The dynamic expansion and contraction of the jovian plasma sheet

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We report here that near noon in the magnetosphere of Jupiter, plasma is observed to flow away from the equatorial current sheet. The motion reverses near dusk, with a subsequent infall of plasma towards the sheet on the nightside. We associate this motion with the compression of magnetic flux tubes on the dayside and their subsequent expansion on the nightside due to the solar wind interaction with Jupiter. Such compression and expansion may be sufficiently rapid that the plasma in the sheet cannot reach quasi-static equilibrium. Dynamic motions at transonic velocities ensue.

The plasma instrument on board the Voyager spacecraft consists of four modulated-grid Faraday cups which measure positive ions and electrons with energies per charge in the range 10–5,950 V (ref. 1). Three of these cups are arranged in a cluster whose symmetry axis normally points towards the Earth. The fourth cup (the D cup) is situated so that its axis is perpendicular to the symmetry axis of the main cluster. The trajectory of Voyager 2, and the orientation of the sensor normals at various points along that trajectory, are shown in Fig. 1; the Voyager 1 trajectory and sensor orientations are qualitatively similar. Plasma flow in the jovian magnetosphere has a tendency to co-rotate with the planet, that is, to move azimuthally at the rotation rate of the planet. The D cup is orientated so that azimuthal flow moves almost directly into that cup on the inbound leg of the trajectory. Near closest approach, strictly co-rotating flow would move into the field of view of the main sensors, and after closest approach out of the field of view of all sensors.

The response functions[2] of the Voyager Faraday cups are broad, with 30% response at an angle of incidence of 60° to axes of cups in the main cluster, and 30% response at an angle of 40° to the side sensor axis. Over much of the inbound trajectory, there is at least one sensor for which the plasma flow velocity is within ~20° of the sensor normal. If, in addition, the plasma is reasonably supersonic (Mach ⩾3), the response function can be taken as unity. In such a situation, the analysis of the positive ion data from that sensor is relatively straightforward, although complicated by the fact that the jovian magnetospheric plasma consists of an admixture of many ionic species (H^+, S^+, S^{2+}, S^{3+}, O^+, O^{2+}, Na^+, SO_2^+). Such single sensor data have been exhaustively analysed since the Jupiter encounters for heavy ion densities and temperatures, as well as for the velocity component along the sensor axis[3–5]. However, only for a brief time near closest approach, and during isolated spacecraft manoeuvres, is the unit response assumption valid for more than one sensor. To obtain all three components of the plasma velocity, we must use information from at least three sensors; because two of the three are usually significantly oblique to the flow, it is necessary to use the full response functions of the sensors. The complete determination of the velocity is more complex and time consuming, and at present can only be done on a limited basis. We discuss some quantitative results from this analysis below.

First, however, we take advantage of the symmetry properties of two of the main cluster sensors with respect to the jovian equatorial plane to obtain some qualitative results about the plasma velocity component perpendicular to that plane. These qualitative results are quantitatively verified by our more sophisticated analysis below. When the attitude of the spacecraft is referenced to the star Canopus, the axes of the A and D cups are essentially in the jovian equatorial plane. The axes of the B and C cups, however, are inclined to that plane in a nearly symmetrical fashion, at angles of 18.6° south and 15.3° north, respectively, for Voyager 2. We compute the flux density in a given cup by taking the total current due to positive ions with energies per charge from 10 to 5,950 V, and dividing by the proton charge and the effective area of the sensor. Figure 2 shows the flux density of the B cup minus the flux density of the C cup, divided by the sum of the flux densities in the B and C cups for a portion of the Voyager 2 trajectory. Because of the orientation of the cups, this difference will be positive for flow towards the north and negative for flow towards the south. Figure 2 also plots the distance of the spacecraft above the magnetic dipole equatorial plane. We indicate at various points the local time, and the distance of the spacecraft from Jupiter, with perijove at 10.1 jovian radii (R_J) (9 July 1979 at 2230 h). We have only plotted data in Fig. 2 when the fluxes in the B and C sensors are high enough to allow a significant comparison, and when the spacecraft was on Canopus. Unfortunately, this means that we can use little data past 1400 h on 10 July 1979.

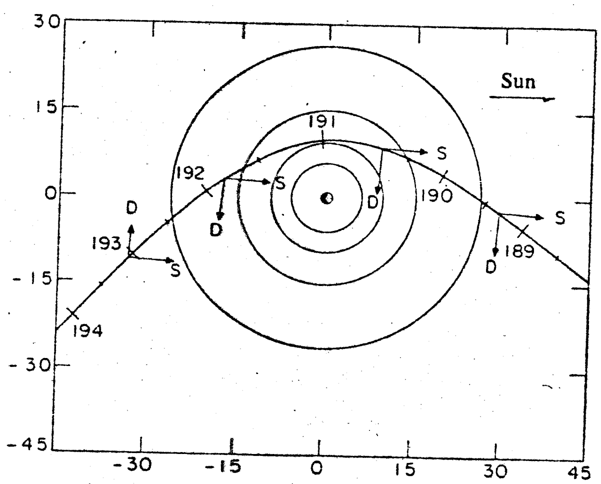

Fig. 1 The Voyager 2 trajectory projected onto the jovian equatorial plane. The line labelled S is the projection of the symmetry axis of the main cluster of Faraday cups, and the line labelled D is the projection of the D cup axis. The A and D cup axes are essentially in the jovian equatorial plane, with the A cup axis ~110° from the D cup axis. The B and C cup axes are inclined ~17° south and north of that plane, respectively, ~75° from the D cup axis. Tic marks along the trajectory are shown every 12 h, with day of year at the beginning of the day (day 190 is 9 July, 1979). The orbits of the four Galilean satellites are also shown. Distances are given in R_J.

Crossings of the magnetic dipole plane are reasonably accurate markers for crossings of the jovian current sheet, especially inside 20R_J. From the Voyager 2 data in Fig. 2, and from similar plots of Voyager 1 data, it is clear that in the dayside jovian magnetosphere near noon, there is a marked tendency for plasma flow to be northward when the spacecraft is north of the magnetic dipole plane, and southward when the spacecraft is south of that plane—thus, the flow is away from the current sheet. This pattern is the same as that observed in Pioneer measurements of the anisotropies of MeV protons in the dayside middle magnetosphere[6,7]. The amplitude of the B–C difference decreases to zero with decreasing radius and increasing local time towards dusk. In the dusk to midnight sector, the B–C

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difference again increases with increasing radius and increasing local time towards midnight. However, in this sector the plasma flow tends to be northward when the spacecraft is south of the magnetic equator, and southward when it is north of the equator—that is, the flow is now towards the current sheet.

The flow pattern can also be seen in a detailed inspection of the positive ion spectra from the various sensors. Figure 3 shows a low-resolution scan of the positive ion flux density near the crossing of the magnetic equatorial plane near $20R_J$ on Voyager 2 inbound (see Fig. 2). The flux density spectrum in the D sensor is an unresolved superposition of H^+, O^{2+}, S^{3+} and S^{2+} (refs 4, 5). At this time, the B and C sensor normals are ~73° and ~67° from the rigid co-rotational flow velocity, with the D sensor normal only ~12° from that velocity. From these spectra, we conclude qualitatively that the flow velocity is mostly azimuthal at this time because the D sensor flux is much higher than fluxes in the main sensor. Moreover, the flow velocity must lie near the equatorial plane because of the near equality of the fluxes in the B and C cups. In contrast, Fig. 4 shows a low resolution scan of the positive ions during a dayside excursion of the spacecraft to $\sim 3.3R_J$ below the magnetic equatorial plane. The B and C sensor fluxes are comparable with those in the D sensor even though the sensor orientation is qualitatively the same as for the spectra in Fig. 3. This implies a significant component of velocity radially towards the planet during this interval. In addition, the C cup flux is larger than the B cup flux, implying a southward

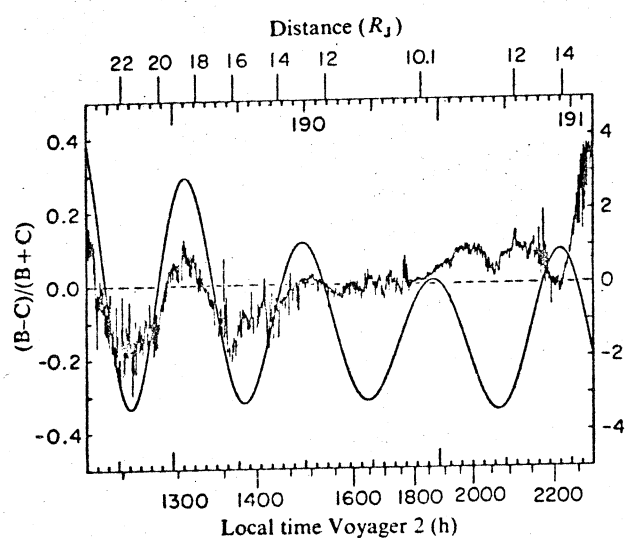

Fig. 2 The difference between the B and C cup fluxes divided by the sum of those fluxes, as a function of time during the Voyager 2 encounter, from 1600 h on 8 July, 1979 (day 189) to 1400 h on 10 July, 1979 (day 191). A positive value for this difference indicates northward flow. Also shown is the distance of the spacecraft above a magnetic dipole plane. Interior tic marks give spacecraft time at one hour intervals, with day of year given at 1200 h. We also indicate values of the local time and the radial distance from Jupiter.

component of flow and thus a flow away from the current sheet. We also note that the main sensor is orientated such that there would be slightly more purely azimuthal flow into the C cup than the B cup on the inbound leg, and vice versa on the outbound leg. Thus even in the absence of any north/south flow, we qualitatively expect to see a negative signature in (B−C)/(B+C) inbound and a positive signature outbound. In fact, the differences in Fig. 2 oscillate about a negative average value inbound and a positive average value outbound, as expected.

This qualitative information on flow patterns is borne out by quantitative analysis of detailed measurements of the positive ion distributions in the various sensors. This analysis is essentially done in stages using an integration code which includes the full sensor responses. For example, we quote results obtained by Voyager 2 near 2009 h on 8 July 1979 (Fig. 4). The spacecraft was near noon, $21.6R_J$ from Jupiter and $-3.3R_J$ below the magnetic dipole plane. An analysis of the proton peak in the B, C and D sensors yields a density of 0.12 cm^{-3} and a thermal speed of 120 km s^{-1}. In a cylindrical coordinate system, where the z-axis is the rotation axis of Jupiter, the radial component of the proton velocity was −167 km s^{-1}, the azimuthal component was 264 km s^{-1} and the z-component was −95 km s^{-1}. These non-azimuthal velocity components should not be taken as typical, since for quantitative analysis, we must at present choose the most pronounced examples of the phenomenon. The azimuthal component here is slightly less than the 270 km s^{-1} velocity expected for rigid co-rotation[3]. In this interval, the plasma was flowing southward (away from the current sheet), in agreement with Fig. 2, and was also flowing radially towards Jupiter, a feature which cannot be deduced from Fig. 2. An analysis of spectra near midnight (at 1300 h on 10 July, 1979) yields similar results, except that the flow is now northward (towards the current sheet) and away from Jupiter.

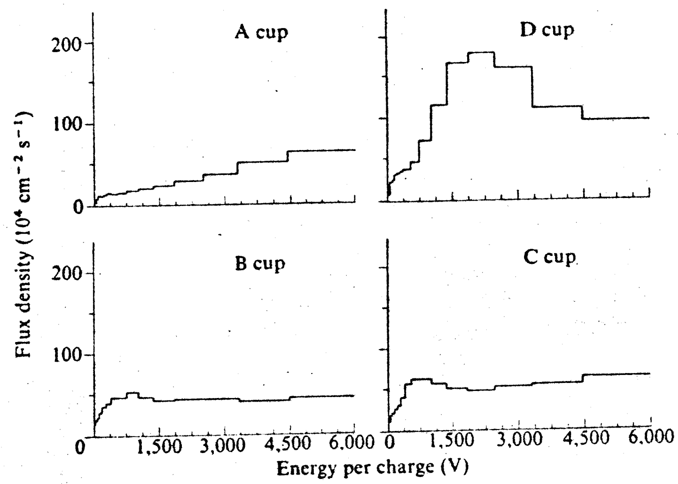

Fig. 3 A low resolution scan of the flux density of positive ions from Voyager 2 inbound 20.0 R_J on day 189 of 1979 at 2250 h 47 min 54 s.

One possible interpretation of these flow patterns is as follows. In a steady state, the distribution of plasma along a given magnetic flux tube is roughly determined by the balance of the pressure gradient of the plasma and the component of centrifugal force along the field. The scale height H for a density distributed in this way is the product of the sound speed C_s, the rotation period of the planet[8] and dimensionless factors of the order of $1/2\pi$. If this static situation is perturbed we still expect a quasi-static density distribution as long as the perturbation time scale is long relative to the dynamic time scale $2\pi H/C_s$. If the perturbation is short relative to this time scale, the plasma cannot adjust in a quasi-static fashion, and plasma motions with velocities up to C_s and beyond can result.

The dynamic time scale for the jovian plasma sheet is thus some fraction of the order of unity of the rotation period of the planet. However, the plasma sheet is perturbed on time scales of this order due to the compression of the dayside magnetosphere by the solar wind. Plasma will tend to move away from the plasma sheet as it moves into the dayside magnetosphere, because of both the compression and the decreasing component of centrifugal force along the field. Because of the rapid time scale, the adjustment of the plasma density distribution along the field line will not be quasi-static, and bulk motion along the field and away from the sheet can ensue. This motion will lead both to a north/south flow and a flow towards the planet on the dayside, as observed. At decreasing radial distances, the

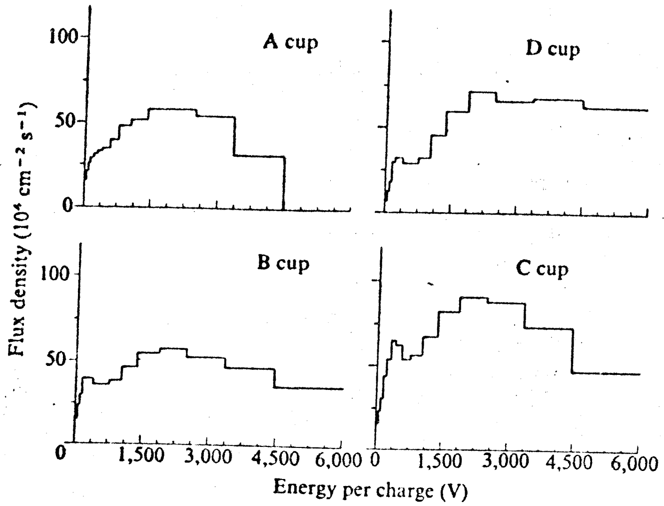

Fig. 4 A low resolution scan of the flux density of positive ions from Voyager 2 inbound 21.6 R_J on day 189 of 1979 at 2009 h 11 min 55 s.

perturbation associated with the solar wind is smaller and leads to a perturbed flow whose amplitude decreases with decreasing radial distance near noon, also in accord with observations (Fig. 2 and ref. 7). Past noon, the magnetic flux tube will begin to expand and move to larger distances. The expansion of the flux tube and the increasing component of centrifugal force will lead to a reversal of the plasma flow near dusk, and cause an infall of material at transonic (or supersonic) velocities in the nightside current sheet.

We note that this picture is very different from what would be expected from a quasi-static expansion and contraction of the plasma sheet due to the solar wind interaction. A quasi-static process would produce a sheet which was thickest at maximum compression (noon), and thinnest at minimum compression (midnight). Any small velocities associated with such a quasi-static process would be zero at noon and midnight, and maximal at dawn and dusk. In contrast, the dynamical velocity pattern described above, especially its phase, arises only in the absence of quasi-static equilibrium. The possibility of such a pattern depends on the fact that the solar wind interaction tends to perturb a given flux tube on the same time scale as it takes the plasma to come to static equilibrium.

These observations and our interpretation of them have two obvious implications for both theory and observation of the jovian magnetosphere. First, irreversible processes such as internal shocks or effective viscosities will lead to a net heating of the plasma as it expands away from and collapses towards the plasma sheet (that is, a fluid analogy of the acceleration mechanism of Goertz[9]). Second, theoretical models of the plasma sheet which assume quasi-static equilibrium, and interpretations of data based on such models, must be re-examined.

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Note added in proof: It has been suggested that the solar wind perturbation is slow enough to allow quasi-static solutions. This reasoning is based on a comparison of the solar wind perturbation time scale to the quasi-static equilibration time scale. Here we attempt to clarify our argument. In a plane parallel atmosphere,

$$\rho\frac{\partial \mathbf{v}}{\partial t} = -\nabla p - \rho g$$

where $\mathbf{v}$ is the plasma velocity, ρ the mass density, p the pressure, and g the gravitational (real centrifugal for Jupiter) acceleration. Taking a time derivative and using mass conservation

$$\rho\frac{\partial^2 \mathbf{v}}{\partial t^2} = +\rho C_S^2\frac{\partial^2 \mathbf{v}}{\partial z^2} + g\rho\frac{\partial \mathbf{v}}{\partial z}$$

where we have assumed that g and $\mathbf{v}$ are in the z direction, and we are only keeping terms of interest for order of magnitude (we have dropped many other terms). Assuming an $\exp(i(kz-\omega t))$ dependence for $\mathbf{v}$, we have

$$\omega^2 = C_S^2k^2 - igk = k(kC_S^2 - ig)$$

The static or quasi-static solution is obtained by setting ω^2 to zero and obtaining $k = +ig/C_S^2$ and thus an $\exp[-z/H]$ falloff, with $H = C_S^2/g$. This solution will be valid as long as $\omega^2 \ll C_S^2k^2$, or $\omega \ll C_SH$. Thus, the angular frequency of any sinusoidal perturbation should be compared to C_SH to determine if the response of the system will be quasi-static.

At Jupiter, C_S/H is the angular rotation rate of the planet ($2\pi/10$ h), to factors of the order of unity ($\sqrt{2/3}$). The angular frequency of the solar wind perturbation is ($2\pi/10$ h). The similarity between these two frequencies is the basis for our contention that the quasi-static situation may not obtain. We have been rather sloppy in this derivation, but the overall conclusion remains even in a more careful consideration.

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1. Bridge, H. S. *et al. Space Sci. Rev.* **21**, 259 (1977).
2. Vasyliunas, V. M. in *Plasma Physics* Vol. 9B (ed. Lovbergs, R. H.) 49 (Academic, London, 1971).
3. McNutt, R. L., Belcher, J. W., Sullivan, J. D., Bagenal, F. & Bridge, H. S. *Nature* **280**, 803 (1979).
4. Bagenal, F., Sullivan, J. D. & Siscoe, G. L. *Geophys. Res. Lett.* **7**, 1 (1980).
5. Belcher, J. W., Goertz, C. K. & Bridge, H. S. *Geophys. Res. Lett.* **7**, 17 (1980).
6. McDonald, F. B., Schardt, A. W. & Trainor, J. H. *J. geophys. Res.* **84**, 2579 (1979).
7. Northrop, T. G., Birmingham, T. J. & Schardt, A. W. *J. geophys. Res.* **83**, 3145 (1978).
8. Hill, T. W. & Michel, F. C., *J. geophys. Res.* **81**, 4561 (1976).
9. Goertz, C. K. *J. geophys. Res.* **83**, 3145 (1978).

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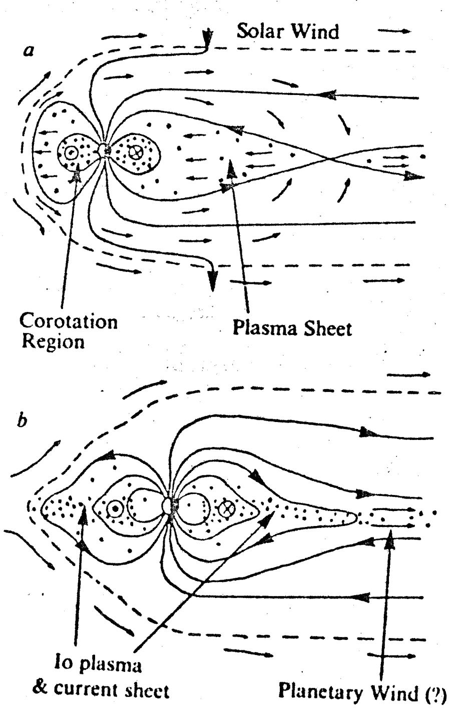
Jupiter's magnetosphere

from S.W.H. Cowley

DIRECT observations by space probes over the past decade have shown that at least three planets in our solar system, in addition to the Earth, possess an intrinsic magnetic field. These are Mercury, Jupiter and Saturn. The solar wind, a tenuous proton-electron plasma blowing radially outwards from the Sun at speeds $\sim$ 400 km s^{-1}, confines this magnetic field to a cavity surrounding the planet forming a planetary magnetosphere from which the solar wind itself is largely excluded. Only Venus is known to be without a magnetic field although limited data suggests that this may also apply to Mars.

Of the four observed magnetospheres, that surrounding the Earth is, of course, the most thoroughly investigated and the best understood. Jupiter comes second, having been the subject of four fly-by encounters, by Pioneer 10 and 11 in 1973 and 1974 and by Voyager 1 and 2 in 1979. The Pioneer flights provided the first mapping of the Jovian magnetic field and the energetic charged particle radiation trapped on Jovian field lines. The Voyagers returned the first detailed data on the thermal plasma component and on plasma waves. Here we shall describe recently published Voyager results on low-energy Jovian plasma, setting them within the context of other major Voyager findings published in *Science* (204, 1979; 206, 1979), *Nature* (280, 1979), and *Geophysical Research Letters* (7, 1980).

The properties of magnetospheric plasmas depend upon the nature of the plasma sources and sinks, and on the internal transport processes. In the Earth's magnetosphere transport is dominated by a large-scale convective flow driven by the solar wind (see Figure *a*). Since highly electrically-conducting plasmas and magnetic fields can be considered to be 'frozen' together we can equivalently describe the flow of field lines. Terrestrial field lines are transported by the solar wind flow from the dayside magnetosphere boundary at $\sim$ 10 R_E (1 R_E = Earth's radius $\sim$ 6,400 km) to the night side, where they are stretched out into a long $\sim$ 1,000 R_E magnetic tail. These flux tubes then flow back to the Earth through the 'centre' of the magnetosphere, heating entrained solar wind plasma and escaped ionospheric plasma up to $\sim$ 10 KeV energies as the tubes contract. A hot 'plasma sheet' is thus formed at the centre of the tail and a hot outer radiation zone around the Earth as shown in the Figure. Near the Earth, however, in a region usually extending to about $\sim$ 4 R_E in the equatorial plane, flows imposed by the Earth's rotation are more important than the solar wind driven convection. Here the flux tubes corotate with the Earth, their 'ends' being 'frozen' into the rotating ionosphere. This region then contains high density cold plasma from the ionosphere, and also, as a very minor constituent, energetic (Van Allen) radiation belt particles. The latter are transported into the region by radial diffusion from the outer radiation zone under the action of fluctuations in the external convection, rapidly gaining energy proportional to the field strength as they move inwards.



Sketch of (a) the terrestrial and (b) Jovian magnetospheres in noon-midnight meridian planes showing plasma flow within them. The Sun is to the left. Solid lines are field lines and the dashed line is the magnetosphere boundary. Flow in the Earth's magnetosphere is dominated by solar wind-driven convection, except near the Earth where corotation prevails and the flux tubes are filled with cold ionospheric plasma (heavy dots). In the Jovian magnetosphere corotation dominates, possibly resulting in a rotationally-driven planetary wind on the nightside. The sketches are not to scale. In linear dimension the Jovian magnetosphere is at least fifty times the size of the Earth's, and five times the size of the sun.

By contrast with the Earth, flow in the main part of the Jovian magnetosphere, extending some 50 R_J (1 R_J = Jupiter radius $\sim$ 71,400 km) on the dayside, is entirely dominated by corotation with the planet (Figure *b*), although this does not preclude the existence of a long (maybe $\sim$ 2 AU) magnetic tail on the night side arising from the solar wind interaction. Thus, like the Earth's corotating 'core' of field lines, the Jovian magnetosphere is dominated by cool plasma from internal sources, but also contains radially diffusing energetic particles of solar wind origin. The radial diffusion is probably driven both by turbulent Jovians atmospheric winds at ionospheric heights and by flux tube interchange motions arising from unstable density distributions of the low energy plasma.

The second important difference between the Earth's and Jupiter's magnetosphere is that the latter is so large that it encompasses the orbits of many of the moons. These bodies can then act both as absorbers of energetic particles, as the Pioneer results demonstrated, and as important sources of low energy plasma. Indeed, the Voyager results indicate that the dominant source of thermal plasma is not Jupiter's ionosphere as might have been expected, but the satellite Io, which orbits at a radial distance of 5.9 R_J, in the inner magnetosphere.

Voyager images show that Io is extremely volcanically active, probably due to intense internal tidal heating, thereby maintaining a tenuous atmosphere which appears to be composed mainly of sulphur dioxide. A small escape flux of this gas (small in relation to total volcanic outflow) followed by ionization then results in the formation of a dense corotating plasma torus in Io's vicinity composed mainly of sulphur and oxygen ions with energies several tens of eV. The torus has a thickness $\sim$ 1 R_J, the ions being retained near the rotation equator by centrifugal forces, and a sharp inner boundary at $\sim$ 5 R_J, where the temperature abruptly drops to a few eV. The latter

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observations indicate that inward radial diffusion of the ions towards Jupiter is rather slow, allowing time for the plasma to radiatively cool, thereby generating the considerable UV and optical emissions observed from the inner torus. The cooling plasma collapses towards rotation equator where the ions and electrons eventually recombine to produce relatively fast neutrals which fly off into the outer magnetosphere and solar wind.

By contrast, the outer part of the torus beyond the Io source appears to be unstable, the density gradient generating flux tube interchange motions which rapidly diffuse the plasma outwards into the magnetosphere. The plasma remains strongly concentrated at the equator, but the density rapidly drops with increasing distance due to the expanding flux tube volume as the field strength weakens. From values of several thousand cm^{-3} in the torus, the equatorial density falls to ~ 1 cm^{-3} at ~ 25 R_J and to $\sim 10^{-2}$ cm^{-3} at 100 R_J on the night side. In order to maintain rigid corotation, the Jovian atmosphere must continuously provide a torque on flux tubes in Io's vicinity where the plasma is created, since the coratation speed increases at a rate ~ 12.5 km s^{-1} R_J^{-1} as the particles diffuse outwards. The torque is provided by atmospheric drag of ionospheric ions at the 'feet' of the flux tubes, but theoretical estimates (Hill *J. Geophys. Res.* 84, 6554; 1979) indicate that the coupling may be too weak to maintain rigid corotation out to large distances. Voyager low energy plasma data indicates that is so, $\sim 20\%$ reductions below expected speeds being inferred at ~ 10 to 20 R_J. Indeed, even at $\sim 40 R_J$ the azimuthal speed is reported as remaining near 200 km s^{-1}, less than half the corotation value. However, analysis of the angular anisotropies of higher energy ions shows good agreement with rigid corotation at such distances and beyond. The reason for this disagreement is currently unknown.

The most recent results on Jovian plasma flow (Belcher & Mc Nutt this issue of *Nature* p813) show that in addition to at least partial corotation, the low energy plasma also has comparably large flows along the field lines, directed toward the equator on the night side and away on the day side. As these authors point out, this flow most probably results from a day-night asymmetry in the magnetic field, which is compressed on the day side relative to the nightside by the dynamic pressure of the solar wind. As flux tubes rotate into the dayside sector they move closer to Jupiter and the plasma flows away from the equator due both to the field compression and to the decreasing centrifugal force. On the nightside the tubes expand and move outwards, the centrifugal force increase and the plasma collapses back toward the equator.

An important feature of a corotation-dominated magentosphere is that if the magnetosphere is large enough, and if corotation is maintained to large enough distances then the plasma kinetic energy density associated with the rotation will always reach and exceed the magnetic energy density at the equator at and beyond a certain distance. At this point the field can no longer retain the plasma, which will break away from corotation and flow rapidly outwards forming a 'planetary wind', a rotationally-driven analogue of the solar wind. Conditions on the dayside Jovian magnetosphere, confined to ~ 50 R_J by the solar wind, seem somewhat marginal for planetary wind formation and no evidence for such an outflow was seen during the Voyager inbound passes near noon. On the nightside conditions are more favourable, and an antisunward flow which may be related to planetary wind formation was observed by Voyager 2 in a layer adjacent to the dawn magnetosphere boundary ~ 130 R_J down-tail from Jupiter, as shown in Figure *b*. One particularly intense burst of such flow was found to consist mainly of heavy ions streaming at $\sim 2{,}000$ s^{-1}.

One final feature of Jupiter's magnetosphere which is receiving much attention is the considerable magnetic field distortions indicated in Figure *b*, due to an equatorial sheet of current carried by magnetospheric plasma in the azimuthal direction. These field distortions are most pronounced on the nightside, where they gradually take on the character of a magnetic tail at sufficiently large distances, but they are also observed on the day side as well. To produce the effects observed beyond ~ 10 R_J the equatorial plasma pressure must be comparable to the field energy density. However, the pressure of the cool (~ 10 to 100 eV) Io torus plasma appears generally to be somewhat too small to account for the observed effects, thus indicating that a significant hot component is also present. Voyager observations at energies above ~ 30 keV show that such a component is indeed present with energies ~ 20–30 keV and an ion composition which includes protons, oxygen and sulphur as major constituents. The heavy ions must originate at Io, but how these particles become heated to such energies remains to be determined. It therefore seems that the Jovian magnetosphere contains at least two thermal plasma components, the cool Io torus plasma which may usually dominate the mass density, and a much hotter plasma also containing Io ions which often dominates the energy density. □

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