indicates that they have significantly larger gyroradii resulting from lower ionization states.

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6. The *L* value for a drift shell in a centered dipole magnetic field corresponds to the equatorial distance (in planetary radii) of the shell from the center of the planet. The values used here were calculated by C. Paranicas and A. F. Cheng as described in *J. Geophys. Res.* **99**, 19433 (1994).
7. The magnetic moment, $M = E_{\perp}/B$ where $E_{\perp}$ is the energy associated with motion perpendicular to the magnetic field and B is the magnetic field strength. M is conserved under radial diffusion.
8. See, for example, T. L. Garrard and E. C. Stone, *Proc. 23rd Intl. Cosmic Ray Conf.* **3**, 384 (1993).
9. This work was supported in part by NASA under NAS7-918.

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Plasma Observations at Io with the Galileo Spacecraft

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Plasma measurements made during the flyby of Io on 7 December 1995 with the Galileo spacecraft plasma analyzers reveal that the spacecraft unexpectedly passed directly through the ionosphere of Io. The ionosphere is identified by a dense plasma that is at rest with respect to Io. This plasma is cool relative to those encountered outside the ionosphere. The composition of the ionospheric plasmas includes O^{++}, O^{+} and S^{++}, S^{+}, and SO_2^{+} ions. The plasma conditions at Io appear to account for the decrease in the magnetic field, without the need to assume that Io has a magnetized interior.

Theoretical models of the interactions of Jupiter's moon, Io, with the co-rotating magnetic field and plasma of Jupiter's magnetosphere (*1*) tried to explain magnetically field-aligned currents as resulting from a conducting Io interior and possibly from an extended ionosphere of Io and the closure of these currents in the jovian ionosphere. Earth-based observations of Io-controlled radio emissions (*2*) and the detection of a neutral Na cloud (*3*) and a torus of ionized S (*4*) provided impetus for the theoretical studies. Further considerations of the interaction of Io with Jupiter's magnetosphere found that the currents should not propagate parallel to the jovian magnetic field in the Io rest frame but at an angle determined by the local Alfvén speed (*5*). This geometry is commonly referred to as "Alfvén wings." Direct measurements of the perturbations of the jovian magnetic field in the vicinity of Io (*6*) were made by the Voyager 1 spacecraft at about 11 Io radii (R_{Io}) below Io. The magnetic perturbations were interpreted in terms of field-aligned currents in excess of 10^6 A. The discovery of active volcanic plumes (*7*) provided direct evidence that the gas and ion environment near the surface of Io is dynamic. The Galileo spacecraft has now provided additional in situ observations at Io, at a closest approach altitude of about 0.5 R_{Io} (900 km).

The Galileo Plasma Analyzer (PLS) was designed to determine the plasma densities, ion composition, and flow velocities of the jovian plasmas (*8*) as the Galileo spacecraft flew past Io. The plasma is flowing in the co-rotational direction with a speed of about 45 km s^{-1} beyond 4 R_{Io}, which is slower than the 57 km s^{-1} speed expected for rigid co-rotational motion of the jovian plasma. The largest uncertainties in this initial evaluation of flow speed, -5 to $+15$ km s^{-1}, are due to the uncertainties associated with the determination of ion composition. Further analysis will be required to determine whether the slower observed speed is due to mass loading or to inaccuracies in the initial assessment of the ion composition. At altitudes of about 1 R_{Io}, the flow velocities (Fig. 1) exhibit the signature of a classical wake for which the plasma is flowing into a void. The increased speed is due to the interaction of the jovian plasma with the neutral particles of Io's atmosphere—that is, the exchange of charges between the plasma ions and the neutrals and the acceleration of these newly born ions by the convection electric fields.

The detection of a plasma at rest relative to Io during closest approach at 17:45:46 UT was not expected. The upper limit for the flows at this time (Fig. 1) is <1 km s^{-1}. At closest approach, the ion densities increase to 18,000 ($\pm$4000) cm^{-3} and the ion temperatures decrease to about 1.3×10^5 K. For comparison, the densities and temperatures of the undisturbed torus flows at 17:35 UT are 3600 ($\pm$400) cm^{-3} and 1.2×10^6 K, respectively. The ion temperatures adjacent to the ionospheric encounter are higher than those of the torus, about 3×10^6 to 5×10^6 K, due to the charge-exchange mechanism. During the periods 17:42 to 17:44 UT and 17:48 to 17:50 UT, the spacecraft is located in the dayside and nightside wakes, respectively. The ion temperatures and energy densities are lower in the nightside wake, but they indicate that there is not a large local-time dependence for the neutral atmosphere densities as a function of altitude.

The PLS was programmed to determine the composition of plasma that was flowing in the direction of a classical wake (*8*). In the cool ionospheric plasma, at rest with respect to Io, the spacecraft ram speed was high enough to give the ions a different direction of arrival at the PLS. Nevertheless, we were able to determine the composition of the heavier ions (Table 1). Some mechanism must be responsible for the containment of the ions in the ionosphere. Otherwise the convection electric fields can be expected to sweep these ions downstream. Indeed, the thermal velocities of the cool ions are still sufficiently high, about 10 km s^{-1} relative to their escape speed from the surface of Io

Table 1. Estimates of plasma composition near closest approach to Io at 17:46 UT on 7 December 1995. The E/Q is 40 to 66 volts, and the percentage is given for the number densities. Mass is given in atomic mass units.

Mass/unit charge	Ions	Percent
8	O^{++}	15 ($\pm$5)
16	O^{+}, S^{++}	50 ($\pm$10)
32	S^{+}	30 ($\pm$5)
64	SO_2^{+}	5 ($\pm$2)

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of 2.6 km s^{-1}, that the ionosphere is not gravitationally bound. The bulk flows closing on the wake axis (Fig. 1) may provide some inertial forces for containing the ionosphere but are unlikely to force the ions to remain at rest relative to Io. The primary candidate for containment is the neutral atmosphere of Io. The ions will be contained if they experience at least one collision with a neutral atom or molecule during a gyroperiod in the local magnetic field. The corresponding minimum neutral densities are about 10^9 cm^{-3} (9). This density is higher than the upper limits derived from remote observations of about 10^7 cm^{-3} (*10*). However, the present in situ measurements indicate greater volcanic activity for Io, on the basis of significantly larger torus densities relative to those seen during the Voyager flyby of Jupiter. The Galileo spacecraft may have fortuitously detected a transiently thickened Io atmosphere.

The perturbations of the jovian magnetic fields in the vicinity of Io, as observed by Galileo, have been interpreted, in the absence of the present plasma data, as evidence that Io has a magnetized interior (*11*). Voyager plasma measurements and the assumption that Io has a thin ionosphere were used for the plasma conditions.

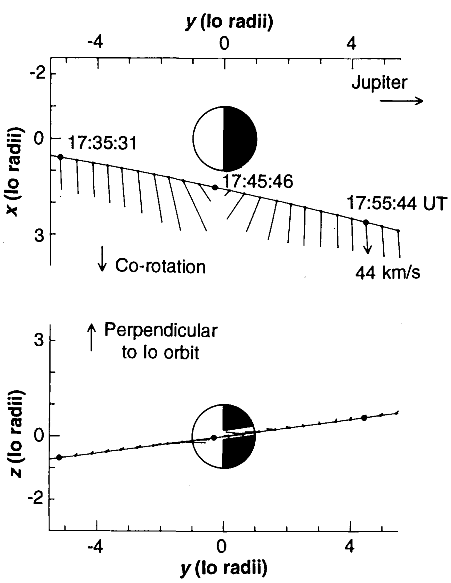

Fig. 1. Plasma flow velocities projected onto the designated two planes as observed along the Galileo spacecraft trajectory in the vicinity of Io. A simple Cartesian coordinate system is chosen for these first results, with y toward Jupiter; z perpendicular to Io's orbit; and x nearly, but not exactly, in the direction of the co-rotational flow of Jupiter's plasmas. The Io radius is 1815 km. The plasma velocity is computed for an average E/Q of 16 atomic mass units. The plasma flow velocities are shown with about 1-min time resolution. The plasma flows are given in the rest frame of Io.

Neubauer (*5*) has derived a relation between the maximum current flowing through Io and an ionosphere, if any, for zero internal resistance for this unipolar generator. This current is proportional to $V_o B_o R'_{Io} \rho_o^{1/2}$ for small Alfvén Mach numbers, where V_o is the plasma bulk speed ~57 km s^{-1}, R'_{Io} is the radius of the Io system (solid body and ionosphere), B_o is the unperturbed jovian magnetic field, and ρ_o is the unperturbed Io torus mass density. The relevant Alfvén Mach number M_A is given by $V_o/V_A \approx 0.4$, where the Alfvén speed $V_A = B_o/(\mu_o \rho_o)^{1/2} \approx 140$ km s^{-1}, where μ_o is the vacuum permeability $= 4\pi \times 10^{-7}$ Ns^2C^{-2}. At closest approach, the magnetometer recorded a decrease of about 500 nT relative to the unperturbed jovian field. The perturbation is primarily in the $+z$ direction (Fig. 1), indicating a current flowing from the Jupiter-facing side of Io to the side facing away from Jupiter. With the plasma parameters taken from the Voyager spacecraft and the assumption of a thin ionosphere, only about 250 nT of the perturbation could be accounted for by the plasma interaction (*11*). Hence, it was concluded that Io may have internal magnetism. However, our measurements of the torus mass densities are about two times greater. In addition, a thick ionosphere is present. So the magnetic perturbation due to the plasma interaction is ~500 nT and is equal to the value measured by the magnetometer. The magnetometer records larger decreases, 600 to 700 nT (*11*), in the regions of high plasma pressures adjacent to closest approach (Fig. 2). However, the gradients in the plasma pressure in these regions give rise to currents that augment those associated with direct interaction. Our estimates of these currents give current densities of $\sim 3 \times 10^{-8}$ to $\sim 5 \times 10^{-8}$ A/m^2, total currents in the range of 10^6 A, and magnetic perturbations between 100 to 200 nT, depending on the spatial geometry of the energy densities. Thus, there is no convincing evidence that Io is endowed with a magnetic moment.

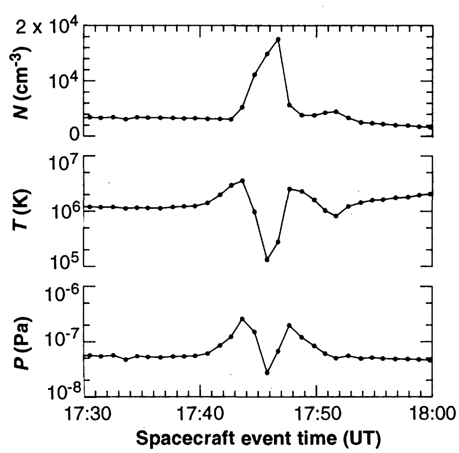

Fig. 2. From top to bottom are shown the plasma number densities, ion temperatures, and plasma pressures in the vicinity of Io.

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9. The gyrofrequency in the ambient magnetic field during closest approach to Io is about 1 s^{-1}. The ion-neutral collision frequency for momentum transfer for SO_2 is about 10^{-9} n, where n is the neutral density, independent of temperature [as given by P. M. Banks and G. Kockarts, *Aeronomy*, Part A (Academic Press, London, 1973), pp. 217–219]. With the assumption that the gyrofrequency is about equal to the collision frequency as the minimum requirement for decoupling the ion motion from the magnetic field, the corresponding neutral density is 10^9 cm^{-3}.
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