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Plasma Observations of the Alfvén Wave Generated by Io

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Measurements of positive ions near the Io flux tube are consistent with the detection of velocity perturbations in the magnetospheric flow due to the southward propagating Alfvén wave generated by Io.

INTRODUCTION

The interaction of Io with the magnetosphere of Jupiter has been, and continues to be, a subject of intense interest in space plasma physics. In most descriptions of the Io interaction, the motion of Io through the corotating magnetosphere results in the generation of an Alfvén wave propagating away from Io into the magnetospheric plasma (see *Neubauer* [1980] or *Goertz* [1980] and references therein). Voyager 1 measurements of the magnetic field perturbation near the Io flux tube have been interpreted as being due to the presence of a large-amplitude Alfvén wave propagating southward along the magnetic field lines from Io [*Ness et al.*, 1979; *Neubauer*, 1980; *Acuña et al.*, this issue]. The velocity perturbation $\delta\mathbf{V}$ associated with this Alfvén wave is related to the field perturbation $\delta\mathbf{B}$ by the usual Alfvénic relation, that is,

$$\delta\mathbf{V}/V_A = -\delta\mathbf{B}/B \quad (1)$$

where V_A is the Alfvén velocity, B the magnetic field magnitude, and the minus sign is appropriate for propagation in the direction of $\mathbf{B}$. We describe below the positive ion measurements obtained near Io by the plasma instrument on board Voyager 1 [*Bridge et al.*, 1977]. These measurements are consistent with the flow field predicted by (1) and lend further support to the Alfvén wave interpretation of the Io-associated perturbations.

THE PLASMA SCIENCE INSTRUMENT

The Voyager 1 Plasma Science instrument consists of a set of four modulated grid Faraday cups. Each cup makes positive ion measurements in the energy per charge range from 10 to 5950 V. There are two energy per charge resolution modes available: (1) the low-resolution L mode, with 16 steps in the above range and a resolution of $\simeq$29%, and (2) the high-resolution M mode, with 128 steps and a resolution of $\simeq$3.6%. The 16 steps of the L mode are measured in 3.84 s, with 96 s between successive measurements. During the encounter, the 128 steps of the M mode are measured in 30.72 s, with 96 s between successive measurements. However, for any given 96-s measurement sequence, only data from 72 of the 128 steps are transmitted. Steps 1 through 72 (10–750 V) are transmitted for every other 96-s sequence, and steps 57 through 128 (400–5950 V) in the alternate 96-s sequence. Thus it takes two sequence times, or 192 s, to obtain a full M mode spectrum.

Three of the four Faraday cups (the A, B, and C cups) are mounted in a cluster whose symmetry axis usually points toward the earth. The fourth (the D cup) has a look direction which is perpendicular to the symmetry axis of the main cluster and is oriented so as to look into corotating flow on the inbound leg of the Voyager trajectories. In the following we shall use the terms cup axis, cup normal, and cup look direction interchangeably. Corotating flow is primarily into the D sensor over most of the inbound leg, shifting into the field of view of the main cluster near 10 R_J inbound through closest approach and out of the field of view of all sensors on the outbound leg. This behavior is shown quantitatively in Figure 1 of *McNutt et al.* [this issue], which gives the response of the various sensors to a cold corotating beam as a function of time along the Voyager 1 trajectory.

Unfortunately, the Io encounter occurred on the outbound leg of the trajectory at a time when corotating flow (properly aberrated for spacecraft velocity) is highly oblique to all sensor normals. Figure 1 illustrates this situation. We show the orientation of the various cup normals at the closest approach to Io (March 5, 1979, 1513 UT), as projected onto the Jovian equatorial plane. The normals to the A and D sensors are essentially in this plane, whereas the C and B sensors are inclined northward and southward, respectively, at angles of approximately ±17°. At this time, a cold rotating beam would enter the A, B, C, and D cups at angles of 67°, 97°, 100°, and 171° to the cup axes, respectively (0° is directly into the cup). Thus the A cup axis is least oblique to the corotational flow of the torus plasma, the B and C cup axes are essentially perpendicular to such flow, and the D cup axis is antiparallel to the flow.

LIMITATIONS OF THE POSITIVE ION DATA ANALYSIS

Since the data to be presented below are obtained at high angles of incidence to the flow, we discuss briefly some of the present limitations in our interpretation of the measured currents. For illustration, consider the total current I measured by a given sensor. Let $f(\mathbf{v})$ be the distribution function of a given ionic species with charge number Z^*, $G(\mathbf{v}, \hat{n})$ the response function of a sensor whose axis lies along the unit vector $\hat{n}$ (normalized to unity at normal incidence), and A_{eff} the effective area at normal incidence. Then the total current I measured by the instrument for this species, summed over all energy per charge channels, is given by

$$I = Z^* e A_{\text{eff}} \iiint_{-\infty}^{\infty} \mathbf{v} \cdot \hat{n} f(\mathbf{v}) G(\mathbf{v}, \hat{n}) \, d^3v \quad (2)$$

There is a similar expression for the current measured in an individual channel [*Vasyliunas*, 1971; see also *Belcher et al.*, 1980]. For multiple species we have a sum of terms such as given in (2).

The response functions of the Voyager Faraday cups, especially the main sensors, are broad, with ~30% acceptance at an angle of incidence of ~60° to the cup axis for the main sen-

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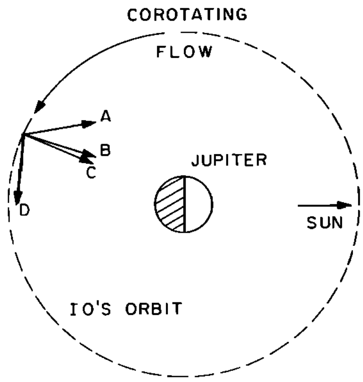

Fig. 1. The orientation of the A, B, C, and D cup normals at closest approach to Io, as projected onto the Jovian equatorial plane.

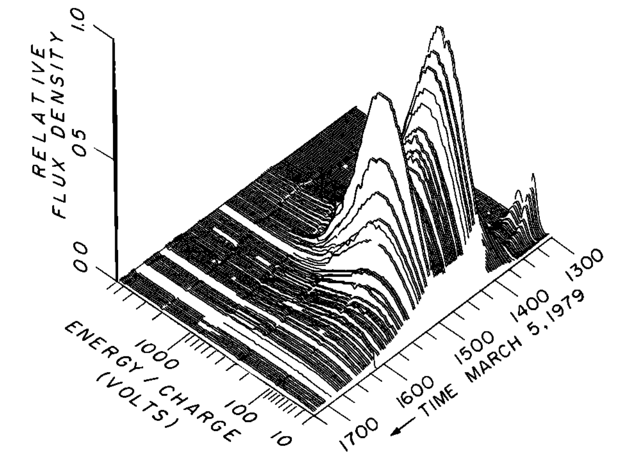

Fig. 3. Flux density spectra versus energy per charge as measured by the A cup between March 5 at 1300 UT and March 5 at 1715 UT. The quantity plotted in Figure 2 is the area under the flux density spectral curves shown here.

sors and at an angle of ~40° to the cup axis for the D cups. This is only a crude characterization—for example, the main cluster cups have very asymmetric response functions. In any case, for such broad response functions, if the flow is reasonably supersonic and reasonably close to normal incidence for a given sensor, one can sensibly assume that the response function $G(\mathbf{v}, \hat{n})$ is unity over that region of velocity space in which $f(\mathbf{v})$ is nonzero. In such a situation, there is a simple analytic relation between the measured currents and the plasma parameters describing the distribution functions, e.g., composition, density, and temperature, and (in the case of a single sensor) that component of velocity along the sensor look direction $\hat{n}$. With such an analytic relation, least squares determination of the plasma parameters from the measured currents is straightforward, and the Plasma Science team has carried out extensive studies of measurements obtained on the inbound trajectories, when such analysis is possible [*McNutt et al.*, 1979; *Bagenal et al.*, 1980; *Bagenal and Sullivan,* this issue; *McNutt et al.*, this issue].

In the less favorable case (e.g., on the outbound legs, where the flows are highly oblique) the positive ion analysis is much more complicated because the full response must be used. To help interpret data obtained in such circumstances, V. M. Vasyliunas and two of the authors (J.D.S. and J.W.B.) have developed a numerical model for $G(\mathbf{v}, \hat{n})$ based on theoretical modeling of particle trajectories in the sensor, coupled with a 'simulation' program which carries out integrations similar to those illustrated in (2). With this program, given the Maxwellian parameters describing a multispecies plasma, we can compute the currents such a plasma would produce in any given sensor. However, because of the inefficiency of our method for computing the response and because of the complexity of the Jovian magnetospheric plasma we cannot reverse this process. That is, we cannot go from the measured currents to the parameters of a least squares fit of model distribution functions. Although, in principle, this can be done, it is a complicated and involved task, and we are not at present in a position to analyze quantitatively the positive ion measurements near the Io flux tube. However, using the simulation program, we can draw some qualitative conclusions from those measurements which are plausible and of substantial physical interest.

OBSERVATIONS

Figure 2 shows the general morphology of the positive ion flux density measured in the A cup between 5.0 R_J and 7.2 R_J outbound, using *M* mode measurements. The quantity plotted is the total measured current in the energy per charge range from 10 to 5950 V, divided by the proton charge and the effective area of the sensor for normal incidence. The A cup measurements on the outbound pass show the same general morphology as those on the inbound pass through the torus [*Bridge et al.*, 1979; *Bagenal et al.*, 1980; *Bagenal and Sullivan,* this issue]—a cold, low-density region inside of ~5.5 R_J, with increasing density and temperature as we move outward through the torus proper and a subsequent decrease in density beyond ~6.0 R_J. All of these features are, of course, distorted by the decreasing response of the A sensor throughout this time period. To give a qualitative feel for this distortion, we also plot in Figure 2 the A cup response to a cold corotating beam. The cup response is essentially that fraction of an incident cold beam which would be measured at the collector (cf. equation (2)). This is, of course, different from the fraction of an incident warm beam which would be measured at the collector, since a thermal spread produces a spread in arrival directions.

Figure 3 shows the energy per charge spectra from which Figure 2 is derived. The two cold peaks near 1300 UT are due to ionic species with mass to charge ratios of 8 and 16 (O^{2+}

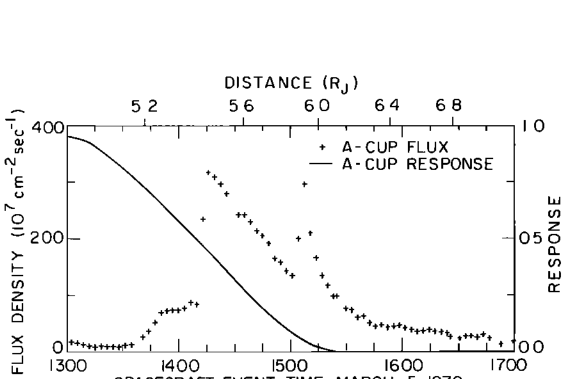

Fig. 2. Positive ion flux densities as measured by the A cup between 5.0 R_J and 7.2 R_J outbound on Voyager 1. Also shown is the response of the A cup to a cold, rigidly corotating beam (properly aberrated for spacecraft motion).

and O^+ or S^{2+}). This identification can be made because the ions are cold and are arriving from the expected corotation direction at a reasonably small angle to the cup normal. Thus the response is near unity, and the velocity component into the cup is known and is large enough to produce a good separation in energy per charge for the various mass to charge ratios. Later on, the corotating flow is much more oblique to the A cup axis, varying from 45° to 1300 UT to 90° at 1700 UT. The cup response is thus smaller, as is the velocity component into the cup, and therefore the species separation in energy per charge is poor even for low temperatures. In addition, the plasma is warmer, which also reduces the mass per charge resolution. As we discussed above, these and other effects make the analysis of the *M* mode spectra after 1330 UT (e.g., for composition, density, and temperature) a complex task and more difficult than the analysis on the inbound leg of the trajectory. However, qualitatively, the measured spectra agree with our expectations based on the inbound analysis; i.e., the outbound spectra are consistent with an unresolved mixture of ionic species with mass to charge ratios of 8, 10-2/3, 16, and 32, with sonic Mach numbers of order 3 (see also Figure 6 and the discussion below).

The feature of most interest in these two figures is the increase in flux density near 1507 UT. This increase in the A cup occurs at the same time as the magnetic field perturbations reported by *Ness et al.* [1979] and is accompanied by similar increases in the B and C cup fluxes. Figure 4 shows the B cup increase on a finer time scale using *L* mode data. The C cup fluxes are similar, and the D cup fluxes are much smaller, by a factor of ~15. We also plot the component of the magnetic field radially away from Jupiter [*Acuña et al.*, this issue] to illustrate the close correspondence between the time profiles of the magnetic field and the plasma features. The *L* mode is most useful for this time profile comparison because of its 96-s time resolution. Unfortunately, the fluxes measured in the *L* mode in the A cup, which should exhibit much higher fluxes than the B or the C cup (compare Figures 2 and 4), are so high that they saturate in the first few channels. The *M* mode measurements, made in a lower gain state, never saturate but are taken at the lower (192 s) time resolution. Nonetheless, they show the same basic time structure and good correspondence with the field variations as do the *L* mode measurements (see also Figure 6 below).

The peak flux in the A cup is ~4 times that of the B and C cups and almost 60 times that of the D cup. We note that the difference between the A cup fluxes and the B, C, and D cup fluxes immediately implies a reasonably supersonic flow moving roughly in the direction of corotation. The flow cannot be too supersonic, however; otherwise we would see no signals in the B and C cups (their response to a cold corotating beam is zero throughout this period). A sonic Mach number of around 3–4 is consistent with the data.

INTERPRETATION

The flux increases discussed above could be due either to an increase in the ambient density or temperature or to a change in the flow velocity of the plasma. The latter alternative is a plausible one, for the following reasons. Equation (1) predicts a change in flow velocity if the magnetic field perturbation is due to an Alfvén wave. At its maximum the observed magnetic field perturbation is essentially radially toward Jupiter [*Acuña et al.*, this issue]. Therefore the predicted velocity perturbation at maximum should be radially away from Jupiter.

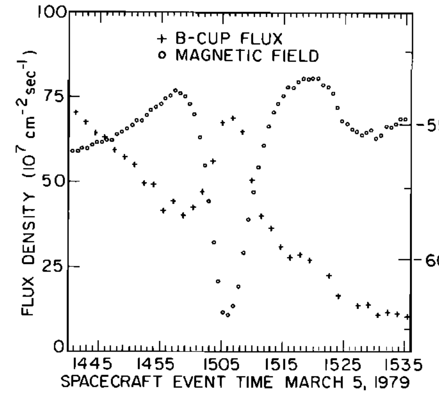

Fig. 4. The B cup flux density as a function of time near the Io flux tube and the component of the magnetic field radially away from Jupiter.

In the context of Figure 1 it is clear that such a velocity perturbation will bring the magnetospheric flow more directly into all of the sensors in the main cluster. Thus we expect to see an increase in the measured fluxes at the maximum field perturbation, if the perturbation is Alfvénic.

To be more quantitative, we take the values of $\delta\mathbf{B}/B$ reported by *Acuña et al.* [this issue] and calculate $\delta\mathbf{V}$ using (1) and an assumed Alfvén velocity. This perturbation velocity is then added to the corotational velocity to obtain the full velocity vector. After compensating for the spacecraft velocity we calculate the response of the A cup assuming a cold beam. This quantity is shown in Figure 5 as a function of time for four different Alfvén velocities (0, 100, 200, and 300 km/s). The angle of incidence of the flow into the A cup is such that even a small change in the angle between the velocity and the cup axis produces a large change in response. Thus although the velocity perturbation for an Alfvén velocity of 200 km/s only produces a maximum deviation of 5.7° from corotational flow (7.5° in the aberrated flow), we easily see measurable effects associated with this perturbation. The similarity in time profiles between Figures 4 and 5 suggests that the observed flux density increases could be entirely due to a change in the

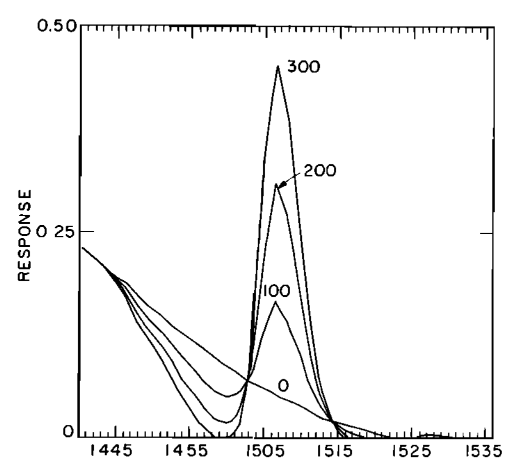

Fig. 5. The response of the A cup for cold magnetospheric flow perturbed in accord with (1), for four values of the Alfvén velocity (0, 100, 200, and 300 km/s, as indicated).

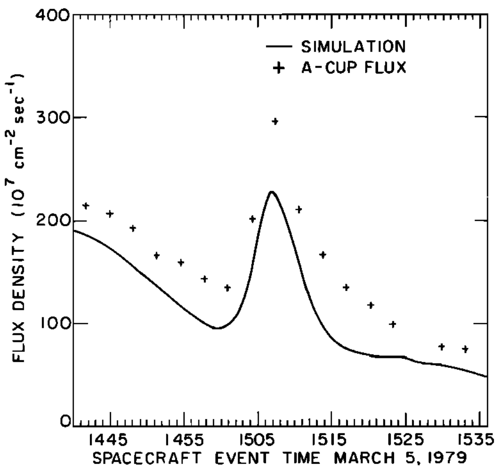

Fig. 6. Theoretical simulation of the A cup flux densities using the plasma parameters measured at the Io *L* shell inbound, the observed magnetic field perturbation at Io [*Acuña et al.*, this issue], and the Alfvén wave theory of *Neubauer* [1980]. The actual observations of the A cup flux densities near Io are shown by the crosses.

plasma flow velocity, with no change in ambient densities or temperature.

To investigate the plausibility of this hypothesis, we use the simulation program discussed above with a warm plasma similar to that observed inbound at the Io *L* shell, when corotating flow is almost directly into the C sensor. A least squares analysis of these inbound data yields an S^+ density of 468 cm^{-3}, an S^{2+} density of 556 cm^{-3}, an S^{3+} density of 174 cm^{-3}, and a thermal speed of 14.9 km/s, if all the ions are assumed to have the same thermal speed (F. Bagenal, private communication, 1980). With a field strength of 1870 γ (characteristic of the magnetic field near 1507 UT) and this total mass density of 3.83×10^4 amu/cm^3, we derive an Alfvén velocity of 208 km/s. We insert these parameters into the simulation program, hold the densities and temperatures fixed, and vary the velocity in the manner prescribed above for an Alfvén velocity of 208 km/s. The results of the simulation for the A cup fluxes are shown by the solid line in Figure 6. For comparison we show also the measured A cup fluxes for this interval. The agreement, although quantitatively lacking, is qualitatively good. The same is true if we compare the detailed spectra from the simulation with the measured spectra shown in Figure 3. Qualitatively, the agreement is reasonable, and in particular, both observation and simulation show a shift in peak current to a higher energy per charge at 1507 UT, consistent with an increased component of velocity into the A cup. In the B and C cups the agreement is not as striking, although again the time profiles are qualitatively the same. Of course, we do not expect exact agreement, because we do not expect the plasma at the Io *L* shell outbound to have the same density, composition, and temperature as inbound (in particular, the spacecraft is at different distances from the centrifugal equator, and we have not included scale height effects).

CONCLUSIONS

We have examined the changes in positive ion flux observed by the Voyager 1 Plasma Science instrument near the Io flux tube. Although we cannot yet analyze these observations for quantitative plasma parameters, it is plausible that the observed changes are due solely to Alfvénic perturbations in the velocity of the magnetospheric plasma, with no change in ambient densities or temperatures. We base this conclusion on a theoretical simulation using (1) the plasma densities and temperatures derived from the inbound observations at the Io *L* shell, (2) the magnetic field perturbations observed outbound near Io by *Acuña et al.* [this issue], and (3) the velocity perturbations derived theoretically from these magnetic field perturbations, using the standard Alfvén wave relations [e.g., *Neubauer,* 1980]. This simulation produces results which are qualitatively in agreement with the observations. In particular, we note that the observed flux increase is consistent only with a southward propagating Alfvén wave; a northward propagating wave would have produced a flux decrease, all other things being equal (cf. equation (1) and the geometrical arguments above). Thus the combined plasma and magnetic field observations imply southward propagation, as expected.

It is, of course, obvious that with our present analysis we can only argue for the qualitative consistency of the data with the Alfvén wave interpretation. This interpretation is not necessarily unique. In particular, there is considerable structure in the ambient densities and temperatures in the Io torus inbound [*Bagenal and Sullivan,* this issue], and there is no a priori way to rule out the possibility that some combination of density, temperature, and velocity changes produces the observed flux density changes rather than a change in velocity alone. What is needed is a sophisticated analysis of the Io data using the full response of the sensors; this will, in principle, provide quantitative estimates of plasma parameters and allow an explicit investigation of the flow field near the Io flux tube. In the absence of such a definitive analysis we can only argue that the present interpretation is a consistent and persuasive one, especially in light of theoretical expectations.

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