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The Jupiter-Io Connection: An Alfvén Engine in Space

JOHN W. BELCHER

Much has been learned about the electromagnetic interaction between Jupiter and its satellite Io from in situ observations. Io, in its motion through the Io plasma torus at Jupiter, continuously generates an Alfvén wing that carries two billion kilowatts of power into the jovian ionosphere. Concurrently, Io is acted upon by a J × B force tending to propel it out of the jovian system. The energy source for these processes is the rotation of Jupiter. This unusual planet-satellite coupling serves as an archetype for the interaction of a large moving conductor with a magnetized plasma, a problem of general space and astrophysical interest.

SPACE PLASMA PHYSICS IS THE STUDY OF PLASMAS IN THE heliosphere, ranging from the solar interior to the boundary between the extended solar atmosphere and the interstellar medium (*1*). Solar system plasmas, which can be probed directly, provide unique insights into general problems in plasma physics, especially those involving the dilute plasmas commonly found in astrophysics. Historically, one of the intriguing puzzles in this field has been the nature of the processes responsible for the radio bursts from Jupiter at decameter wavelengths. In this article, I review spacecraft measurements made in 1979 in the vicinity of Io, which demonstrate quantitatively that these decameter bursts are powered by the rotation of Jupiter through the intermediary of its satellite Io. These measurements illustrate the central role of in situ observations in understanding the complex physical processes occurring in the large-scale plasma systems found in nature.

The jovian decameter radio bursts were first discovered in 1954 (*2*). Subsequently, and surprisingly, the decameter bursts were found to be strongly controlled by the innermost Galilean satellite Io (*3*). Io is located 5.9 jovian radii (R_J) from the center of Jupiter (R_J = 71,400 km), has a diameter D of 3672 km, and has no known intrinsic magnetic field. Io was found to influence the decameter bursts through its magnetic "flux tube." The Io flux tube (IFT) is that bundle of jovian magnetic field lines that instantaneously thread Io, as illustrated to scale in Fig. 1. A significant fraction of the decameter bursts are found to come from the region in the jovian ionosphere at the ends of the IFT, over 300,000 km away from Io, with the radiation emitted in a highly anisotropic fashion along the surface of cones (*4, 5*). A number of theoretical models were advanced to explain this puzzling phenomenon (*6–13*).

The Voyager Science Steering Group decided in the early 1970s to target the Voyager 1 spacecraft for the IFT, some 20,500 km south of Io (Fig. 1). Voyager observations near the IFT have provided a quantitative understanding of the energy source for the decameter bursts and have revealed the exotic nature of the plasma environment in which Io resides. A detailed analysis of the magnetic field observations near the IFT has been available for some time (*14*), but data from the plasma measurements there have only recently been fully reduced because of the difficulty of the analysis (*15, 16*). As I discuss here, the complete plasma and magnetic field data sets near the IFT show remarkable agreement with the Alfvén wing theory first advanced by Drell, Foley, and Ruderman in 1965 (*17*). To understand the IFT measurements, however, we must first discuss the bizarre plasma environment near Io, since this environment determines the nature of the Jupiter-Io electromagnetic interaction.

The Io Plasma Torus

Io is one of the major plasma sources in the jovian magnetosphere. For reasons still not completely understood, but perhaps related to its active volcanism, Io is accompanied in its orbit by extended clouds of neutral gasses (sodium, potassium, sulfur, and oxygen) that have escaped from its surface (*18–20*). These neutral clouds move at approximately Io's orbital velocity of 17 km/sec and are limited in spatial extent because of the finite lifetime (a few tens of hours) of the neutrals before they are collisionally ionized by

The author is professor of physics and a member of the Center for Space Research, Massachusetts Institute of Technology, Cambridge, MA 02139.

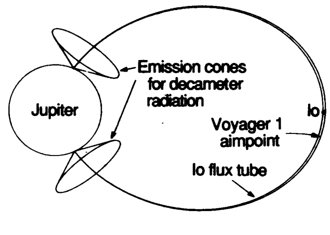


Fig. 1. The Io flux tube and its associated decameter emission cones, to scale.

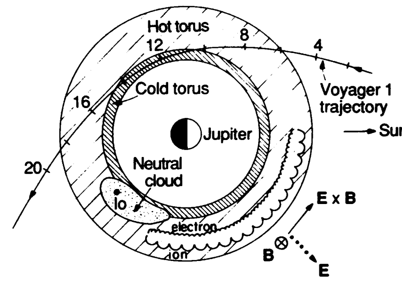


Fig. 2. A schematic of the Io plasma torus, looking down on the plane of Io's orbit. Also shown is the Voyager 1 trajectory projected onto Io's orbital plane, labeled with times in Universal Time (UT) on 5 March 1979. The radii of gyration of the newly created electrons and ions are greatly exaggerated.

magnetospheric electrons. The ionization of these neutral clouds gives rise to a vast plasma torus that co-rotates with Jupiter, as illustrated in Fig. 2. Co-rotation is azimuthal motion about Jupiter with the angular velocity $\mathbf{\Omega}$ of Jupiter, corresponding to the jovian rotation period of 9.93 hours. This overall motion of charge occurs because newly created electrons and positive ions see not only the magnetic field **B** of Jupiter, but also a co-rotational electric field **E** given by $-\mathbf{V} \times \mathbf{B}$, where **V** is the co-rotational velocity $\mathbf{\Omega} \times \mathbf{r}$. This is the motional electric field that must be present in a nonco-rotating frame so that the electric field in the rest frame of the co-rotating plasma is zero. At Io's orbit, this electric field is directed radially outward, with a magnitude of 0.15 V/m. Charged particles in perpendicular magnetic and electric fields drift at a velocity $\mathbf{E} \times \mathbf{B}/B^2$, and in the above electric field this is an azimuthal drift at the co-rotational velocity (see Fig. 2).

At Io's orbit, the co-rotational speed is 74 km/sec, significantly greater than Io's orbital velocity of 17 km/sec, and thus the Io plasma torus is continually overtaking Io at a relative speed of 57 km/sec. In addition to the co-rotational drift, freshly created ions and electrons will gyrate in the co-rotating frame with a speed equal to the speed they had in that frame when they were "born"—that is, 57 km/sec. Each heavy ion picked up in this way acquires a few hundreds of electron volts of gyrational energy in the co-rotating frame, depending on its mass. This gyrational energy is eventually thermalized. Some of this ion thermal energy is transferred to the electrons by collisions, providing a hot-electron population for further ionization and excitation of both ions and neutrals. The excited ions subsequently radiate about 2×10^9 kW in the ultraviolet (*21*), which acts as a significant cooling mechanism for the plasma.

The Io plasma torus was discovered from ground-based optical observations (*22*), and many of its properties can be monitored from Earth and Earth orbit (*20, 23, 24*). In addition, measurements obtained during the Voyager and Pioneer encounters provide snapshots of the torus and of the jovian magnetosphere in which it is embedded (*25, 26*). Figure 3 shows a positive ion energy-per-charge spectrum taken in the cold torus near 5.3 R_J (*27*) by one of the detectors of the Voyager Plasma Science (PLS) experiment (*28*). The different peaks in the spectrum represent different ions, all with a common co-rotational speed into the detector, but appearing at different values of the energy-per-charge because of their different mass-to-charge ratios. From spectra like this, information can be obtained about the velocity of the plasma (*29*), the number densities of the various ionic species, and their temperatures, with similar information available for the electrons (*30, 31*).

An overview of the Voyager 1 ion and electron measurements in the torus is shown in the energy-time color spectrogram of Fig. 4. Figure 2 shows the trajectory of the spacecraft for the time period covered by Fig. 4. Outside about 5.7 R_J (in the hot torus, see Fig. 2), the ion temperature is approximately 100 eV. At these ion temperatures, the various mass-to-charge peaks merge because of their large thermal spreads. The electron temperature in the hot torus is tens of electron volts, typically an order of magnitude less

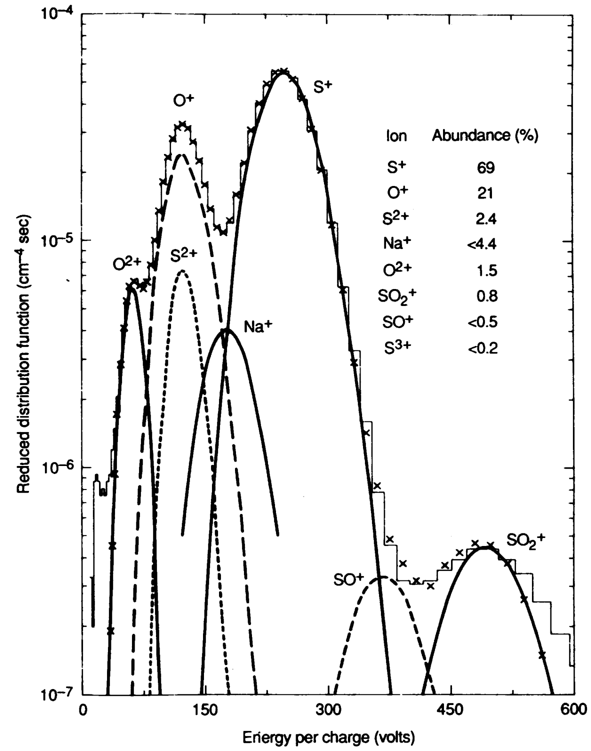
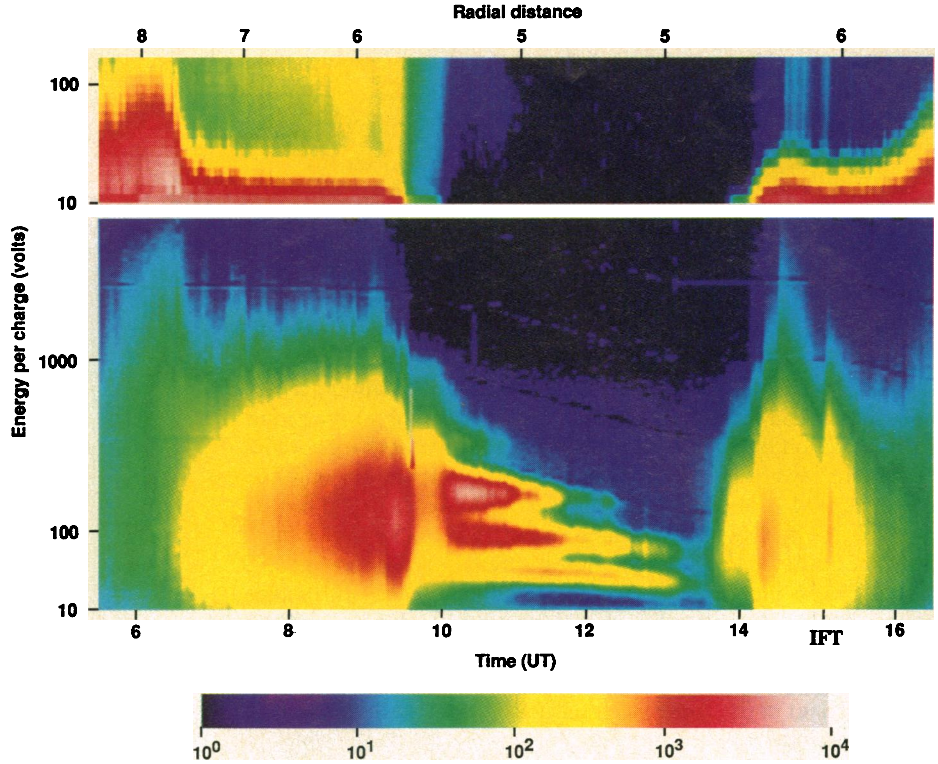


Fig. 3. Reduced positive-ion distribution function versus energy-per-charge as observed in the jovian magnetosphere near 5.3 R_J, at 1016 UT on 5 March 1979. The histogram-like curve is the plot of the data, and the other symbols and curves represent fits of convected Maxwellians to those data. [Adapted from (*27*), with permission from the American Geophysical Union (1981)]

than the ion temperature. The plasma is far from local thermodynamic equilibrium, because the various equilibrium time scales are of the same order as the residence time of the plasma in the system. Inside about 5.7 R_J (in the cold torus), there is a precipitous drop in ion temperature, from 100 eV to less than 1 eV. In this region, the electrons cool to temperatures below the 10-eV threshold of the PLS instrument and are not observed. In Fig. 4, the positive ion data outbound (after 1200 UT) appear different from the inbound data, because the plasma detector, which was looking into co-rotating flow inbound, swings away from that direction on the outbound leg. The closest approach to Io occurred outbound near 1507 UT, and the signature of the IFT is visible near this time in the positive ion data. The broader feature in the electron data near 1507 UT is thought to arise from the cooling of the electrons as they interact with an extended neutral corona surrounding Io (*31*).

The measurements on the inbound trajectory have been used to construct the meridional cross section of the torus shown in Fig. 5. In rarefied space plasmas, plasma can diffuse only slowly across magnetic field lines but is relatively free to move along magnetic field lines. The component of centrifugal force along a magnetic

Fig. 4. A color spectrogram of energy-per-charge versus time for the Voyager PLS measurements in the Io torus. The horizontal axis indicates both time (**bottom**) and distance (**top**) from Jupiter. The relative intensity of particle flux in a given energy-per-charge range is color-coded as indicated in the color bar. The top panel shows the electron measurements in the range from 10 to 140 V, and the bottom panel shows positive ion measurements in the range from 10 to 5960 V. The ion peaks in the cold torus (centered around 1200 UT) are, in order of increasing energy-per-charge, O^{2+}, O^{+} or S^{2+}, S^{+}, and SO_2^{+} (see Fig. 3).



field line will try to push a co-rotating plasma parcel along the magnetic field line to a position as far from the rotation axis as possible. This position defines the centrifugal equator (*32*), which is intermediate between the rotational and magnetic equators (the jovian magnetic dipole equator is tilted about 10° from the rotational equator, as at Earth). However, plasma is held away from the centrifugal equator by its thermal pressure, as in a static atmosphere. The charge density model of the torus in Fig. 5 is constructed with temperatures and densities measured along the inbound trajectory, extrapolated to other latitudes with the assumption of an isothermal static "atmosphere" along magnetic field lines (*27, 33*). The vertical height in Fig. 5 is the distance from the centrifugal equator.

Energetics and Transport in the Torus

The total mass of the torus in the model shown in Fig. 5 is about 3×10^9 kg (*27*). About 10^3 kg of freshly ionized plasma are added to the torus per second (*19*). The power necessary to accelerate this amount of freshly ionized material from orbital to co-rotational velocities is about 4×10^9 kW. This power is obtained by tapping the rotational energy of Jupiter. For each new electron/positive ion pair created by ionization of a neutral near Io, the average position of the ion is displaced slightly outward from the average position of the electron, as is evident in Fig. 2. As a result, near Io's orbit there is a radially outward current density **J** that is proportional to the mass addition rate of newly ionized material. The sense of this current is such as to discharge the co-rotational electric field near Io's orbit, and, if the torus were electrically isolated from Jupiter, the addition of new material would eventually bring the torus to a halt. This does not happen because the addition of electron/positive ion pairs near Io's orbit drives the current system shown in Fig. 6 (dashed lines). The circuit is completed in the dense jovian ionosphere because there ion/neutral collisions are sufficiently frequent to allow return currents to flow across magnetic field lines. The **J** × **B** forces in this current system are such as to spin up the new plasma in the torus at the expense of spinning down the jovian ionosphere, as indicated. The jovian ionosphere is collisionally coupled to the neutral atmosphere, by way of ion-neutral collisions, and this frictional coupling taps the rotational energy of Jupiter and ultimately enforces co-rotation on the Io plasma torus, far from Jupiter (*34*).

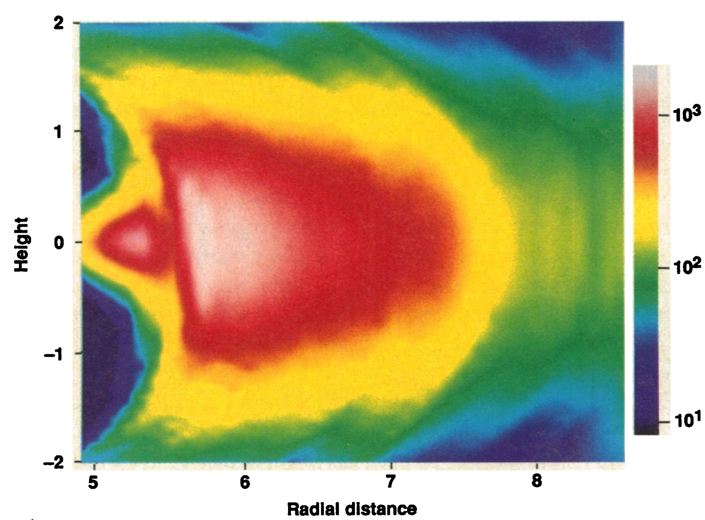


Fig. 5. A two-dimensional cross section in a meridian plane of charge densities in the Io plasma torus, in units of elementary charges per cubic centimeter.

Once plasma is created near the orbit of Io, it is thought to be slowly lost as a result of a relatively gentle diffusive process known as flux tube interchange (*35, 36*). Because there is an effective "gravity" outward due to the centrifugal force associated with co-rotation, a higher plasma density closer to Jupiter is Rayleigh-Taylor unstable, just as is a heavy fluid on top of a light fluid in a gravitational field. The preferred direction of transport is outward, or "downhill" in the effective gravity. The cool inner region of the torus, which is so prominent in Figs. 4 and 5, exists because plasma that diffuses inward from Io toward Jupiter is going uphill in the centrifugal potential and moves inward slowly. It has time to radiate away a substantial amount of its thermal energy, thereby cool, and then collapse toward the centrifugal equator (*37*). Plasma that diffuses outward from Io (downhill in the centrifugal potential) is transported outward so rapidly that it does not have time to cool drastically as a result of radiation.

The Io plasma torus and the jovian magnetosphere in which it is embedded is one of the most complex plasma structures in the solar system, and there are many fascinating and poorly understood aspects of its composition, energetics, transport, time variability, and structure that I have not touched upon (*38*). The next in situ measurements of the torus will occur in 1996 from the orbiting Galileo spacecraft. These extended observations should add immensely to our knowledge of the jovian magnetosphere. Systematic monitoring of the torus prior to that time from ground-based observatories and Earth-orbiting satellites is planned under an International Jupiter Watch program.

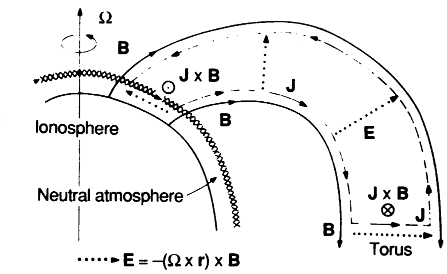


Fig. 6. A schematic in a meridian plane of the current system that links Jupiter and the Io plasma torus (not to scale). The dashed lines represent the currents **J**, the dotted lines represent the co-rotational electric field **E**, as given in the text, and the solid lines labeled **B** represent the planetary magnetic field.

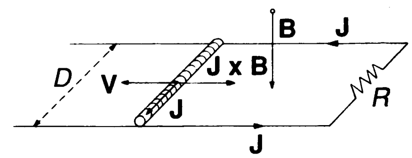


Fig. 7. A schematic of a simple unipolar generator.

The Io Flux Tube

I discuss here only the distant, asymptotic aspects of the Io interaction. The situation nearer Io is more involved, and correspondingly richer in expected physical phenomena. The immediate vicinity of Io will be explored by the Galileo spacecraft, which will pass through the co-rotational wake of Io some 1000 km above its surface (*39*).

Because of its ionosphere (*40*), Io is a conductor immersed in the co-rotating jovian magnetic field and plasma torus, and as such acts as a unipolar generator. I illustrate this basic concept with a sketch in Fig. 7 of a conducting rod moving along frictionless rails, perpendicular to a constant magnetic field **B**. If the width of the rails is D, and the velocity of the conductor is **V**, then the electromotive force (EMF) in this circuit (the time rate of change of the linked magnetic flux) is DVB. The total current in the circuit is then the EMF divided by the total resistance, and the total power available is the EMF times the current. This power comes from the decrease of the kinetic energy of the rod as the $\mathbf{J} \times \mathbf{B}$ force slows the rod relative to the magnetic field. In the case of Io, the value of DVB is just the diameter of Io, 3672 km, multiplied by the co-rotational electric field as seen in Io's rest frame, 0.11 V/m, or 411 kV. The efficiency with which one can tap this EMF depends on whether one can complete the external circuit (and on the associated value of the external resistance), as well as on the value of the internal resistance of Io.

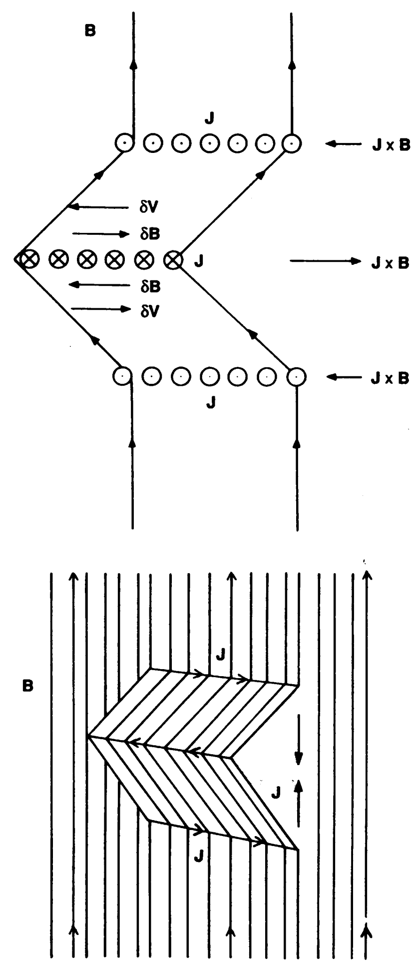


Fig. 8. Illustration of the nature of an Alfvén wave. (**Top**) Side view of propagating kink. (**Bottom**) Oblique view of constrained kink.

At Io, the external circuit is completed by the generation of Alfvén waves. The Alfvén wave is analogous to a transverse wave on a string, with the string being the magnetic field, which provides the restoring force, and with the inertia of the string provided by the plasma frozen to the field. Figure 8 (top diagram) illustrates an Alfvénic kink in the magnetic field propagating along the field, and also shows the current sheets that must be present according to Ampere's law to produce these changes in the direction of **B**. As the kink propagates upward, the $\mathbf{J} \times \mathbf{B}$ impulse in the first current sheet accelerates plasma from rest up to velocity $\delta\mathbf{V}$ to the left, and the next two current sheets, respectively, reverse the direction of $\delta\mathbf{V}$ and bring the plasma back to rest as the wave moves on. Figure 8 (bottom diagram) demonstrates that the spatial extent of an Alfvén wave can be limited to a bundle of field lines, as in the case of the strings on a harp, by adding magnetic field–aligned currents as shown. The group velocity of the wave is along the magnetic field, with the Alfvén velocity **A** equal to $\mathbf{B}/(\mu_0\rho)^{1/2}$ where μ_0 is the permeability of free space and ρ is the mass density.

The co-rotational electric field of Figs. 2 and 6 will drive a current through Io's ionosphere, radially away from Jupiter. If Io were sitting in this co-rotational electric field in a vacuum, it would merely become charged, positive on the face away from Jupiter and negative on the face toward Jupiter, until the electric field in its rest frame was zero, and current would cease to flow. However, Io is not electrically isolated, and current can flow away from Io, most easily along magnetic field lines. In many pre-Voyager models of the IFT, current was thought to flow between Io and Jupiter in a dc circuit similar to the current pattern shown in Fig. 6. The magnitude of the current flow in such models is controlled by a combination of the cross-field resistance in the jovian ionosphere and of the cross-field

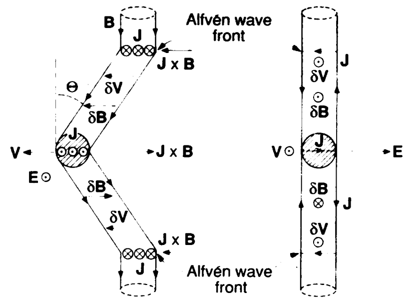


Fig. 9. Two views of the perturbations produced by Io in the rest frame of the co-rotating plasma as Io moves through that frame. (**Left**) Jupiter behind plane of figure. (**Right**) Jupiter to left of figure.

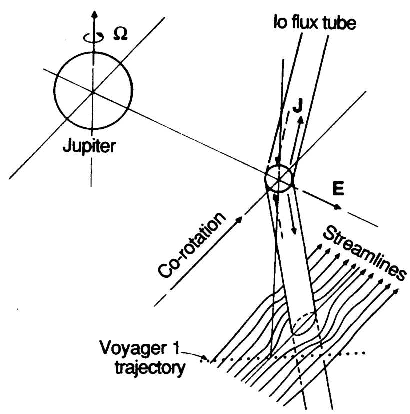


Fig. 10. A perspective of the Alfvén wing generated by Io, with the Voyager 1 trajectory indicated.

resistance in the ionian ionosphere. The amount of time it takes to set up such a dc circuit is determined by the Alfvén speed in the plasma, since the Alfvén wave is the only large-scale plasma wave that can carry field-aligned currents. If the Alfvén wave travel time from Io to the jovian ionosphere and back is much less than the time it takes Io to move onto a new set of co-rotating magnetic field lines (3672 km divided by 57 km/sec, or about 1 minute), then a dc circuit can be set up between Io and Jupiter. Prior to the Voyager encounter, plasma densities near Io were generally thought to be low, and thus the Alfvén speed high, and the round-trip Alfvén wave travel time between Io and Jupiter was estimated to be less than 1 minute (*9*). Thus, before the Voyager encounters, the dc circuit model was thought to be a plausible description of the Jupiter-Io interaction. However, the existence of the massive hot-plasma torus discovered by Voyager (*21, 25*) implies a round-trip travel time much longer than previously estimated. The Voyager-based model of the Io plasma torus in Fig. 5 can be used to calculate the round-trip travel time and it is at a minimum about 6 minutes (*41*). Thus Io has moved on before the Alfvén wave returns, and it is difficult to establish a dc circuit between Io and Jupiter (although it may still be possible in some circumstances, as I discuss below). The nature of the external load in our simple picture of Fig. 7 can instead be related to the rate at which Io can radiate power into Alfvén waves.

Because it is a conductor, Io generates Alfvén waves as it moves through the rest frame of the co-rotating plasma. Figure 9 is a sketch of the perturbations generated by Io's motion through the torus plasma, as seen in the rest frame of the co-rotating plasma and from two perspectives: (i) with Jupiter behind the plane of the figure and (ii) with Jupiter to the left of the figure. For illustrative purposes, I assume that Io instantaneously appeared at some time in the past moving at velocity **V**, and we are observing the effect it has produced at a time T later. Since Io is a good conductor, it tries to drag along the jovian magnetic field lines which threaded it at the time it appeared. This generates Alfvén waves propagating both up and down the field lines at the Alfvén speed A. After a time T, Io will have moved a distance VT and the Alfvén wave fronts will have propagated along the magnetic field a distance AT. Thus the field lines passing through Io will be tilted from the vertical by an angle V/A equal to 57 km/sec divided by a typical Alfvén velocity in the torus of 300 km/sec, or about 10° (Fig. 9, left).

The physical picture is clearest if we consider the currents associated with this system. In Fig. 9 (right), we see the current driven radially away from Jupiter though the ionian ionosphere by the co-rotation electric field. The current then flows out of the face of Io away from Jupiter, along field lines toward the jovian ionosphere, across field lines at the Alfvén wave front, and thence back along field lines into the face of Io toward Jupiter. These currents are just what is needed both to produce the perturbation in **B** and to accelerate the ambient plasma (by **J** × **B** forces) up to motion with Io as the wave front moves along the field. Io is trying to drag the plasma and field along with it, and it does so by generating an Alfvén wave that produces exactly that effect as it propagates away from Io along the magnetic field lines. This dragging of torus plasma is done at the expense of a decrease in the momentum of Io in the co-rotating frame. An order of magnitude estimate of the maximum current I possible in this process can be obtained by equating Io's rate of loss of momentum to the rate of gain of momentum of the ambient plasma. Assuming that this plasma is brought up to Io's full velocity

$$I\,B\,D = 2\,(\rho V)\,(\pi D^2/4)\,A \qquad (1)$$

This equation gives to within factors of order unity a maximum current of $DVB/\mu_0 A$, where $\mu_0 A$ is the Alfvénic radiation impedance, about 0.4 ohm for an Alfvén speed A of 300 km/sec. Thus the maximum current possible is 411 keV/0.4 ohm, or about 10^6A. A more careful derivation gives a value of 3×10^6 A (*42*). In the limit that T goes to infinity, Io will generate an Alfvén "wing" (*17*), as shown in Fig. 10.

Voyager 1 Observations Near the Io Flux Tube

Unfortunately, as indicated in Fig. 10, after traveling almost half a billion kilometers, Voyager 1 passed a few thousand kilometers upstream of the IFT. However, the spacecraft did obtain data that give a good indication of what is happening in the IFT itself (*14, 15*). Ambient plasma co-rotating with Jupiter moving into the vicinity of the IFT must deviate from rigid co-rotation so as to flow around the plasma frozen to the IFT and moving with Io. The theoretically expected flow pattern of ambient plasma around the IFT is that of incompressible flow around a cylinder, and this is the streamline pattern sketched in Fig. 10. Figure 11 shows a view looking down from the north onto the plane of the spacecraft trajectory, giving theoretical streamlines in the rest frame of the IFT and measured velocities from the Voyager PLS experiment (solid arrows) (*15*). Figure 12 shows the two components of plasma velocity (vertical bars) in the plane of Fig. 11, as well as the components of the magnetic field perturbation (dashes) (*14*). The solid line is a fit of the plasma velocities to the theoretical model. The direction of the ambient flow deviates first slightly toward and then strongly away from Jupiter (speeding up as it does so), as the ambient plasma moving with Jupiter flows around the plasma frozen to the IFT (Figs. 11 and 12). The magnetic field perturbations associated with these plasma velocity perturbations are precisely those expected for a southwardly propagating Alfvénic wave pattern [that is, $\delta\mathbf{B}$ equal to $-\delta\mathbf{V}\,(\mu_0\rho)^{1/2}$ as in Fig. 8 (top)], and both are in quantitative agreement with the Alfvén wing theory of Drell, Foley, and Ruderman (*17*). One can estimate from these upstream observations and the Alfvén wing model both the location of the IFT

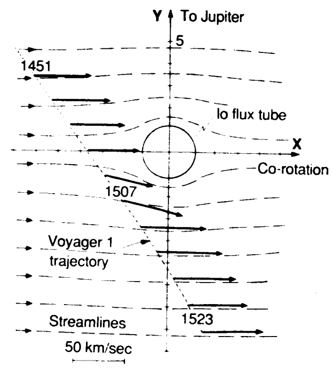


Fig. 11. Theoretically expected streamlines in the rest frame of the IFT, looking down from the north, and plasma velocities (arrows) observed along the Voyager 1 trajectory, with times of the measurements as indicated. Units along the axes are in Ionian radii. [Adapted from (*15*), with permission from the American Geophysical Union (1986)]

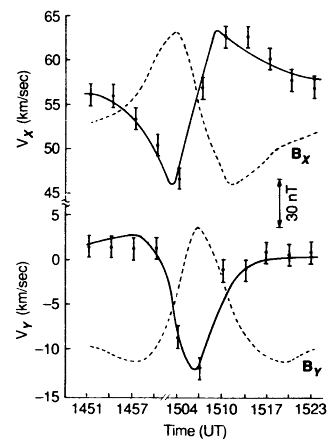


Fig. 12. Components of the plasma velocity (vertical bars) and magnetic field (dashes) in the plane of Fig. 11, with a model fit to the velocities (solid lines). The error bars in the velocity components correspond to an uncertainty of 1.25 km/sec, as discussed in (*15*). [Adapted from (*14*) and (*15*) with permission from the American Geophysical Union (1981 and 1986)]

relative to the spacecraft trajectory and the current flow and total energy flux in the Alfvén wing. As a measure of the internal self-consistency of the model and observations, I note that the local Alfvén speed is determined in three independent ways (from direct measurement, from the geometry of the tilt of the flux tube, and from the constant of proportionality between $\delta \mathbf{V}$ and $\delta \mathbf{B}$), and that all of these determinations agree to within 25% (*15*). The estimated current in the IFT is 3×10^6 A, close to the maximum value expected theoretically. This indicates both that the internal resistance of Io's ionosphere is small compared to the Alfvénic impedance $\mu_0 A$, and that the plasma on the IFT is moving substantially with Io, rather than co-rotating with Jupiter (*14, 43*). The energy flux in the wing is about 2×10^9 kW. This copious amount of energy pouring down along magnetic field lines toward Jupiter drives the decameter emission at the ends of the IFT (Fig. 1), through processes that are complicated and not yet fully understood (*5*).

In fairness to the dc circuit models discussed above, I note that if Io is highly conducting, so that the plasma on the flux tube moves slowly with respect to Io, then an Alfvén wave that is partially reflected from the jovian ionosphere may be able to return to Io before the plasma slips through the tube. In that case, a dc circuit could be set up, with the total current again controlled by the cross-field resistance of the jovian ionosphere, rather than the local Alfvénic impedance (*19*). If, in addition, the resistance of the jovian ionosphere serendipitously matches the local Alfvénic impedance, the resultant flow and field perturbations would match those described above. Thus, these local Voyager observations do not unambiguously rule out the dc circuit models, although the energy flux determined from these observations is correct in either circumstance. However, there is strong evidence from radio observations by Voyager that the Alfvén wings generated by Io and partially reflected from the jovian ionosphere do not return to Io, but rather trail Io, bouncing back and forth between the northern and southern jovian ionosphere on the order of ten or more times (*44*). Thus, the Alfvén wing model is at present the preferred model for the Jupiter-Io interaction.

Summary

Io is interacting electromagnetically with its own progeny to tap the rotational energy of Jupiter, in the circuitous fashion I have described. Given the nature of the plasma environment in which Io resides, the quantitative details of this interaction are in remarkable agreement with theoretical expectations. The energy involved comes from a decrease in the relative velocity between Io and the co-rotating jovian magnetic field. A drag decreasing the velocity between Io and the jovian magnetic field decreases Jupiter's rotational energy but increases Io's orbital energy, and thus ultimately moves Io further away from Jupiter. Thus the Alfvén drag on Io acts as an "Alfvén engine" serving to propel Io out of the jovian system. The energy requirements of this propulsion, as well as of the decameter bursts, are provided by Jupiter's rotation. For the currents quoted above, the $\mathbf{J} \times \mathbf{B}$ force on Io [see Fig. 9 (left)] provides about 5×10^7 N of thrust to Io, roughly the equivalent of a Saturn V launch vehicle. Even over a billion years, this thrust is only enough to move Io some few hundred kilometers outward from Jupiter.

The discovery of exotic radio emissions from Jupiter in 1954, has led some 25 years later to the direct exploration and understanding of the energy source for these emissions. The insights provided by quantitative measurements in complicated systems such as this help us to understand better the physics of other large-scale plasma systems found in nature, the vast majority of which are not accessible to direct investigations.

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The Growth and Composition of the U.S. Labor Force

VERNON M. BRIGGS, JR.

In sharp contrast with the experiences of all other industrialized nations, the size of the labor force of the United States is growing rapidly while, simultaneously, its age, gender, and ethnic composition are changing markedly. Consequently, human resource issues present an unprecedented challenge in the nation's quest to achieve a fully employed and equitable society. New public policies that focus on labor market adjustment policies will be required if these developments are to be a boon rather than a bane to the emerging postindustrial economy.

OF ALL THE EXPLANATIONS FOR ECONOMIC PROGRESS BY industrialized nations during the last half of the 20th century, the most insightful has been the recognition of "human resources as the wealth of nations" (*1*). Countries with limited physical resources, such as Japan and West Germany, have sustained superior economic performances in this new competitive era largely because they have been forced, by lack of alternatives, to focus national economic policy on human resource issues.

One approach to the study of human resources is the quantitative perspective. It examines the effects that population trends and characteristics have on the size and composition of the civilian labor force that is available for employment. Another is the qualitative vantage point. It involves issues pertaining to the actual preparation of the available labor supply for employment. In the contemporary era of rapid technological change and enhanced international competition, all industrialized nations must address qualitative issues. But no other nation in the 1980s is simultaneously confronted with a labor force that is growing as fast and whose composition is changing as rapidly as is that of the United States. Constancy of size and homogeneity of composition are convenient labor force assumptions of standard economic theory. Neither proposition, however, is an operational concept for understanding the current challenges to labor market adjustment and public policy formulation in the United States.

The author is a professor at the New York State School of Industrial and Labor Relations at Cornell University, Ithaca, NY 14851.

The Relation of Population to Labor Force Changes

A nation acquires its population in two ways: people are native born within its boundaries or foreign-born people immigrate for permanent or temporary settlement. Alterations in the size and characteristics of the population, in turn, are transmitted to the economy through labor force participation.

Analysis of the size of the native-born population that may be available for employment over time is a relatively straightforward process. The available statistics pertaining to their potential number and their characteristics are reasonably predictable. Accounting for the foreign-born portion of the population, however, has proved to be a more difficult task. Official figures on the foreign born are only available every 10 years as a product of the decennial census, but immigration to the United States is a continuous daily process.

Immigration accounted for at least one-third of the annual growth rate of the U.S. population (and probably a higher percentage of the labor force) in the 1980s. It is anticipated that the percentage will increase in the 1990s. Despite the complex and highly legalistic nature of the nation's immigration and refugee admission systems, substantial illegal immigration has circumvented these formal procedures. Measuring the size and flow of illegal immigrants has been a frustrating process (*2*). Obviously, there are no official data series. Only administrative data on actual apprehensions by the U.S. Immigration and Naturalization Service are available. These numbers have soared to record heights in the mid-1980s—totaling more than 1.2 million apprehensions in 1986. But apprehension statistics include multiple countings of the same people so they cannot be used to measure the actual number of individuals involved. On the other hand, it is commonly acknowledged that the vast majority of illegal immigrants are never apprehended—especially those who overstay their visas and who mostly come from nations other than Mexico. Yet even most Mexicans, who usually cross the border without a visa and who are believed to account for about one-half of the annual flow of illegal immigrants, eventually get into the United States through sheer repetition of entry efforts.

Immigration flows are also less predictable because immigration policy in the United States is set on purely political criteria. The economic implications of various administrative decisions, judicial

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