Rapid energy dissipation and variability of the Io–Jupiter electrodynamic circuit

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THE electrodynamic interaction between Jupiter and the closest of its large moons, Io, is unique in the Solar system. Io's volcanoes eject a considerable amount of material into the inner jovian system (>1 tonne per second), much of it in the form of ions[1]; the motion of Io through Jupiter's powerful magnetic field in turn generates a million-ampere current[2] between the charged near-Io environment and the planet's ionosphere. This current is presumably carried by Alfvén waves[3], the electromagnetic equivalent of sound waves. Here we present far-ultraviolet observations of the atmospheric footprint of this current, which demonstrate that most of the energy is dissipated rapidly when the waves first encounter Jupiter's ionosphere; the position of the footprint varies with time. We see no evidence for the multiple ionospheric interactions that have been proposed to explain the structure of the radio emissions associated with these waves[4].

The images we present here were taken in the far-ultraviolet (FUV) using the Faint Object Camera aboard the Hubble Space Telescope (HST), after the successful COSTAR upgrade. This upgrade enabled us to pinpoint, for the first time in the FUV, the specific footprint of the moon Io, well resolved from, and as bright as, the auroral emission. The FUV emission is caused by collisional excitation, a uniquely direct signature of a particle-precipitation process. Thus we have been able to detect jovian aurora directly generated by Io. Our observations also allow us to use a relationship between auroral brightness and particle-precipitation flux to estimate primary energy deposition[5].

Previously, long-term observations of jovian radio emissions and Voyager data had suggested an electrodynamic circuit closing through Io and Jupiter's ionosphere, with a system of intense magnetic-field-aligned currents, generally believed to be carried by kinetic Alfvén waves generated by Io's motion across the jovian magnetic field[6–9]. Several important issues were raised by these earlier observations. (1) To what extent the source of the current system is localized to the immediate vicinity of Io, rather than in an extended Io wake or Io magnetosphere (as discussed by Southwood *et al.*[9] when considering the *in situ* data from Voyager). (2) If the source were Io, to what extent, if any, the path of the current deviates from the instantaneous field tube (IFT) connecting Io to the jovian ionosphere; the jovian radio bursts indirectly suggest[10,11] active field lines ahead of it ('leading') by 20° on average with a dispersion of ±15°, whereas present-day Alfvén-wave interaction models can account only for a few degrees. (3) Whether the energy is deposited directly, or after a number of interhemispheric reflections on the ionosphere or on the dense Io plasma-torus, as suggested by the "multiple-arc" structure found in radio emissions from Voyager and ground-based observations[4,12].

Connerney and co-workers[13] have recently identified the IFT footprint from ground-based observations in the near-infrared H_3^+ rotational-vibrational transitions. The infrared hotspot lies some 15–20° ahead of surface footprint of the IFT.

Figure 1 shows the north (top of image) and south (bottom) polar regions of Jupiter on 9 August, 1994, in the H_2 Lyman bands near 1,550 Å. The physical pixel size is (0.014 arcsec)^2. The total energy point-spread function (PSF) at half-maximum is <0.05″ in radius (3 pixels), including contributions of the telescope, camera and filters, exceeding by far the capabilities of any other instrument.

The important feature in Fig. 1 is the bright spot in the southern hemisphere near the east limb (left on the figure), north of the auroral oval. At the time, Io was on the dayside, near the dawn meridian, and there is every reason to identify the spot with the locus of energetic-particle precipitation from a source connected in some way to Io.

Figure 3 shows photon count-rates along tracks across the spot. The spot is narrow in latitude (about the size of the PSF) and slightly elongated in longitude. The apparent longitudinal extent, ~5° at half-maximum, exceeds only slightly the distance the Io footprint moved during exposure. This is consistent with the light being emitted from an instantaneous source comparable in size to Io's projection along the magnetic field. The bulk of the interaction must be confined within a few radii of Io, with Io itself or its ionosphere; much less, if any, seems to originate from a cometary-like Io wake or from a reconnected Io magnetosphere possibly extended along Io's orbit (Fig. 1).

The total power radiated by the spot in the H_2 Werner–Lyman bands is $\sim 5 \times 10^{10}$ W. Using a model of energy degradation for the precipitating particles[5], we can deduce the fraction of the incident energy going into excitation of H_2, and we estimate the power input from precipitation in the IFT as $\sim (2\text{–}3) \times 10^{11}$ W. This is a remarkably high figure, showing that the energetic electrons deposit ~1/4 of the total system energy provided by the motion of Io across jovian magnetic field lines (estimated[8] as of the order of 10^{12} W per hemisphere) in this one spot. As there must also be substantial, comparable energy dissipated by Joule heating of the atmosphere, it seems that most of the energy of the Alfvén waves, which carry the disturbance, is deposited in the first interaction with the ionosphere. It is thus unsurprising that our images show evidence only of a single bright spot. But this raises a serious problem. "Multiple-arc" patterns are consistently observed in Io-controlled frequency–time spectrograms of the decametric radio emission[12,14]. The most satisfying explanation proposed multiple bounces of standing Alfvén waves between the northern and southern ionospheres, or between the ionosphere and the dense plasma-torus generated by Io along its orbit[4,7,15]. Longitudinal spacings of a few degrees are expected between adjacent Alfvén wings (~5° on average) and up to 100 consecutive bounces could occur before the wave is totally absorbed. This implies good reflection on the ionosphere, and only a small energy loss on each bounce, less than 10–20% (refs 4, 16). This does not seem to fit with our data which support large local energy dissipation in the first ionospheric interaction ($\geqslant 50\%$), and which show no indication of consecutive spots of comparable brightness aligned along Io's orbit footprint (the structured arc extending westward of Io, if related, is much fainter). Accommodating our new observations with the apparent structural complexity of the radio source will be a major challenge.

In the standard ionospheric interaction model[1], the implication of a low reflection coefficient, $R = (1 - \Sigma_J/\Sigma_A)(1 + \Sigma_J/\Sigma_A)$ would be that the ionospheric conductance Σ_J (hitherto fairly unconstrained) must well match the wave conductance Σ_A (which is well known). Another important consequence is that any microphysical model of Alfvén-wave interaction must now be able to account for the acceleration of such a large electron flux.

Comparing the power input with the power radiated by the most intense radio bursts from the IFT, $\gg 10^9$ W (ref. 17), we infer also that the mechanism converting particle energy into

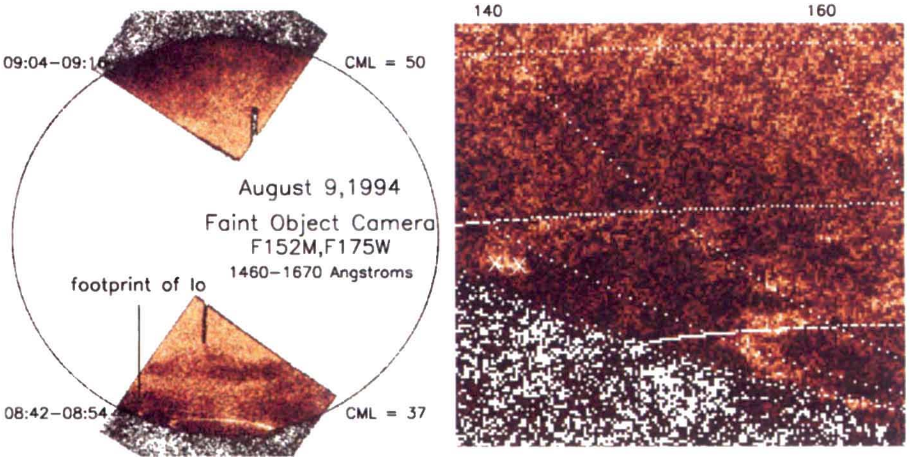

FIG. 1 Left, images of the FUV Jovian aurorae taken by the HST Faint Object Camera. The bright disk is due to Rayleigh-scattered solar flux, and the dark belt in the south to clouds produced by the impact of comet Shoemaker-Levy 9. The black elongated features are coronographic fingers. Jupiter rotated by ~7° during exposures. Spatial resolution permits to detect the FUV Io footprint (in the south) (see also ref. 21). A two-dimensional spatial-filtering code improves visibility of the limb and of real features. The images are rebinned into 512 × 512 arrays of $(0.028\,\mathrm{arcsec})^2$-pixels, and an oblate spheroid is fitted to the disk outside the aurorae. Right, magnified view of the spot. It extends from (−62.75°, 111.25°) to (−63.15°, 114.25°) (latitude, phase angle from the anti-Earth direction) (between crosses). Uncertainties in the offset between images, limb fitting and spot location are within $\mp 2.25°$ and $\pm 0.6°$ respectively (4–5 pixels). An emission altitude of 200–800 km above the "surface" (800 eV–150 keV incident electrons in the model of ref. 5) increases the phase angle by 0.3–1.1°. Io is at longitudes ~126° and ~135° for the south and north images, near the centre of the plasma torus. Its phase is ~89.6° and ~93.2°, respectively (near the dawn meridian), and the calculated phases of its magnetic footprints vary from 102.3° to 105.2°, and 79.4° to 79.17°, respectively, during exposures. The south FUV-spot is therefore 9.6° (−2.45°, +2.75°) ahead of the model footprint in the direction of Io's motion. The magnetically conjugate north spot is not detected, despite a very dark background and the high expected signal-to-noise ratio. This suggests it is still beyond the limb, <10.5° from the IFT footprint (considering the emission altitude might decrease this upper limit down to 3–7°). Both values are significantly smaller than the value derived from the H_3^+ emission[13]. Additionally, a tenuous westward arc originating near the spot may suggest some very faint interaction extending ~20° (~40 Io radii) in the direction of Io's motion.

electromagnetic waves must be more efficient even than for the Earth's auroral kilometric radiation (> 1%).

Finally, the energy flux input through the IFT, ~10–15 W m^{-2}, is enormous (equivalent to the total Earth's auroral power concentrated in a 60 × 200 km area), and must trigger violent local plasma and atmospheric processes.

Knowledge of the exact location of the spot is also of importance in the determination of a number of magnetospheric parameters which are involved in the Io/inner-magnetosphere interaction. The Io-generated signature should be carried by an Alfvén wave whose propagation speed along the field, $V_A = B/(\mu_0\rho)^{1/2}$, depends on the field-strength B and the local plasma mass-density ρ. Meanwhile, the magnetic field line rotates past Io with a relative velocity of $57\,\mathrm{km\,s^{-1}}$, so that the wave reaches the ionosphere ahead of Io's footprint. The value of the lead angle is thus controlled by the high-density, low-field regions of the Alfvén-wave path through the torus. A Voyager-derived model of the Io torus[18] supports displacements of a few degrees ($\leqslant 8°$) (refs 1, 8).

We have taken considerable efforts to fit the limb of the planet and estimate all possible uncertainties (Fig. 1 legend). This leads us to locate the centre of the spot at System III (SIII) magnetic longitude 102.85° (−2.45°, +2.75°), latitude 63° ± 0.6°, slightly poleward of the model footprint of Io's orbit, in close agreement with the locus of the IFT determined by Connerney *et al.*[13] (Fig. 2).

We follow Connerney *et al.* in comparing the position of the

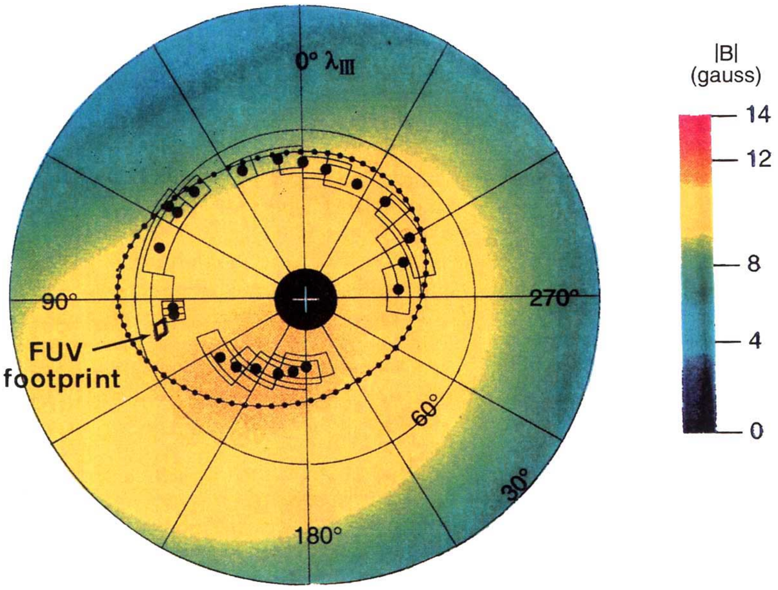

FIG. 2 Polar plot of the footprint of the IFT. The boxes and circles are the infrared spots observed[13] in 1992 with their error boxes, the parallelogram is our FUV spot (including error bars), and the dotted curve is the theoretical footprint of the orbit of Io in the O_6 magnetic-field model. We see that the ultraviolet signature we have detected is well within the locus of the infrared signatures. Both are significantly poleward of the model footprint at the longitude of interest, hence there is some uncertainty in the models near the "surface" of Jupiter which may affect the determination of the lead angles in absolute value, but not their relative value at any given location. The infrared spots used in ref. 13 to determine the lead angle are those closest to the ultraviolet spot.

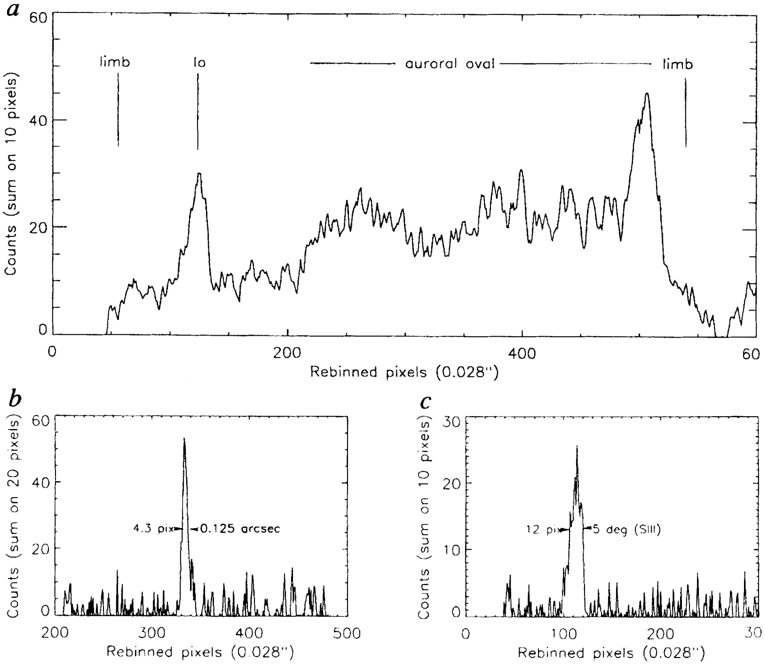

FIG. 3 *a*, Plot across the track of the Io footprint and the aurora (dashed line in Fig. 1), smoothed over 2 pixels. Abscissa are (rebinned)-pixel numbers, ordinates are counts per pixel along the plot (derived from a sum over the number of pixels indicated perpendicular to the plot. The signature of Io is at about the 12σ level, and 65–120% of the auroral signal. *b*, *c*, North–south and east–west plots (respectively) across the track, with the disk background subtracted. Both plots display very sharp gradients. At half-maximum, the spot extends over 12 pixels in the direction of motion, that is ~5° in longitude, and 4.3 pixels (0.12 arcsec) in the transverse direction, that is, ~0.9° in latitude. This is in fair agreement with the size of the IFT footprint (2 × 0.5 pixels projected on the image, or 0.5° × 0.1°), its motion during the exposure (~3°), and the PSF, and is consistent with 75% of the spot energy originating from a region within ~5 Io radii from Io's surface (not corrected from noise contribution and any dispersive spreading of the Alfvén wave[12]). The peak brightness corresponds to 0.7×10^6 rayleigh of total emission in the FUV H_2 Lyman–Werner bands[22], comparable to auroral brightnesses. By contrast, the infrared spot[13] was significantly fainter than the nearby auroral emissions, presumably due to spreading of the emission by a larger PSF. Converted into power units, the total flux is 5×10^{10} W radiated in the FUV H_2 emission. A code of energy degradation of energetic charged particles precipitating in the Jovian atmosphere[5] allows us to compute the fraction of the incident energy lost in excitation of the H_2 bands. This fraction ranges from ~1/4 to ~1/6 for 1–200 keV electrons and 25–500 keV protons, leading to a total flux of $(2\text{–}3) \times 10^{11}\,\mathrm{W\,m^{-2}}$ carried down to the FUV spot by the energetic particles flowing along the IFT.

spot with the instantaneous footprint predicted by the O_6 magnetic-model[15]. These workers found the spot leading the IFT by 15–20°, but our lead angle is only 7–12.3°. The apparent consistency with model predictions cannot be trusted because the magnetic field is still uncertain by a few degrees. By contrast, the difference between the two measurements is of importance. Both datasets were obtained with Io at almost the same longitude (~120°), so that neither uncertainties in the field model nor Io's position in the torus can explain this discrepancy. We now consider other possibilities. (1) Uncertainties in the location of the FUV spot have been carefully estimated. Additionally, a small lead angle is also derived in the north, where we fix an upper limit of 7.5° ± 3° (Fig. 1). By contrast, although the infrared spot is less well defined, much fainter than and not well resolved from nearby aurora, several independent observations were used. We doubt that the results can be reconciled within experimental uncertainties. (2) The generation mechanisms of the infrared emissions must in principle be distinguished from those responsible for the FUV. H_3^+ emissions are believed to be mainly thermalized, due either to collisional heating of the atmosphere by particle precipitation or to Joule heating, rather than being a direct signature of collisional excitation, like the FUV emission. The ultraviolet and infrared signatures are unlikely to separate, however, as here the precipitating particles carry a large portion of the current responsible for Joule heating, and because the absence of strong H_3^+ hot-bands shows that thermalization is rapid. (3) Temporal effects therefore remain the only source of variability. A second set of images obtained on 13 July, with Io at nearly the same longitude, and with the IFT model footprints also just beyond the limb, shows no sign of any bright spot. This sets an upper limit of the lead angle at that date of 7° ± 3° in the south and only 4° ± 3° in the north, even less than on 9 August.

Up to now, the separation between the magnetic footprint of Io and its "auroral" footprint had been assumed to have a single particular value (still to be determined) at any given location, and any discrepancy between datasets was attenuated to observational uncertainties. The above discussion now strongly suggests that this separation is intrinsically variable. Local increases or decreases by a factor of four of the mass density in the plasma torus may lead to the reported variations of ~2. Such density variations could either result from local corotating density variations (like those discovered recently by Ulysses from the narrow-band kilometre-wave radio emission), or from time-varying volcanic activity, ionization of Io's atmosphere, or composition in the vicinity of Io (molecular ions).

Precise understanding of the mechanisms at work in the Io–Jupiter interaction will come only from long-term monitoring of the brightness and lead-angle variabilities, in particular of their dependence on Io's SIII longitude, of their north–south asymmetry, and of their temporal variability. This study thus opens up the possibility, in the longer term, of monitoring the source and transport of plasma in the inner magnetosphere (more accurate magnetic field models will soon become available), and the ionospheric conductivity, two important inputs for magnetospheric models. ☐

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