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M. H. Acuña, F. M. Neubauer, and N. F. Ness

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# STANDING ALFVEN WAVE CURRENT SYSTEM AT Io: VOYAGER 1 OBSERVATIONS

M. H. Acuna, F. M. Neubauer and N. F. Ness

## Abstract

The enigmatic control of the occurrence frequency of Jupiter's decametric emissions by the satellite Io has been explained theoretically on the basis of its strong electrodynamic interaction with the co-rotating Jovian magnetosphere leading to field aligned currents connecting Io with the Jovian ionosphere. Direct measurements of the perturbation magnetic fields due to this current system were obtained by the GSFC magnetic field experiment on Voyager 1 on 5 March 1979 when it passed within 20,500 km south of Io. An interpretation in the framework of Alfven waves radiated by Io leads to current estimates of $2.8 \times 10^6$ amps. A mass density of 7400 to 13600 proton mass units per $cm^3$ is derived which compares very favorably with independent observations of the torus composition characterized by 7-9 proton mass units per electron for a local electron density of 1050 to 1500 $cm^{-3}$. The power dissipated in the current system may be important for heating the Io heavy ion torus, inner magnetosphere, Jovian ionosphere and possibly the ionosphere or even the interior of Io.

## Introduction

The Voyager 1 spacecraft encounter with the planet Jupiter occurred on 5 March 1979 with a closest approach distance of 4.9 $R_J$ (1 $R_J$ = 71372 Km) at 12:04 UT. The encounter trajectory had been designed specifically to provide a passage through the magnetic flux tube which links the Galilean satellite Io with the Jovian atmosphere and ionosphere, at close range to the satellite. Distortions of the flux tube associated with Io's interaction with the Jovian magnetosphere were not considered in the trajectory optimization analysis due to the absence of definitive information regarding the magnitude of the expected perturbation. The selected trajectory was designed to provide a passage through Io's southern flux tube at a closest approach distance of 20500 km from the satellite.

The twin Voyager magnetic field experiments (Behannon et al., 1977) consist of an array of four triaxial fluxgate magnetometers designed to measure magnetic fields over an extremely wide dynamic range, from the noise level of the low field magnetometers (LFM's), 0.006 nT RMS, to the upper limit of $2\times10^6$ nT per axis for the high field magnetometers (HFM's). Two LFM's are mounted on a 13 meter boom and arranged in a dual magnetometer configuration which allows the continuous estimation and elimination of spacecraft generated magnetic fields; the two HFM's are mounted on the boom cannister support structure and are designed to measure large planetary fields, up to $2\times10^6$ nT per component.

During the time interval associated with the anticipated Io flux tube passage, the GSFC magnetic field experiment detected significant perturbations superimposed on the much larger background planetary field. We interpret these perturbations as associated with intense currents electrodynamically induced in Io and/or its ionosphere as the Jovian magnetosphere sweeps past the satellite.

A preliminary report and analysis of quick look data obtained at the time of the encounter has been given by Ness et al. (1979). These preliminary analyses did not consider the ramifications of the observations reported by complementary investigations aboard the spacecraft. Of particular importance are the plasma inertial effects introduced by the presence of the Io plasma torus (Broadfoot et al., 1979; Warwick et al., 1979; Bridge et al., 1979). It is the purpose of this paper to present a more detailed and expanded report of the magnetic field observations and the results of analyses carried out taking into account a more accurate physical description of the interaction between Io, its environment and the Jovian magnetosphere and using updated and much more accurate spacecraft trajectory and especially attitude information.

We show that the observations can be interpreted within the general framework of theoretical predictions based upon two oppositely directed currents in each Jovian hemisphere flowing along the direction of Alfven wave group propagation, approximately parallel to Io's magnetic flux tube and generating a field perturbation whose general characteristics can be well represented by the field associated with a two dimensional dipole. This more accurate interpretation of the observations in terms of a non-linear, standing Alfven current system (Drell et al., 1965; Neubauer, 1979) yields estimates of the local ion mass density. These are in excellent agreement with the results derived from the observations by the ultraviolet experiment (Broadfoot et al., 1979), the planetary radio astronomy experiment (Warwick et al., 1979) and the plasma science experiment (Bagenal et al., 1980; Belcher et al, 1980). In addition a number of interesting conclusions can be derived about the general nature of the electrodynamic interaction in the vicinity of Io.

## Earlier Studies

The role of Io as a unipolar generator and the induction of large electrical currents flowing aligned to the magnetic field along the flux tube had been suggested on observational and theoretical grounds by Piddington (1967) and Piddington and Drake (1968). Further studies on the resulting current system, its possible closure geometry and on charged particles in the flux tube and their acceleration, have been presented by Goldreich and Lynden-Bell (1969), Gurnett (1972), Goertz (1973), Goertz and Deift (1973), Deift and Goertz (1973), Shawhan et al. (1975), Dessler and Hill (1975, 1979), Cloutier et al. (1978), and Dessler and Chamberlain (1979). The strong theoretical interest in this unique phenomenon is directly associated with the observed correlation between Io's orbital phase, the Jovian Central Meridian Longitude (CML) and the probability of detection of Jovian radio emissions at decametric wavelengths at the earth (e.g., see recent review by Carr and Desch, 1976 and references therein). These phenomena and the recent discoveries by Voyager 1 of the Io plasma torus (Broadfoot et al., 1979) and of active volcanism on the surface of the satellite (Smith et al., 1979) undoubtedly make Io one of the most interesting objects in the solar system.

A widely accepted model for the current system consists of field aligned currents emanating from the outer face of Io and flowing both southward and northward towards the Jovian ionosphere. The return currents then flow along the flux tube on its inner face. The closure of these currents at the extremes of the circuit requires the existence of regions of high conductivity transverse to the magnetic field. These were generally associated with the conductivity of the Jovian ionosphere, Io's ionosphere and/or its interior.

The description of the interaction in terms of a non-linear standing Alfven current system (Neubauer, 1980) also implies the possibility that these waves may be reflected at the Jovian ionosphere or torus boundary. This would lead to a partial closure of the current system in the near vicinity of Io. In addition, in the Alfven wave system description, the currents are not strictly field aligned and the separation between current stream lines and magnetic field lines can become appreciable if followed all the way down to the Jovian ionosphere (Neubauer, 1980). This can have important implications for the interpretation of Jovian decametric radio emissions as a function of CML and Io-phase since it further enhances the distortion of field lines away from simple meridional planes associated with the non-dipolar nature of the Jovian magnetic field (see, for example, Goldreich and Lynden-Bell, 1969).

## Observations and Analyses

A projection of the spacecraft encounter trajectory onto the Jovian magnetic equatorial plane in System III (1965) coordinates is shown in Fig. 1. The position of Io is also indicated in the figure for reference. The Io L-shell is crossed during the inbound leg at 0900 SCET while the predicted Io flux tube traversal occurs on the outbound leg at 1502 SCET. One interesting feature of this trajectory is that the spacecraft remains relatively close to Io for ~ 8 hrs, thus potentially allowing the detailed study of various phenomena (i.e., ion cyclotron waves) associated with the Io torus. These studies will be the subject of a future report and are not included here.

The selected flux tube geometry relative to the spacecraft trajectory was calculated using the $O_4$ magnetic field model of Acuna and Ness (1976) and the $D_4$ model of Smith et al. (1975), neglecting any possible distortions of the flux tube due to the current system. The probability of intercepting the central part of the flux tube, as computed from the above models, was essentially identical for both, the only difference being the encounter time, with the $O_4$ model predicting a flux tube encounter $\sim$ 1 minute later than the $D_4$ model. The detailed trajectory near Io's closest approach is shown in Fig. 2 in a coordinate system centered at and moving with Io. In this analysis system, the Z-axis is parallel to Jupiter's rotation axis, the X-axis is oriented in the direction of corotational flow and the Y-axis points toward Jupiter. The closest approach point to the satellite occurs at 1513 SCET at a distance of 20500 km from Io's center and at a System III(1965) longitude of $328^{\circ}$.

To ensure the acquisition of maximum resolution data during the Io flux tube passage, the outboard LFM was commanded to operate in a fixed (non-automatic ranging) mode corresponding to a maximum measurement capability of 2400 nT per axis, close to the maximum anticipated for this time period from the analytical models of the field. This operational mode, in conjunction with the experiment 12-bit A to D converter and fast sampling rate, yielded a data set with 0.5 nT and 60 msec resolution respectively.

The magnetic field data obtained from 1424 SCET to 1550 SCET are shown in Figure 3, where 1.92 second averages of the three field components, $B_r$, $B_\theta$, $B_\phi$ in a spherical coordinate system centered at Jupiter and aligned with the rotation axis are shown. It is important to note that the spacecraft performed a number of attitude maneuvers after 15:22 SCET associated with optimum positioning of the scan platform for observing Io. The spacecraft attitude for some of these maneuvers has been reconstructed from the magnetic field data itself due to the lack of adequate high time resolution engineering data.

During and adjacent to the time interval associated with the geometrical flux tube passage, strong, smooth perturbations of the background field can be observed. Although 1.92 second averages are shown in the figure, detailed analysis of the high time resolution data reveals the absence of short period coherent perturbations in the measured field. A power spectral analysis of these data, up to the instrument's Nyquist frequency confirms the absence of significant maxima in the spectra, the power spectral density vs. frequency curves being characteristic of quantization noise associated with the ± 0.5 nT digitization uncertainty for frequencies greater than ≈ 1 Hertz.

In order to study the characteristics of the perturbation, the large background field must be subtracted from the measurements. Although analytical models of the main magnetic field of Jupiter can be utilized in principle to represent the field, this approach does not take into account the diamagnetic effects associated with Io's plasma torus and/or perturbation fields associated with the Jovian equatorial current sheet which are significant at this radial distance, considering the magnitude of Io's current system signature detected by Voyager 1.

Estimates of the components of the local background magnetic field have been obtained by performing a quadratic least squares regression analysis of the data excluding the interval where the principal Io induced perturbations are observed. This approach yields a more accurate local representation of the background field for the purpose of its subtraction from the measurements. After this is carried out, the resulting perturbation field components $\Delta B_R$, $\Delta B_\theta$ and $\Delta B_\phi$ clearly indicate that the observed perturbation is nearly transverse to the ambient magnetic field, as shown in Fig. 4. Since the spacecraft latitude is close to the Jovian equatorial plane, the measured $B_\theta$ component is approximately aligned with the ambient field direction. Note that the largest perturbations are observed in $B_R$ and $B_\phi$ pointing to the transverse nature of the perturbation field. This is further illustrated in the top panel of Fig. 4 where the angle between the background and the perturbation field has been plotted showing that it approaches $90^\circ$ during this time. The computed perturbation vectors exhibit a weak dependence upon the selected intervals for the calculation of the background field and this leads to the quoted uncertainties in the estimation of parameters for the model described below.

At this point, we can raise the question about the observed perturbation being due to an intrinsic Ionian magnetic field which is strong enough to be observed at the spacecraft location. Two simple dimensional arguments can be easily put forward to rule out this possibility: 1) the magnitude of the transverse perturbation vector shown in Fig. 4 as a function of time varies with a characteristic scale length at its full-width-half-maximum points corresponding to a distance of 9000 km, as seen by an observer on Io, which is small compared with the closest approach distance of 20,500 km and 2) the perturbation is characterized by a change in ambient field direction rather than field magnitude. On the other hand, the possible existence of a small intrinsic Ionian field (Neubauer, 1978; Kivelson et al., 1979) cannot be ruled out on the basis of these observations. The existence of an intrinsic magnetic field of Io would physically affect the current system responsible for the observed perturbation in the immediate vicinity of the satellite (Neubauer, 1980) and would cause energetic particles to be selectively deflected as a function of their energy. This latter effect has been reported by Krimigis et al. (1979) although no definitive statements have been made regarding the possible existence of an Ionian magnetic field.

Qualitatively, the extremely smooth variation of the pertubation field together with its simple appearance suggest that Voyager 1 did not pass through the main current carrying region but flew near it. As reported by Ness et al. (1979), the observations can be represented to a good approximation by the magnetic field generated by two oppositely directed line currents flowing approximately parallel to the average magnetic field direction.

Because of the infinite number of possibilities available to explain the given magnetic field observations along the spacecraft trajectory in terms of a spatial distribution of currents, detailed interpretations of the observational results have to be guided by appropriate physical ideas about the nature of the plasma currents. Further insight into the geometry of the current carrying region can be gained by considering the inertia of the ambient plasma (Io torus) which will cause the currents to deviate from flowing strictly parallel to the magnetic field. This problem has been addressed recently by Neubauer (1980) where a full non-linear solution is given for the system of standing Alfven waves generated by the interaction of Io with the co-rotating magnetosphere. The current tube in this case forms an angle $\theta_A$ with the ambient magnetic field and is determined by the local Alfven characteristic direction, as illustrated in Figure 5. This description of the interaction suggests that the observations should be analyzed in a coordinate system aligned with the direction of Alfven characteristics $C_A^{+}$ (see Fig. 5). Since the magnitude of $\theta_A$ depends on the local Alfven Mach number and this is not known a priori, it must be assumed. Thus, the orientation of the analysis coordinate system with respect to the local magnetic field is determined by the assumed Alfven Mach number, which yields a local characteristic direction by

$$\vec{V}_A{}^{+} = \frac{\vec{B}}{|\vec{B}|} + M_A \vec{\phi} \qquad (1)$$

where $\vec{B}$ is the average background field vector, $M_A$ is the local Alfven Mach number ($M_A = V_{rel}/V_A$) and $\vec{\phi}$ the unit vector in the $\phi$ direction of the spherical coordinate system centered at Jupiter. $V_{rel}$ and $V_A$ are the speed of Io relative to the magnetospheric plasma and the Alfven speed respectively. Equation (1) reflects the fact that the $\vec{\phi}$ direction represents the direction of corotational flow.

We choose to orient the Z-axis of our Io-centered analysis coordinate system antiparallel to the direction of Alfven characteristics $C_A^{+}$, and define the X-Z plane to contain the direction of corotational flow. The Y-axis then completes the right handed system and is roughly directed radially towards Jupiter. The magnetic field perturbation data and spacecraft positional information are then rotated into the analysis coordinate system. Note that because equation (1) the unperturbed background magnetic field $\vec{B}_o$ is not aligned with one of the coordinate system axes. Therefore the perturbation magnetic field has three non-zero components in this representation.

The coordinate system chosen is most suitable for model fitting. Except for the immediate vicinity of the source, Io, the physical quantities $\Delta\vec{B}$, $\Delta\vec{V}$, etc. do not depend on the Z-coordinate and the magnetic field components $\Delta B_x$, $\Delta B_y$ can be represented by a scalar potential $\Psi(x,y)$ if the current component along the Z-direction, $j_z = 0$. These currents $j_z$ $(x,y)$ feed the currents in Io's inmediate vicinity or are fed by them. $\Delta B_z$ is then given by the requirement of constant magnnetic field magnitude. The component $\Delta B_z$ $(x,y)$ is due to the relatively small currents forming closed loops in the X,Y-plane. Strictly speaking, the general current streamlines are therefore helices with small pitch angles.

The lowest order terms in the expansion for the potential $\Psi$ of the field generated by a system of currents $j_z$ (with net current = 0) flowing parallel and anti-parallel to the Z-axis in our coordinate system is a 2-dimensional dipole whose potential, $\psi$, is given by

$$\psi(\vec{X}) = \frac{\vec{m} \cdot (\vec{X} - \vec{D})}{2\pi(|\vec{X}| - |\vec{D}|^2)} \tag{1}$$

and

$$\Delta\vec{B} = - \mu_o \nabla\psi \tag{2}$$

where $\Delta\vec{B}$ corresponds to the perturbation field, $\vec{X}$ is the spacecraft position vector $\vec{X}(x,y)$., $\vec{m}$ is the dipole moment and $\vec{D}$ the dipole location in the X-Y plane.

The observations can then be fitted to the model in the analysis coordinate frame in a least squares sense. Given the Alfven Mach number $M_A$ which defines the orientation of the coordinate system, we determine the parameters $\vec{m}$ and $\vec{D}$ by means of an iterative "walking dipole" algorithm which minimizes the root-mean square sum of the residuals. Since the coordinate system is centered at Io and the current must flow approximately parallel to the Z-axis to connect with the satellite, the dipole location obtained must be as close to the origin as possible (note however that the curvature of the field lines is ignored although the fly-by distance of 20,500 km is not insignificant). If a dipole location reasonably close to the origin is not obtained, the assumed Alfven Mach number is incremented and the fitting process repeated for each Alfven Mach number chosen.

This process was carried out for Alfven Mach numbers in the range of $.01 \leq M_A \leq .25$. The best fit to the observations in terms of the connection of the current system to Io is obtained for an Alfven Mach number of 0.15 ± .01. The perturbation field vectors along the spacecraft trajectory in the Alfvenic coordinate system are shown in Fig. 6 for $M_A$ = 0.15. Also shown are the orientation and location of the 2-dimensional dipole moment $\vec{m}$ obtained from the fit to the observations. The orientation of the dipole, approximately parallel to the direction of corotational flow, is in excellent agreement with theoretical expectations, that is, a downward current flowing along the outer face of the current tube while the upwards return current flows along the inner face. The Y-coordinate of the dipole location is not exactly zero but exhibits a small negative value which agrees reasonably well in magnitude and direction with the fact that the small spatial variations of the global background magnetic field of Jupiter, i.e. its curvature, have been ignored in this model. Other mechanisms which could account for small displacements of the center of the current system include the effects of finite frequency corrections to the MHD equations, an asymmetry of the interaction region near Io, etc. The circle in the figure represents the projection of Io on the X-Y plane and the dipole moment $\vec{m}$ obtained is $8.1 \pm .2 \times 10^9$ amperes km. This is consistent with the earlier estimates (Ness et al., 1979) but at their lower limits. If it is assumed that the currents flow on the periphery of a cylinder of Io's diameter (3680 km) according to a $\sin\phi$ distribution, as indicated in the figure, the derived current flowing along the Alfvenic tube is $2.8 \pm .1 \times 10^6$ amperes.

The Voyager 1 magnetic field observations constitute the first in situ experimental verification of the existence of a current system induced by the interaction of Io with the magnetosphere. However, since the observations are restricted to the the spacecraft trajectory and its single traversal of the flux tube region, no unique conclusions can be drawn from these observations regarding the location of the current closure regions, at Io or in the Jovian ionosphere, their geometry, or any possible dependence of the intensity of the currents upon the relative location of the flux tube with respect to Jovian longitude.

It is important to note that the quantity derived from the observations is the dipole moment $\vec{m}$ and not the current. A few remarks on the uniqueness problem are in order at this point. Although the above choice of a current distribution is a reasonable one for physical models where the current closes in the interior of Io or its adjacent ionosphere, there is an infinite number of current distributions which produce the same field as an idealized two-dimensional dipole along the fly-by trajectory in the X,Y-plane. This is apart from the ambiguity due to observational uncertainties and the fast decrease of higher multipoles as a function of distance from the origin. In addition, it cannot be concluded that the current carrying region is remote from the spacecraft trajectory from the fact that a two-dimensional dipole is the lowest order term, i.e. the far field term, in the expansion of an arbitrary distribution of current $j_z$ with net current zero. For example, a cylinder of diameter 8700 km which just touches the Voyager trajectory and carries a sinusoidal current distribution with total current = $1.2 \times 10^6$ amperes, yields exactly the same perturbation field as the current distribution above. The smallest total current consistent with the observations is obtained by a sheet current located just inside the fly-by trajectory as seen from Io. Its value is given by $I_{min.} = 6 \times 10^5$ amperes. Both examples illustrate the non-uniqueness problem. The final justification for a current distribution must come from auxiliary observations and physical modeling.

Figure 7 illustrates the excellent agreement between the observations (48 second averages) and the results derived from the model. The small discrepancy which is evident after 1520 SCET is not completely understood at the present time. The inclusion of terms of higher order than the dipole in the expansion for the scalar potential $\psi$ does not appear to be justified to explain this discrepancy since the model fits the observations extremely well elsewhere prior to 1520 SCET. The possibility that these observations reflect some temporal effects cannot be ruled out at the present time and further analysis, taking into account correlative observations by other experiments on the spacecraft, is required. There may also remain some uncorrected spacecraft attitude errors.

Discussion and Summary

The results presented above, based upon more accurate trajectory and attitude data, support the interpretation of the Voyager 1 magnetic field observations near Io (Ness et al., 1979). They show that the spacecraft did not traverse the current carrying region itself but passed approximately 4350 km from its center. The results given here take into account the high plasma densities implied by the presence of the Io torus. Strong support for the interpretation of the observations in terms of a standing Alfven current system is given by the fact that the Alfven Mach number required to connect the currents to Io utilizing a 2-dimensional dipole model is 0.15 ± .01. This value is in excellent agreement with that derived from the results reported by the planetary radio astronomy and ultraviolet experiments. Warwick et al.(1979) and Birmingham et al. (1980, this issue) have estimated the electron density in the torus at this time as 1050-1500 el/cm$^3$. Taking into account the Alfven Mach number derived from the magnetic field observations, $M_A$ = .15, we can estimate the ion mass composition in the torus as 7-9 proton masses per electron, in excellent agreement with the results reported by Broadfoot et al. (1979) for the plasma composition ($S_{III}$, $S_{IV}$, $O_{III}$). From the value of the Alfven Mach number we can also derive the external Alfvenic conductance $\Sigma_A = 1/(\mu_o V_A)$ (Neubauer, 1980). In addition, the Alfven wave theory predicts a simple relation between the magnetic field and velocity perturbations: $\Delta\vec{V} = -\Delta\vec{B}/(\mu_o\rho)^{1/2}$. For example, the maximum magnetic field perturbation of 70 nT yields $|\Delta\vec{V}|_{max}$ = 14 km/sec. It will be interesting to test the predictions of the theory with the plasma ion observations during the Io encounter. The predicted velocity perturbation vectors have been indicated in Figures 6 and 7. Preliminary comparisons with plasma observations ( Belcher et al., 1980) indicate good agreement with this picture.

Neubauer (1980) has derived a maximum magnetic moment which can be generated by the current system as

$$\vec{m}_{max} = \frac{2\pi R^2_{Io}\, B_o\, M_A}{\mu_o(1 + M_A^2)^{1/2}} \quad (3)$$

where we have assumed $\theta = 0$, corresponding to transverse flow (see Neubauer, 1980 for derivation), $B_o$ is the ambient magnetic field and $2\ R_{Io}$ is the current system diameter. For $B_o = 1900$ nT, $M_A = 0.15$, $R_{Io} = 1840$ km we obtain $\vec{m}_{max} = 4.77 \times 10^9$ amperes km, which is smaller than the value derived from the observations. As pointed out by Neubauer (1980), this would imply that the current carrying region may have larger dimensions than the assumed Io diameter and that the ionosphere of Io may play a more significant role than its interior in providing a closure path for the currents. To obtain the derived moment of $8.1 \times 10^9$ amperes-km, the 'effective radius' of Io in equation (3) has to be increased to approximately 2400 km. This would imply that the current carrying region is located 560 km above Io's surface. This value should be compared with the results obtained by Kliore et al., 1974 for the extent (750 km) and scale height (200 km) of the daytime Ionian ionosphere. It is interesting to note that volcanic ejecta can reach altitudes of 270-300 km during an eruption (Smith et al., 1979) and thus could contribute a significant amount of ionization at these heights through collisional processes with the charged particle population in the radiation belts or the torus plasma. An alternate explanation for the large magnetic moment may be the non-negligible effect of reflected Alfven waves in the case of very efficient short-circuiting of the electric field by Io (or non-stationary processes). For this case to occur the short-circuited electric field inside the current tube $E_i$ must be below an upper limit given by the condition that the round trip travel time of the Alfven waves to the reflecting boundary (torus or Jovian ionosphere) equals the time it takes for the plasma to traverse an Io diameter. In a torus of diameter $2R_j$ we obtain

$$(E_i/E_o)\ M_A = R_{Io}/R_j \qquad (4)$$

which represents a generalization of equation (29) of Neubauer (1980) and is also valid for Alfven waves in the region of strong short-circuiting. Here $E_o$ is the corotational electric field (see also Goertz, 1980). Using $M_A = 0.15$ we obtain $E_i/E_o = 0.17$. Should the reflected waves be insignificant we must have $E_i/E_o \gtrsim 0.17$. Since the average value of the density and therefore $M_A$ in the torus is probably somewhat larger than between Io and Voyager, the transition electric field may be even smaller than this value.

The implications of the derived current intensity of $2.8 \times 10^6$ amperes for the electrodynamic interaction of Io with its environment are extremely interesting, particularly the power dissipated in the northern and southern portions of the current system. In deriving this quantity we have to take into account that the various closed current filaments are subjected to differing voltage drops. Therefore an average voltage drop has to be multiplied by the total current. We obtain $P = 2|\vec{m} x \vec{E}_o|$. Using $\vec{E}_o = \vec{V}_{rel} x \vec{B}_o \cdot \vec{\phi}$ and $B_o = 1900$ nT a value of $P = 1.8 \times 10^{12}$ watts is obtained which is independent of the diameter of the current carrying cylinder and therefore less model dependent than the total current. This value of P, as pointed by Ness et al., 1979, is comparable to the energy dissipated in Io's interior by tidal forces (Peale and Cassen, 1979) and the energy radiated by the plasma torus at ultraviolet wavelengths (Broadfoot et al., 1979). For the total power to be available for heating Io or its atmosphere or ionosphere it would be necessary that Io and its environment provide the largest resistance in the total current circuit. This would be in contradiction to the observation that the magnetic moment $\vec{m}$ is close to its maximum value or even exceeds it. Essentially total short-circuiting of the electric field in Io's vicinity is required for $\vec{m}$ (observed) $\approx \vec{m}_{max}$ to be attained and therefore negligible resistance in Io and its neighborhood. We therefore conclude that most of the power is dissipated outside Io and its immediate environment, i.e. the torus, the inner magnetosphere or the Jovian ionosphere. We estimate the maximum power dissipation in Io's atmosphere or possibly its interior due to Joule heating to be $P/10 = 2 \times 10^{11}$ watts.

The currents flowing through the Io system will also give rise to an accelerating torque due to the rotation of the Jovian magnetic field, as first discussed by Goldreich and Lynden-Bell, (1969). The value of this torque, calculated using ($T = 2\ r_{Io} . \vec{m} . B_o$) with $r_{Io}$ = the distance of Io from Jupiter, is $1.3 \times 10^{16}$ Newton-meters which is insignificant compared to Io's orbital angular momentum of $6.5 \times 10^{35}$ kg.m$^2$/sec. Thus, conclusions reached by Goldreich and Lynden-Bell (1969) regarding the characteristic doubling time for Io's angular momentum of $10^{12}$ years stand unchanged. (Note that these authors used values of 3500 nT and $1.1 \times 10^6$ amperes for the magnetic field and current intensity, respectively). We also mention that only a fraction of the torque is generally applied to the solid body of Io. For example the portion of the current near Io due to the pick-up of newly generated ions by the magnetic field (Goertz, 1980) will not contribute to a torque on the solid body if these ions experience no further collisions with Io's surface or atmospheric neutrals after generation. Currents in a collison dominated region of the neutral atmosphere will contribute to the torque via viscous forces.

Prior to the discovery of the Io plasma torus, it was generally accepted that the magnitude of the currents flowing in the flux tube was limited primarily by the Jovian ionospheric conductivity (Cloutier et al., 1978; Dessler and Hill, 1979). The magnetic field models developed after the Pioneer 10 and 11 encounters with Jupiter (Smith et al., 1975; Acuna and Ness, 1976) indicated that the field was asymmetrical and that the surface field intensity exhibited broad minima at certain longitudes where enhanced particle precipitation would be expected (Roederer et al., 1977; Dessler and Hill, 1979). This led Dessler and Hill (1979) to postulate that the Jovian ionospheric conductivity at the foot of the Io flux tube would be greatly increased at these longitudes due to the enhanced particle participation, and this, in turn, would lead to an enhancement of the Io flux tube currents. This "active hemisphere" or "magnetic anomaly" model predicts that the Io currents should increase to over $10^6$ amperes in the range of System III (1965) longitudes of 200-260$^\circ$, compared to a value of $\sim 10^5$ amperes over all other longitudes (Cloutier, 1978; Dessler and Hill, 1979). The results deduced here from the Voyager 1 observations at a System III longitude of $310^\circ < \lambda < 335^\circ$, corresponding to the Io flux tube crossing interval, show that this current is $2.8 \times 10^6$ amps rather than the expected $\sim 10^5$ amps. Since the magnetic anomaly model does not take into account the existence of the plasma torus, the role played by it in providing local closure to the currents must be fully evaluated. The observations reported here suggest that Io acts as a generator of strong Alfven waves with its associated currents, magnetic field and velocity perturbations. In contrast to the classical models by Piddington (1967), Goldreich and Lynden-Bell (1969) etc. the disturbances issuing from Io during the Voyager-1 encounter were most likely determined by the local torus properties while the interaction with the torus boundary or Jovian ionosphere was small (a more detailed discussion of this point is contained in Neubauer, 1980). We also conclude that most of the power dissipation in this current system occurred in the Jovian ionosphere, inner magnetosphere or torus but not inside Io or its immediate vicinity.

From the picture presented above it is clear that the coupling between Io and the Jovian ionosphere is not as strong nor as conceptually simple as envisioned prior to the Voyager 1 observations and plasma torus discovery. This raises new and interesting questions regarding the mechanism of Io's control of decametric radio emissions. Although it could be concluded that the lead angle provided by the Alfven wings ($8.5^{\circ}$) is a reasonable explanation for the observed Io-phase asymmetry in the probability of detecting decametric emissions, little is known about the geometry of the postulated reflection of the Alfven wave at the Jovian ionosphere. The large increase in Alfven velocity outside of the plasma torus significantly reduces the magnitude of this angle leading to a possible overlap of the downgoing and reflected waves. This effect would further complicate the reflection geometry at the foot of the flux tube where presumably the emissions originate.

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## Figure Captions

Figure 1. Voyager 1 trajectory and position of Io in System III longitude (1965) and radial distance (in units of Jovian Radii) on 5 March 1979.

Figure 2. Relative position of Voyager 1 and Io during Io current system studies.

Figure 3. GSFC magnetic field observations in spherical coordinates. The three orthogonal components of the field are shown, as is the magnitude. Data points are 1.92 second averages of 60 msec. vector samples.

Figure 4. Perturbation magnetic field associated with the Io current system, as detected by Voyager 1. In addition to the three orthogonal components in spherical coordinates the angle between the background field and perturbation field has been computed in the upper panel.

Figure 5. Schematic diagram illustrating the electrodynamic interaction of Io generating Alfven waves in the ambient plasma torus. The specific Mach numbers chosen are for illustration purposes only and do not refer to the results obtained by Voyager 1 except that the flow is sub-Alfvenic and probably not supersonic.

Figure 6. Perturbation field due to Io current system as observed by Voyager 1 along its trajectory and the position of the equivalent dipole moment, $\vec{m}$, of the current system. Also shown is the current density vector along a circle with Io's radius. The predicted scale for velocity perturbations is also indicated. See text.

Figure 7a. Comparison of magnitudes of magnetic field perturbation due to Io current system as observed (+) and predicted (continuous curve) from dipole line currents model.

Figure 7b. Same as Figure 7a. but a different fitting interval for the background magnetic field has been used. In this case the value of $M_A$ obtained is 0.16.

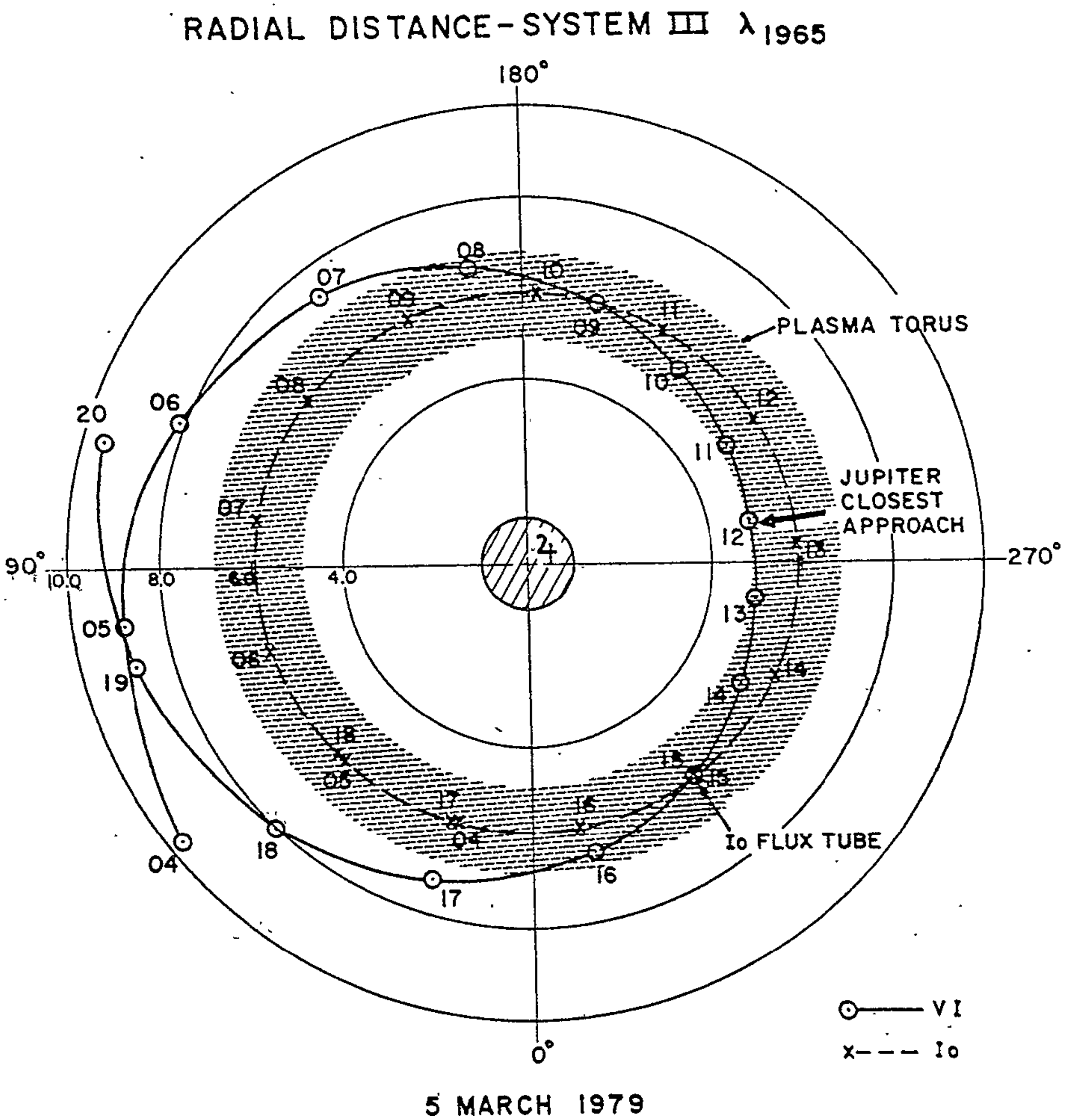

RADIAL DISTANCE-SYSTEM III λ 1965
180°
90°
270°
0°
10.0
8.0
6.0
4.0
PLASMA TORUS
JUPITER
CLOSEST
APPROACH
Io FLUX TUBE
VI
Io
5 MARCH 1979



FIGURE 1

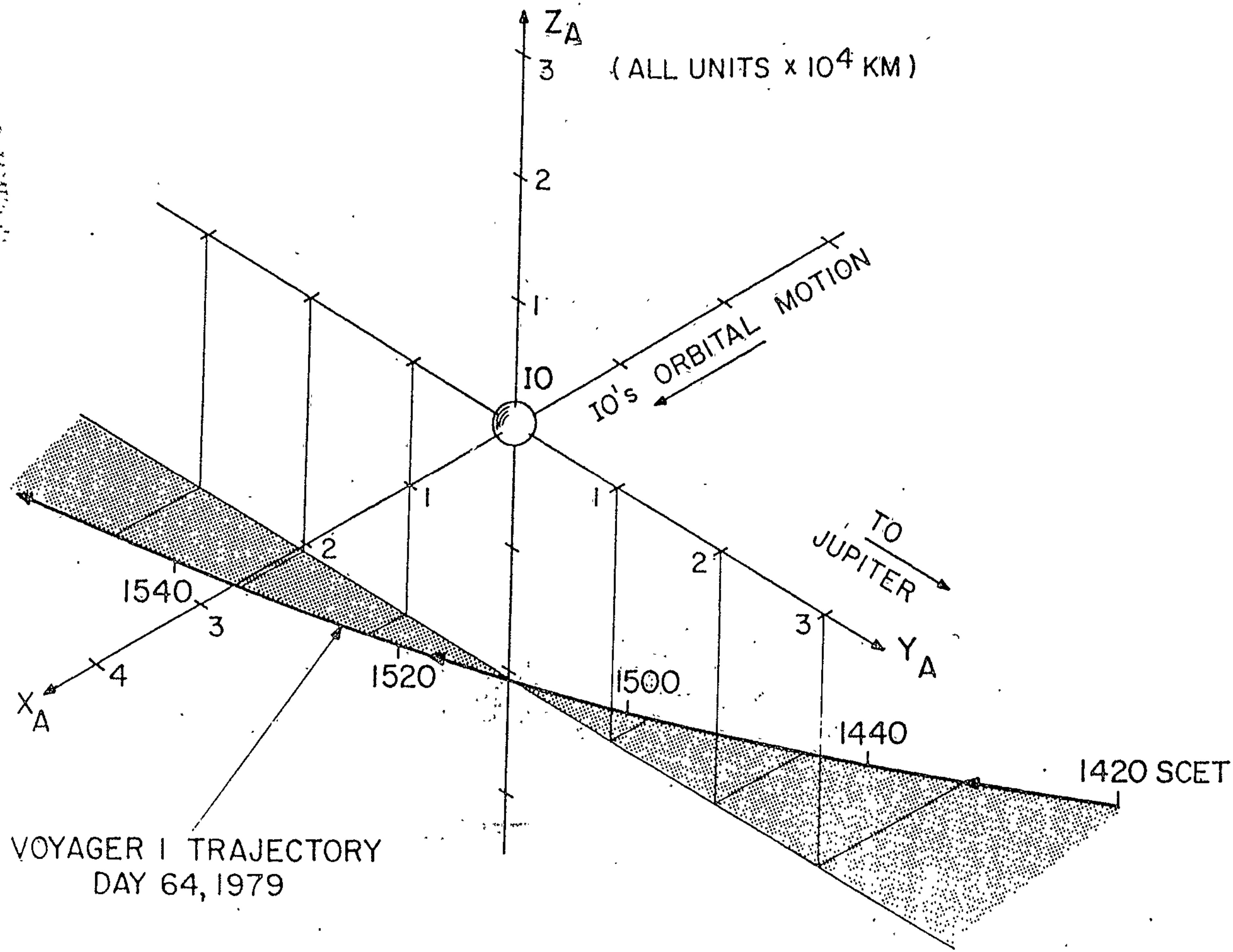
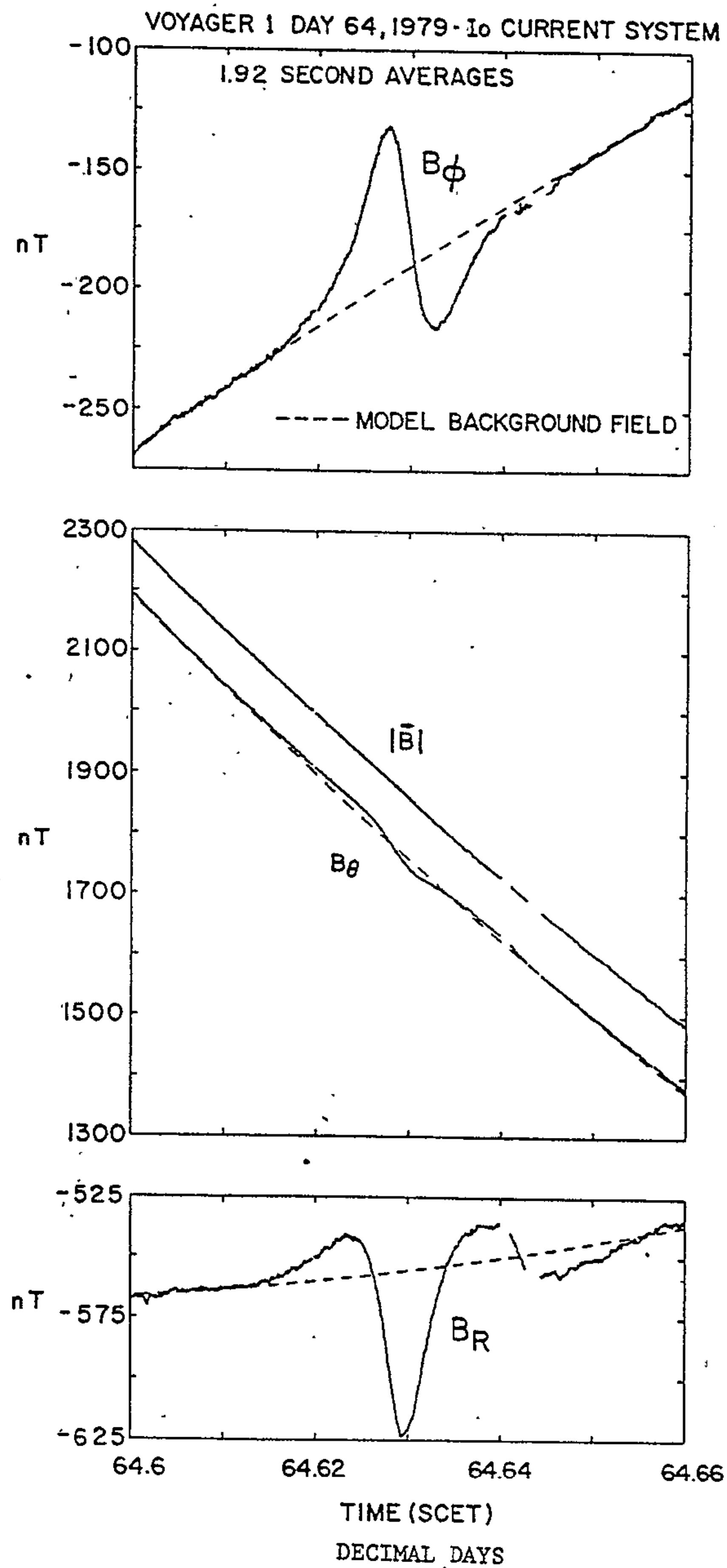
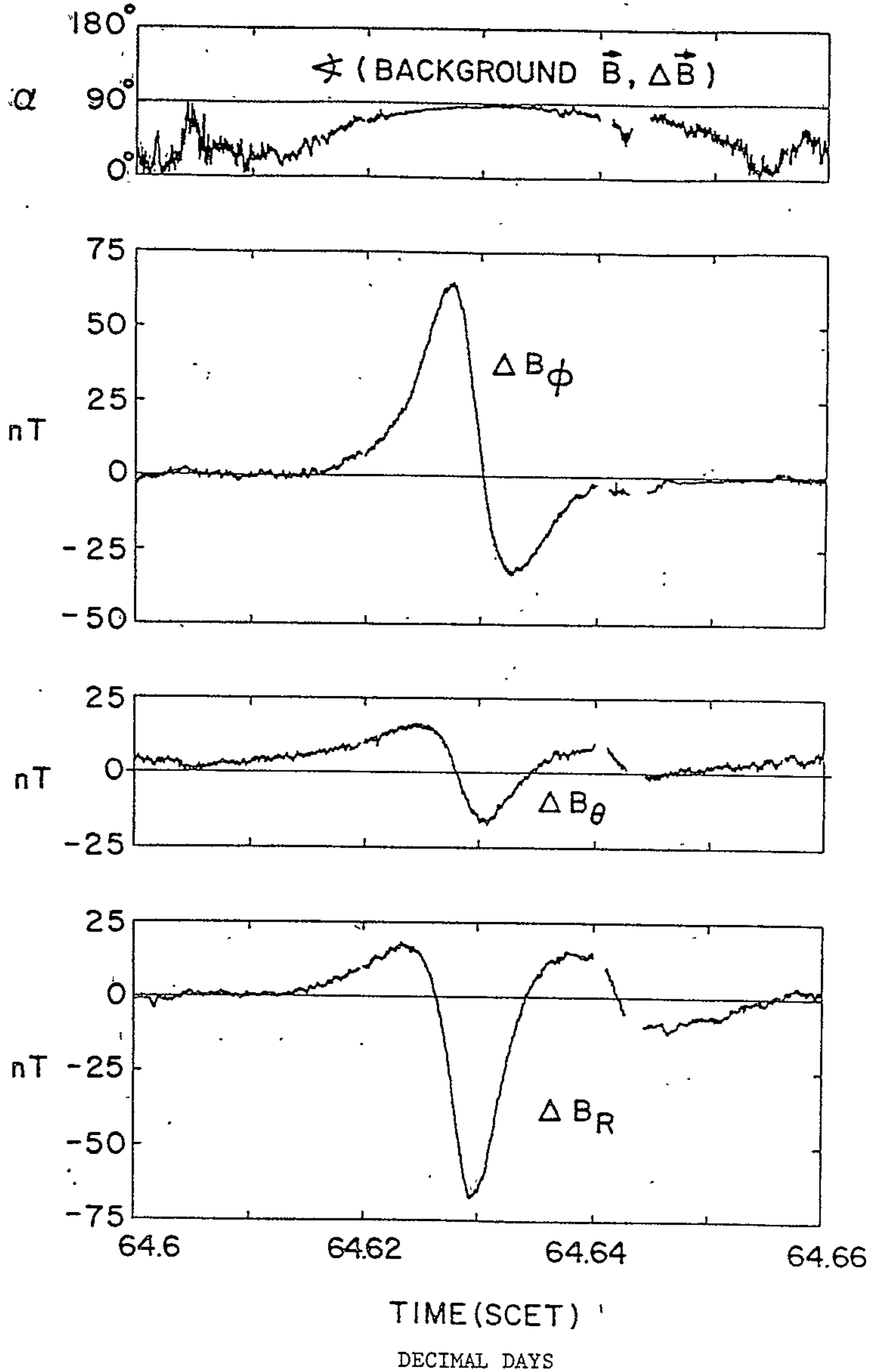
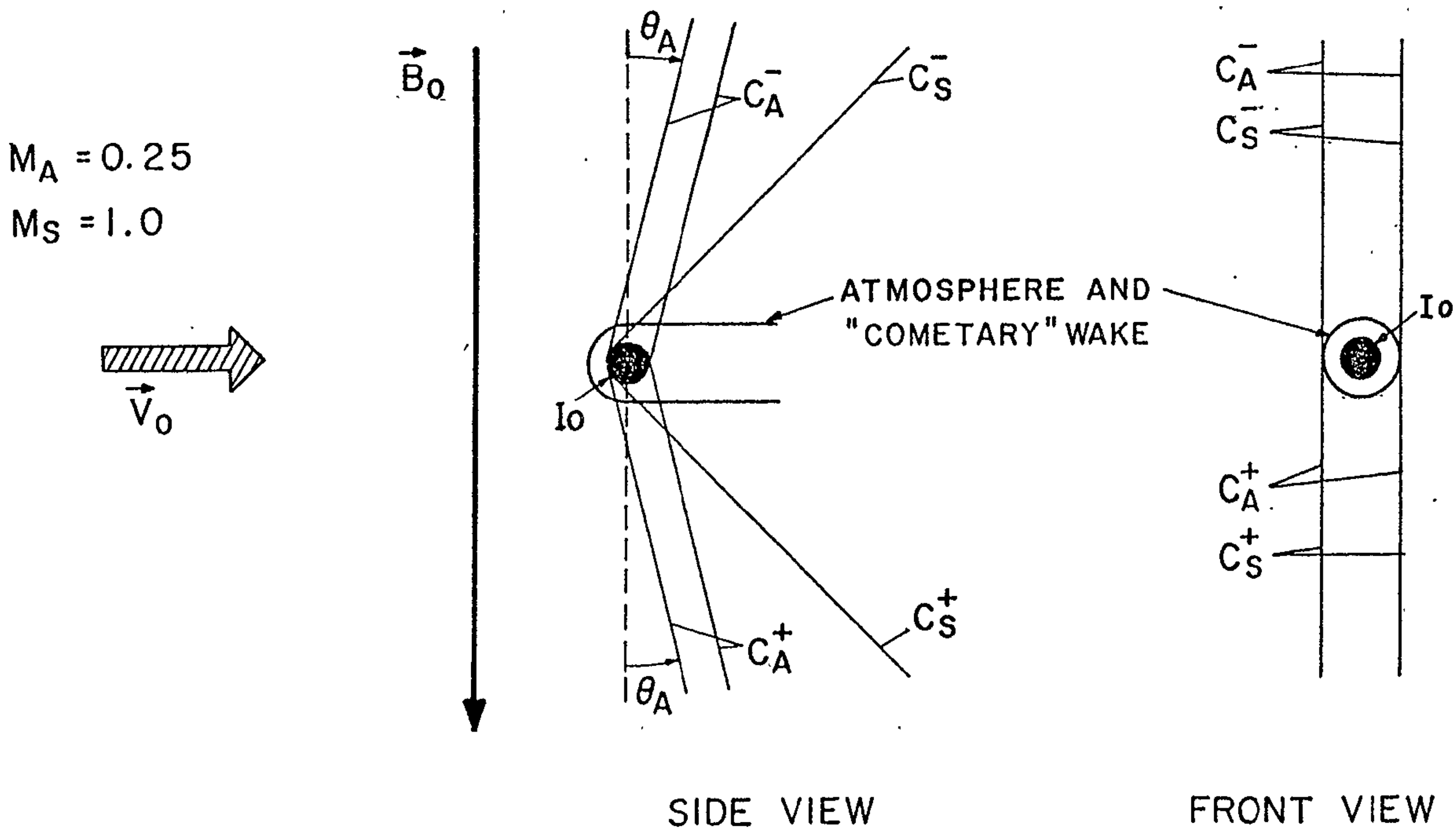

Z_A
(ALL UNITS x 10^4 KM)
3
2
1
IO
IO's ORBITAL MOTION
1
2
3
4
X_A
1
2
3
Y_A
TO JUPITER
1540
1520
1500
1440
1420 SCET
VOYAGER I TRAJECTORY
DAY 64, 1979

FIGURE 2


VOYAGER 1 DAY 64, 1979 - Io CURRENT SYSTEM
1.92 SECOND AVERAGES
-100
-150
-200
-250
nT
Bφ
MODEL BACKGROUND FIELD
2300
2100
1900
1700
1500
1300
nT
|B|
Bθ
-525
-575
-625
nT
BR
64.6
64.62
64.64
64.66
TIME (SCET)
DECIMAL DAYS

VOYAGER 1 DAY 64, 1979 - Io CURRENT SYSTEM





$M_A = 0.25$
$M_S = 1.0$
$\vec{V}_0$
$\vec{B}_0$
$\theta_A$
$C_A^-$
$C_S^-$
$C_A^+$
$C_S^+$
$\theta_A$
Io
ATMOSPHERE AND
"COMETARY" WAKE
Io
$C_A^-$
$C_S^-$
$C_A^+$
$C_S^+$
SIDE VIEW
FRONT VIEW


FIGURE 5

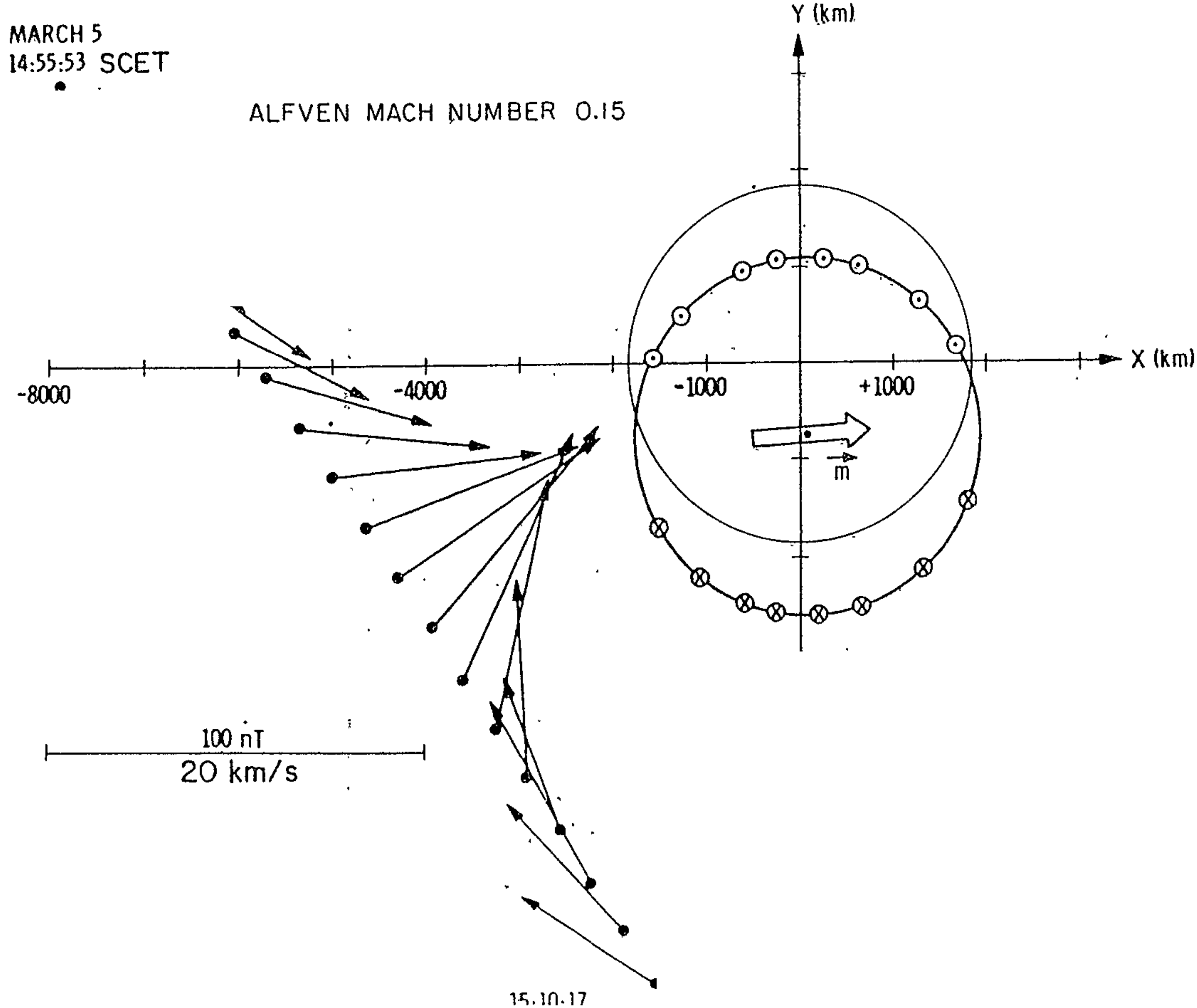

MARCH 5
14:55:53 SCET
ALFVEN MACH NUMBER 0.15
Y (km)
X (km)
-8000
-4000
-1000
+1000
m
100 nT
20 km/s
15:10:17

FIGURE 6

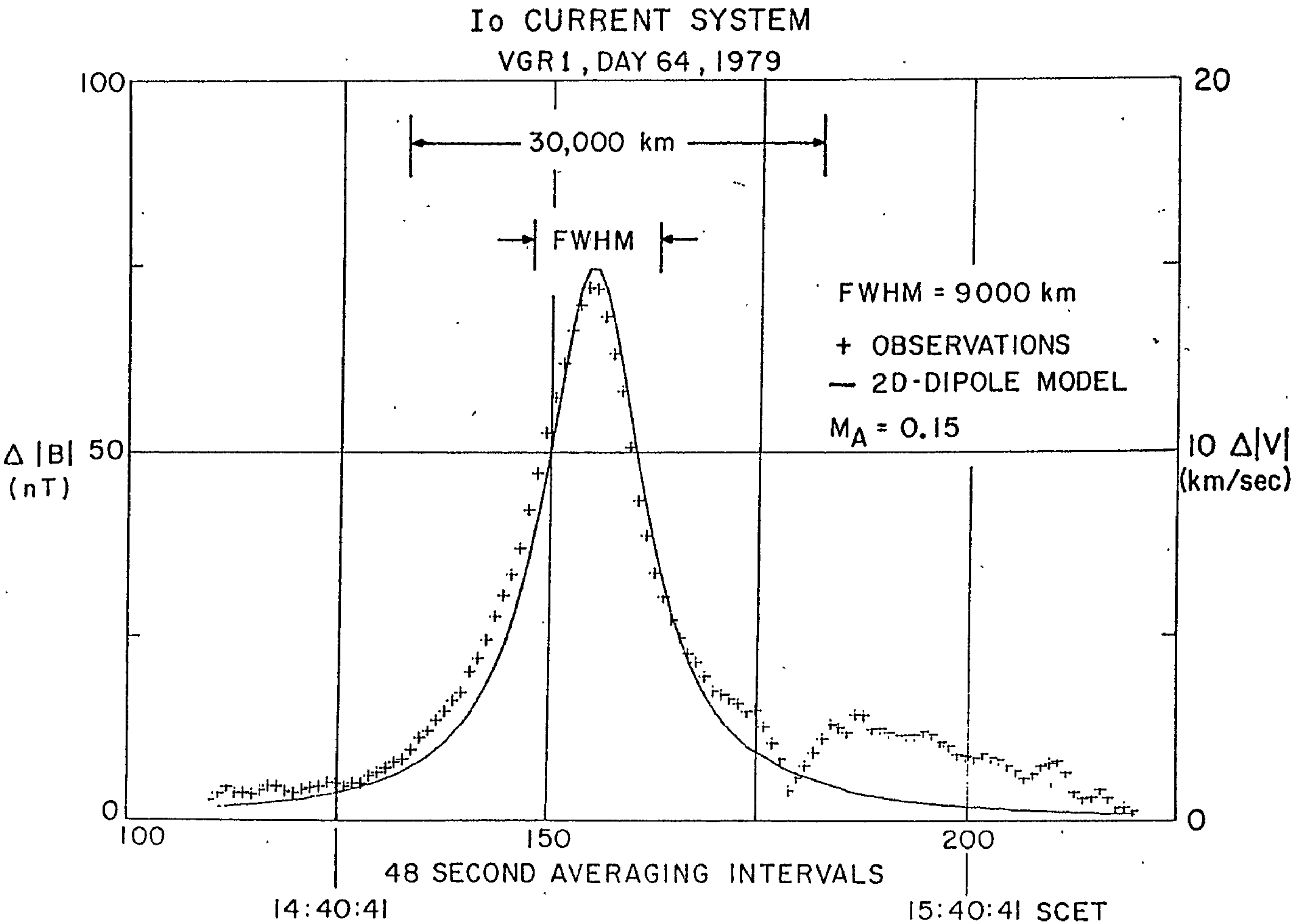

Io CURRENT SYSTEM
VGR1, DAY 64, 1979
30,000 km
FWHM
FWHM = 9000 km
+ OBSERVATIONS
— 2D-DIPOLE MODEL
$M_A$ = 0.15
Δ |B| (nT)
10 Δ|V| (km/sec)
100
50
0
20
10
0
100
150
200
48 SECOND AVERAGING INTERVALS
14:40:41
15:40:41 SCET

FIGURE 7a

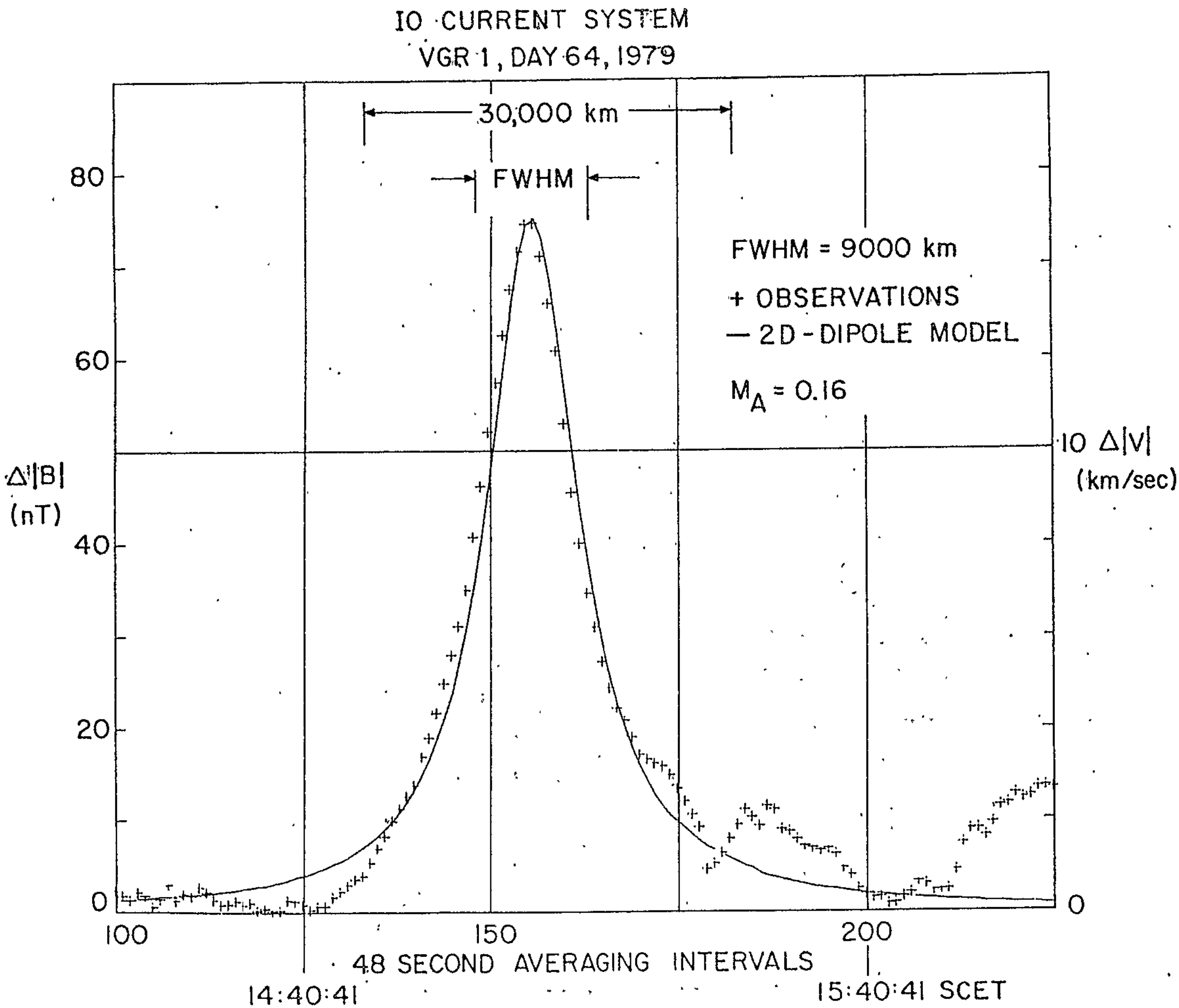

IO CURRENT SYSTEM
VGR 1, DAY 64, 1979
30,000 km
FWHM
FWHM = 9000 km
+ OBSERVATIONS
— 2D-DIPOLE MODEL
$M_A$ = 0.16
Δ|B| (nT)
10 Δ|V| (km/sec)
0
20
40
60
80
100
150
200
48 SECOND AVERAGING INTERVALS
14:40:41
15:40:41 SCET

FIGURE 7b

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16. Abstract

The enigmatic control of the occurrence frequency of Jupiter's decametric emissions by the satellite Io has been explained theoretically on the basis of its strong electrodynamic interaction with the co-rotating Jovian magnetosphere leading to field aligned currents connecting Io with the Jovian ionosphere. Direct measurements of the perturbation magnetic fields due to this current system were obtained by the GSFC magnetic field experiment on Voyager 1 on 5 March 1979 when it passed within 20,500 km south of Io. An interpretation in the framework of Alfven waves radiated by Io leads to current estimates of $2.8 \times 10^6$ amps. A mass density of 7400 to 13600 proton mass units per $cm^3$ is derived which compares very favorably with independent observations of the torus composition characterized by 7-9 proton mass units per electron for a local electron density of 1050 to 1500 $cm^{-3}$. The power dissipated in the current system may be important for heating the Io heavy ion torus, inner magnetosphere, Jovian ionosphere and possibly the ionosphere or even the interior of Io.

| | |
|---|---|
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