near Io for a reconnected magnetosphere. Solid black rectangles and dashed lines are as in figure 6. In (*a*) the field is viewed in a meridian plane through Io, while (*b*) shows an azimuthal plane. Diagram (*c*) shows an equatorial plane view of the region containing field lines that connect both with Io and with Jupiter.

km/s), diversion of the flow can occur without the intervention of a shock, and so the bow shock will be absent. However, most other features of the interaction should be largely independent of the Alfvénic Mach number (Kivelson *et al.* 1979; Southwood *et al.* 1980), although this point has been challenged (S. Kumar, personal communication). It is reassuring to note that I.S.E.E. investigators (Gosling *et al.* 1980) have identified a day on which the solar wind at Earth became sub-Alfvénic. Although flow speeds and plasma temperatures were found to be

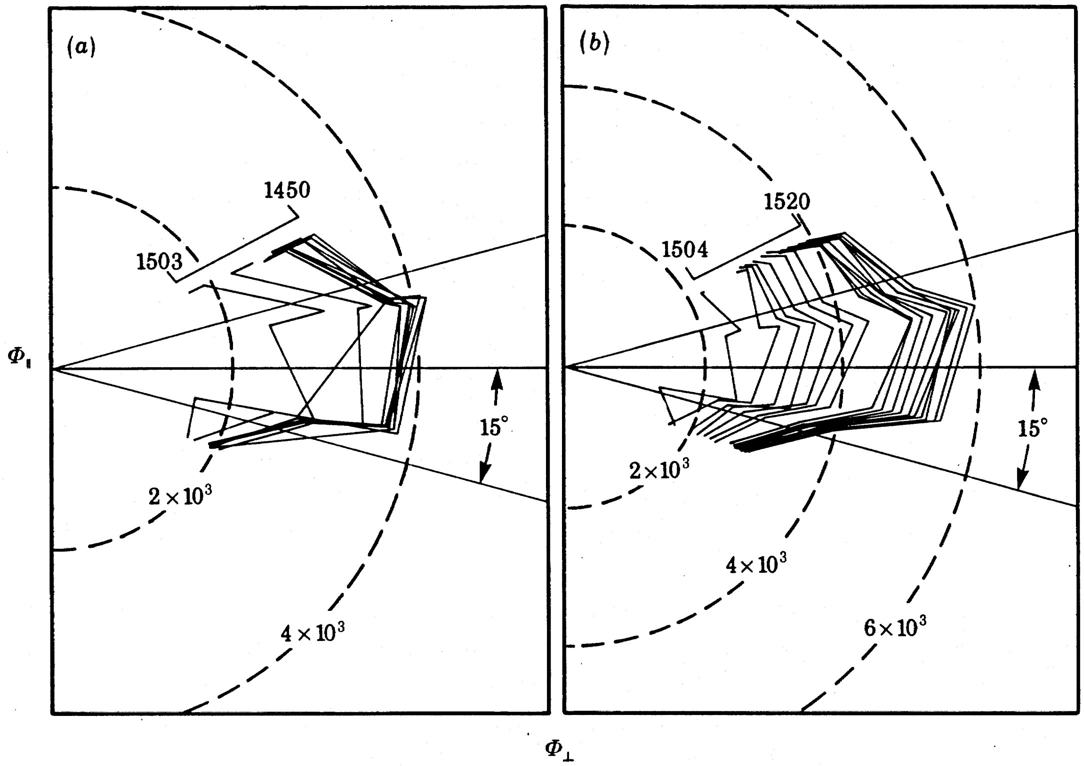


Figure 8. Energetic electron fluxes (≥ 10 Mev) as Voyager 1 entered (*a*) and emerged from (*b*) the Io flux tube. The vertical axis is antiparallel to the Jovian magnetic field. The magnitude of the flux as a function of direction is shown in a polar plot (dashed lines labelled with count rate/s^{-1}). The diagram is adapted from Lanzerotti *et al.* (1980). Lines at $90\pm15°$ show the loss cone predicted if Io has a magnetic field (see text).

somewhat anomalous near the magnetopause, the large-scale structure near the boundary was not substantially modified.

The scale of a possible Ionian magnetosphere was estimated by Kivelson *et al.* (1979). They noted that the Ionian ionosphere, whose density profile had been obtained by Kliore *et al.* (1975) from Pioneer 10 occultation data, terminated abruptly at an altitude of about 200 km above the surface on the side of Io upstream relative to the corotating plasma. They proposed that the sharp boundary might be coincident with Io's magnetopause and from the magnetopause stand-off distance inferred Io's magnetic moment. Their assumption required a dipole moment of 6.5×10^{18} T cm^3 (6.5×10^{19} A m^2), which means that Io's magnetosphere is very small even when expressed in terms of planetary radii. The distance from the surface to the upstream magnetopause is only $0.1\,R_{\mathrm{Io}}$.

The fact that field-aligned currents must couple Io to the torus plasma requires Io's dipole moment to be antiparallel to Jupiter's, a situation that results in an open configuration first discussed by Dungey (1961). The expected configuration is illustrated schematically in figure 7. In this case, too, perturbations are confined within Alfvén wings. The region penetrated by the Voyager 1 spacecraft, as shown in figure 6, was upstream of the major perturbations.

Southwood *et al.* (1980) argue that the magnetic field perturbations in the Io flux tube reported by Ness *et al.* (1979) can be modelled with the assumption that field-aligned currents flow in parallel sheets upstream of the spacecraft and close through Io. The parameters of their model characterize the spatial scale of the Io interaction region (plate separation and length in the direction of orbital motion), the strength of the currents flowing through Io, and the Alfvénic Mach number of the plasma, which sets the distance to the upstream edge of the plates. The plates themselves represent the Alfvén wings. The calculations demonstrate that the scale of the interaction in the radial direction cannot substantially exceed the diameter of Io. The fits are quite insensitive to the scale length along the orbital direction because only upstream fringing fields are sensed. This result unfortunately means that it is not possible to determine the length of a possible magnetotail. The distance to the upstream edge is found to be compatible with an Alfvénic Mach number of 0.15, which appears acceptable in terms of direct plasma measurements.

Strong absorption of relativistic (*ca.* 10 MeV) electrons in Io's flux tube was reported by Krimigis *et al.* (1979), whose measurements show little change in the flux of ions. Southwood *et al.* (1980) note that the absence of signatures in ions can be explained in terms of their relatively slow motion along the field direction. Losses will be observed only for those energies and species for which the spacecraft is in Io's 'shadow'. This situation applies for *ca.* 10 MeV electrons but not for intermediate energy ions. Why then are only about 35% of the electrons lost?

If Io is merely a conductor, there appears not to be an answer to this question. If Io is magnetized, an answer is readily available. Most of the bouncing electrons can mirror in the enhanced fields of Io's polar cap. Only those in the 'loss cone' will be lost, and for the assumed dipole moment and the instrumental configuration reported by Krimigis (1979) the loss is calculated to be close to the observed 35%.

Southwood *et al.* (1980) thus predict that energetic electron flux in Io's flux tube should be strongly pitch angle dependent with cut-offs at *ca.* 75° and *ca.* 105° from the local field direction. Subsequently Lanzerotti *et al.* (1980) analysed the pitch angle dependences of the energetic electrons in the Io flux tube and obtained the results shown in figure 8. Unfortunately their instrument sampled only a limited range of angles near 90° but the fluxes clearly fall off near the edge of their pitch angle range as predicted by the magnetospheric model with the assumed magnetic moment. The dependence of flux on pitch angle has not been predicted by other models of the interaction; so this evidence supports the hypothesis of an Ionian magnetosphere.

If Io has a magnetosphere, it should have an aurora and indeed it does. Cook *et al.* (1981) have reported auroral glows on Io's night side, both near the poles and over known volcanoes. (Elsewhere the atmosphere is so cold that it freezes out.) Though an aurora is suggestive, it is not necessarily produced by magnetospheric processes and further study is needed.

One really does hope that Io is magnetized, for its magnetosphere would be truly unique. It would be our only example of a magnetosphere in a sub-Alfvénic flow, the smallest absolutely and also the smallest on the scale of its own radius. It would be the first magnetosphere within a magnetosphere (though possibly others may be found). At this point, though, the jury is out.

7. Conclusions

It is fortunate that the Galileo dual-spacecraft mission will once again give us an observer on the scene at Jupiter. The brief glimpses provided by the Pioneer and Voyager missions have left us with questions and have convinced us that further surprises may be in store. The Galileo mission's satellite encounters and a prolonged orbital tour may help reveal those surprises.

At the present time a passage through Io's wake is proposed for an early orbit. The possibility that Io has a magnetosphere has consequently become a practical issue. The worry is that if Io has a magnetosphere it may be subject to the type of instability that at Earth is called a substorm. What would happen to the Galileo spacecraft if a sub-storm occurred during its 4 min wake passage? With an entire mission relying on the survival of the spacecraft, one would like to be confident in one's predictions of the probable environment. At present it is still a challenge.

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