NASA

Technical Memorandum 83882

Voyager I Assessment of Jupiter's Planetary Magnetic Field

J. E. P. Connerney, M. H. Acuna,
and N. F. Ness

DECEMBER 1981

National Aeronautics and
Space Administration

Goddard Space Flight Center
Greenbelt, Maryland 20771

(NASA-TM-83882) VOYAGER 1 ASSESSMENT OF JUPITER'S PLANETARY MAGNETIC FIELD (NASA) 20 p HC A02/MF A01 CSCL 03B
N82-18105
Unclas
G3/91 11734

VOYAGER 1 ASSESSMENT OF JUPITER'S PLANETARY MAGNETIC FIELD

J. E. P. Connerney, M. H. Acuña and N. F. Ness
NASA/Goddard Space Flight Center
Laboratory for Extraterrestrial Physics
Greenbelt, Maryland 20771

ABSTRACT

A new estimate of Jupiter's planetary magnetic field is obtained from the Voyager 1 observations of the jovian magnetosphere. An explicit model for the magnetodisc current system is combined with a spherical harmonic model of the planetary field with both sets of parameters determined simultaneously using a non-linear generalized inverse methodology. The resulting model fits the observations extremely well throughout the analysis interval (r < 20 Jovian radii). The Jovian internal field model obtained from the Voyager 1 data is very similar to the octopole Pioneer 11 models. The best fitting magnetodisc lies in the centrifugal equator, 2/3 of the way between the rotational and magnetic equators, as appropriate for centrifugal loading of the magnetosphere by a cold plasma. No statistically significant evidence is found for secular change of the equivalent dipole estimated from Pioneer 11 (1974.9) and Voyager 1 (1979.2) data.

INTRODUCTION

The Voyager 1 (V1) encounter with Jupiter in March 1979 was the third of four such encounters to provide detailed in situ observations of the Jovian magnetosphere. The low-latitude approach of Pioneer 10 in December 1973 to within 2.8 Jovian Radii planetocentric distance (1 R_J = 71323 km) provided the first observations of the Jovian magnetodisc (Smith et al., 1974; Van Allen et al., 1974) as well as the first estimates of Jupiter's internal magnetic field based on in situ observations (Smith et al., 1974). The high-latitude, retrograde approach of the Pioneer 11 (P11) spacecraft to within ~ 1.6 R_J in December 1974 proved to be the most favorable for the estimation of Jupiter's internal field and led to spherical harmonic magnetic field models based on the vector helium magnetometer observations (Smith et al., 1976) and the high field fluxgate magnetometer observtions (Acuna and Ness, 1976).

Preliminary attempts to obtain an internal field model from V1 magnetometer observations (Ness et al., 1979) were frustrated by the large periapsis of V1 relative to P10 and P11 (4.9 versus 2.8 and 1.6 R_J) and the ubiquitious presence of a large scale equatorial current system associated with the Jovian magnetodisc. This disc-like system of eastward azimuthal currents extends from inside the orbit of Io (at 5.9 R_J) outward to ~ 50 R_J and beyond (Connerney et al., 1981). The 9.6° tilt of Jupiter's magnetic dipole with respect to the rotation axis and the near-equatorial approach of Voyager 1 resulted in the periodic immersion of the Voyager spacecraft in the current-carrying region as it traversed the inner Jovian magnetopshere. Thus the traditional methods of analysis of such data, utilizing orthogonal spherical harmonic functions to represent the magnetic field, are not applicable since they require that the observations be obtained in a source free (current-free) region of space. This is equivalent to the assumption that the magnetic field is derivable from a scalar potential function.

Connerney (1981) demonstrated how small errors or unmodeled contributions to the observed magnetic field (such as those due to local current systems) can lead to large errors in derived magnetic field models. It is therefore essential to interpret the Voyager observations within the context of a model which is as representative of the physical situation as possible. Connerney (1981) introduced such a model for the analysis of magnetic field observations at Jupiter, incorporating explicitly the field contribution of large-scale external current systems in the Jovian magnetosphere. The observed field is modeled as the sum of two components. The planetary field is derivable from a scalar potential and represented by the usual spherical harmonic expansion. The external field, due to the distributed currents in Jupiter's magnetosphere is derived from an appropriate vector potential. The parameters of both the model external current system and the model internal field are then determined simultaneously by inversion of the magnetic field observations. From the Voyager 1 observations we are thus able to obtain an estimate of Jupiter's internal magnetic field at epoch 1979.2 as well as a characterization of the magnetodisc current system. We assume that the field of the external current system does not vary appreciably during the encounter period. Such a variation could possibly masquerade as a spatial variation of the field which would be reflected and not identified correctly in both sets of model parameters.

METHODOLOGY

The two essential (and novel) features of our analysis of the Voyager magnetic field observations are (1) the use of a model in which external currents are explicitly represented and (2) the use of generalized inverse techniques to obtain a satisfactory solution. Both are described in detail by Connerney (1981) as applied to the analysis of Pioneer 11 observations at Jupiter; we will only outline the methodology as it applies to the Voyager observations and as it has been extended for the present analysis.

The model field is represented as the sum of an internal field B' derivable from a scalar potential and an external field b due to magnetodisc currents

$$B = B' + b.$$

The internal magnetic field B' is expressed as the gradient of a scalar potential function V, $B' = -\nabla V$, where

$$V = a \sum_{n=1}^{n_{max}} (a/r)^{n+1} \sum_{m=0}^{n} P_n^m (\cos\theta) \{ g_n^m \cos(m\phi) + h_n^m \sin(m\phi)\}$$

r is the distance to the planet's center, a is the planetary radius, θ and ϕ are co-latitude and longitude, respectively; the P_n^m are the associated Legendre functions with Schmidt normalization, and the g_n^m, h_n^m (Schmidt coefficients) are the internal field parameters.

Following Connerney et al. (1981) we assume that external azimuthal currents of the magnetodisc are confined to an azimuthally symmetric, planetocentric annular disc (Figure 1). The disc model parameters are the inner and outer edge radii R_0 and R_1, the disc half-thickness D, and a scale constant I_0 for the current density, which varies inversely with distance from Jupiter. Two additional free parameters θ_0 and ϕ_0 specify the orientation of the current disc with respect to Jupiter (System III 1965): the normal to the current disc makes an angle θ_0 with Jupiter's rotation axis and lies in the ϕ_0 (west) longitudinal meridian. The external field b due to these currents is computed numerically.

With the addition of the magnetodisc current system, the model magnetic field is no longer linear in the model parameters and we must use an iterative inversion technique described by Connerney (1981), appropriately modified to accommodate the parameters of the current disc as free parameters. The linearized system to be solved at each iteration is

$$y = Ax$$

where y is a column vector of the model residuals (the observed minus modeled field), x is a column vector consisting of the parameter corrections required to bring the model into closer agreement with the data, and the matrix A is a matrix of partial derivatives of the model field with respect to the model parameters. The vector y is of length N, x is of length M, and A is an N by M matrix, where N is the number of (component) magnetic field observations, and M is the number of free parameters

$$M = (n_{max} + 1)^2 - 1 + 6$$

associated with the internal field expansion to order n_{max} and the 6 parameters of the current disc. Inclusion of the disc parameters R_o R_1, D, I_o, θ_o and ϕ_o requires a transformation (scaling) of the parameter vector (not discussed by Connerney (1981); see, e.g., Lawson and Hanson (1974)):

$$x_i' = x_i/\sigma_i$$

where σ_i is the expected standard deviation of the parameter correction x_i. We adopt a relative scaling of $\sigma_i = 1$ for the internal field parameter corrections (Δg_n^m, Δh_n^m) and suitably chosen σ_i for the corrections to the disc parameters such that in program units the components of the solution vector x are approximately equal in magnitude. Additionally the partial derivatives of the model with respect to the parameters of the model current disc (rightmost 6 columns of the A matrix) must be computed numerically, as is the model field.

With these modifications, the method of constructing solutions outlined in Connerney (1981) is used. We choose an internal spherical harmonic expansion of order $n_{max} = 3$ to facilitate direct and meaningful comparisons of V1 internal field models with previous models (of internal order 3) obtained from P11 observations. Our model thus has 21 free parameters, not all of which will be determined from the available V1 observations; the interpretation of such insufficient data requires the construction of partial solutions. The singular value decomposition of Lanczos (Lanczos, 1961) is used to reformulate the problem in terms of independent parameter vectors (eigenparameters) which are linear combinations of the original model parameters. A solution is constructed by summation over a subset of the eigenparameters, starting with a few well determined parameter vectors and successively increasing the number of eigenparameters in the solution. As additional eigenparameters are added, more of the original model parameters are resolved; eventually reaching a point where the remaining parameter vectors are so poorly determined (due to the limited observations) that inclusion seriously degrades the solution. The partial solution constructed in this way represents the best available estimate of the solution, and it is understood that the remaining parameter vectors (not used in the solution) are undetermined.

RESULTS

Our Voyager 1 data set selected for inversion consists of ~ 500 vector observations of the magnetic field taken every 6 minutes during the interval from ~ hour 16 day 63 to ~ hour 8 day 65, during which the radial distance of Voyager 1 from Jupiter ranged from 20 R_J to the close approach (hour 12, day 64) distance of ~ 4.9 R_J. Each observation is a 48 second average of vector observations obtained every 60 msec with an estimated accuracy of 0.2 nT ±0.1% of full scale (Ness et al., 1979). The more distant observations that are less sensitive to the internal field parameters are included because they greatly improve the resolution of the current disc parameters. Improved resolution of the current disc parameters leads to a more confident separation of internal and external (local) fields and ultimately an improved internal field model. More traditional analyses of such data that do not explicitly include models of the external current system (e.g., Acuña and Ness (1976);

Acuña et al., (1981); Smith et al., (1976)) limit the observations used to r < 8 or 10 R_J in an attempt to minimize the impact of such external field contributions.

The iterative inversion technique requires an initial parameter set about which the problem is considered to be sufficiently linear locally that successive applications of the linear generalized inverse techniques result in a convergent solution. We selected as initial models simple tilted dipole internal fields (n = 1 terms) combined with the V1 model magnetosphere current disc parameters (Connerney et al. (1981)). Several dipolar internal field models, intentionally displaced from the lowest order dipole obtained from P11 observations, were used to demonstrate that the final solution did not depend on the initial model. A typical initial internal field model is characterized by the parameter set $g_1^0 = 4.0$ G, $g_1^1 = .3$ G, $h_1^1 = .3$ G, $g_n^m = 0$ and $h_n^m = 0$ for all n > 1, corresponding to a simple dipole tilted by 6° towards a System III longitude of 225°. By comparison, the P11 dipoles are typically tilted by ~10° towards λ_{III} of ~ 200°.

After 12 iterations we obtain the solution listed in Table 1. No entry is made in the table for the model parameters that are unresolved (defined as parameters with corresponding resolution matrix elements of $R_{xx} < 0.95$; (see, e.g., Connerney (1981); Wiggins (1972); or Jackson (1972)). For comparison we list in Table 1 several models based on the Pioneer 11 observations; in general an excellent agreement is found between the V1 parameters and those of the P11 based models. The unweighted RMS of the V1 model residuals throughout the entire data interval of R < 20 R_J is 7.8 nT. The quantity ϵ listed with the V1 model internal field parameters corresponds to an estimated 2σ error assuming uncorrelated errors; the true estimated errors are certainly greater than ϵ since the errors are in fact correlated. But the quantity ϵ is expected to give some indication of the relative errors among the parameters and are presented for that purpose.

The resulting parameters of the current disc are not unlike those quoted by Connerney et al. although that model was not an optimal fit to the observations. The most interesting difference between the two is that the V1 optimal fit yields a current disc which is not coincident with the magnetic equator (tilted by 9.6° from the rotation axes) but instead is tilted by 6.5°, approximately 2/3 of the way between the rotation axis and the magnetic equator.

An illustration of how well the model fits the Voyager 1 observations is shown in Figure 2. The perturbation field $\Delta\vec{B}$ is the difference between the observed magnetic field at any position and the field of internal origin as obtained from the model fit. The dashed line is the field of the model current disc; the difference between the observations and the dashed line represents the residuals, i.e., the model misfit. This representation is chosen to emphasize the relative magnitude of the field due to the local magnetodisc currents, and it facilitates an interpretation of the remaining model residuals. The residuals are very small for $r < 10\ R_J$; most of the 7.8 nT RMS residuals appears at larger radial distances where the field of the external currents is a large fraction of the total field. The residuals for $r < 10\ R_J$ are an exceedingly small fraction of the total field, which grows to 3330 nT at close approach (4.9 R_J). The very large and localized feature evident at day 64 hour 15 is the signature of the intense current system generated by the interaction of the Jovian magnetosphere with the satellite Io (Ness et al., 1979; Acuña et al., 1981).

DISCUSSION

The model of Jupiter's internal magnetic field at epoch 1979.2 obtained from the Voyager 1 observations bears a very close relationship to the epoch 1974.9 models obtained from Pioneer 11 observations. In general, the parameters (e.g., g_1^1, h_1^1) that are expected to be relatively well determined are indeed the most consistent. The close correspondence between the dipole terms (n = 1) of the Voyager 1 model and the (Pioneer 11) O_4 model is particularly striking. The V1 and O_4 dipole terms g_1^0, g_1^1 and h_1^1 differ by only 0.24, 0.61 and 1.2%, respectively. These differences are much smaller than the estimated parameter uncertainties. It is interesting to note that the Voyager 1 parameters which do not agree as well with the Pioneer 11 models (g_2^0 and g_3^3) are also the subject of some disagreement among the Pioneer 11 models obtained from the two magnetic field experiments onboard Pioneer 11. In comparison, the preliminary estimates of Jupiter's magnetic field obtained from a conventional spherical harmonic analysis of the Voyager 1 observations (Ness et al., 1979) yielded estimates of Jupiter's dipole tilt ranging from 9.6° to 13.3° towards longitudes of 189° to 194°; estimates of the dipole magnitude ranged from 3.76 G-R_J^3 to 4.09 G-R_J^3. P10 models (Smith et al., 1976) bear much less resemblance to either the P11 or V1 model, particularly in the higher order coefficients. It is clear that the Pioneer 10 observations were also heavily influenced by the magnetodisc currents (Connerney et al., 1981).

Among the unresolved V1 model parameters, R_0, the inner current sheet edge, and g_3^0 will almost certainly never be obtainable from the Voyager 1 observations alone. These two parameters are heavily represented in the most poorly determined eigenvector (21), which is ~2 orders of magnitude more poorly determined than any included in the Voyager 1 solution. That is, within the context of the chosen physical model, the observations are simply insufficient to determine the values of these parameters, as a consequence of the spatial distribution of the observations. The difficulty of determining the inner edge of the current sheet (R_0) from Voyager 1 observations was deduced intuitively by Connerney et al. (1981) and is confirmed by the generalized inverse analysis. Independent observations, however, suggest that R_0 is indeed close to 5 R_J: the near axis external field deduced from P11 observations (Smith et al., 1976) is very close to that expected of the current disc of R_0 ~ 5 R_J. The remaining unresolved parameters g_3^1 and h_3^1 are associated with eigenvectors (18 and 19) that are not as discouraging as the most poorly determined eigenvector. It is conceivable that further analysis may provide at least some information about these parameters.

The most interesting result of the optimal fit to the Voyager 1 observations with respect to the current disc in Jupiter's inner magnetosphere is its orientation. The Voyager 1 observations at radial distances of less than 20 R_J are best fit by a current disc not in the magnetic equator, as argued by Connerney et al. (1981), Goertz et al. (1976) and Goertz (1976, 1979), but rather a current disc residing in a plane tilted only ~2/3 of the way towards the magnetic equator. Connerney et al. (1981) noted that the distant V1 observations were insensitive to the disc orientation parameter θ_0 and argued as did Goertz (1976, 1979), that the current sheet resides close to the magnetic equator on the basis of P10 observations.

Prior to any of the Jupiter encounters, Gledhill (1967) predicted that the centrifugal force due to Jupiter's rapid rotation would confine a plasma to a disc-shaped region in a plane tilted by 7° to Jupiter's equator. Hill et al. (1974) referred to that plane as the 'centrifugal symmetry surface' to which cold plasma would be confined (see also Goertz, 1976). For a hot plasma, the pressure gradient and magnetic mirror forces dominate the centrifugal forces (e.g., Goertz, 1976) and the plasma would reside in the magnetic equator. Thus it would appear that, within the context of our model, these results require the current in Jupiter's (inner) magnetosphere to be carried by 'cold' and not 'hot' plasma. However, it is precisely at this level of interpretation that the limitations of our current disc model arise. In particular, the disc thickness is assumed constant in radial distance, and the model azimuthal current is distributed uniformly in $\hat{z}$. While such a model is capable of fitting the observations exceedingly well, it is possible that an equally good fit can be obtained with an alternate model. It may be possible, for example, to adjust the distribution of current in $\hat{z}$ within the disc and the disc orientation to obtain a model field similar to that illustrated in Figure 2 but with a disc oriented in the magnetic equator. Until the physical validity of our present current disc model can be ascertained by a self-consistent treatment of the Jovian plasma and magnetic field, we regard the inferred orientation of the current disc as tentative.

CONCLUSIONS

The kind of model applied herein to the Voyager 1 observations, in which an internal spherical harmonic expansion is combined with an explicit model of the field due to external current systems is regarded as essential to understanding and integrating the magnetic field observations of each of the Jovian encounters. Indeed, the success of the model used is a very encouraging indication of the extent of present knowledge of Jupiter's magnetic field (and external current system). We obtain from the Voyager 1 data a Jovian internal field model for epoch 1979.2 that is independent of the previous Pioneer 11 observations and quite consistent with the epoch 1974.9 Pioneer 11 models.

The Voyager 1 internal field model deduced here should provide a basis for a rational discussion of a possible secular variation of Jupiter's internal field. The striking resemblance between the V1 and O_4 models suggests that Jupiter's internal magnetic field has not changed between the Pioneer 11 encounter in December 1974 and the Voyager 1 encounter in March 1979. For example, equivalent tilted, centered dipoles of the V1 and O_4 models differ by only 0.25% in magnitude, 0.04° in tilt and 0.1° in longitude and these are much smaller than the estimated parameter uncertainties. Thus we find no statistically significant evidence for any secular change. Our goal was to provide the best independent estimate of Jupiter's internal field; a combined fit to various of the data sets available may yield an improved internal field model provided the observations themselves (Voyagers 1 and 2; Pioneers 10 and 11) can be sensibly integrated.

REFERENCES

Acuña, M. H., and N. F. Ness, Results from the GSFC fluxgate magnetometer on Pioneer 11, in Jupiter, ed. T. Gehrels, pp. 830-847, University of Arizona Press, Tucson, AZ, 1976.

Acuña, M. H., F. M. Neubauer, and N. F. Ness, Standing Alfvén wave current system at Io: Voyager 1 observations, J. Geophys. Res., 86, 8513-8523, 1981.

Acuña, M. H., K. W. Behannon, and J. E. Connerney, Magnetic field and magnetosphere, in Physics of the Jovian Magnetosphere, ed. A. J. Dessler, Cambridge University Press, in press.

Connerney, J. E. P., M. H. Acuña, and N. F. Ness, Modeling the Jovian current sheet and inner magnetosphere, J. Geophys. Res., 86, 8370-8384, 1981.

Connerney, J. E. P., The magnetic field of Jupiter: A generalized inverse approach, J. Geophys. Res., 86, 7679-7693, 1981.

Gledhill, J. A., Magnetosphere of Jupiter, Nature, 214, 155-156, 1967.

Goertz, C. K., The current sheet in Jupiter's magnetosphere, J. Geophys. Res., 81, 3368-3372, 1976.

Goertz, C. K., D. E. Jones, B. A. Randall, E. J. Smith, and M. F. Thomsen, Evidence for open field lines in Jupiter's magnetosphere, J. Geophys. Res., 81, 3393-3398, 1976.

Goertz, C. K., The Jovian magnetodisc, Space Sci. Rev., 23, 319-343, 1979.

Hill, T. W., A. J. Dessler, F. C. Michel, Configuration of the Jovian magnetosphere, Geophys. Res. Lett., 1, 1-6, 1974.

Jackson, D. D., Interpretation of inaccurate, insufficient, and inconsistent data, Geophys. J. R. Astr. Soc., 28, 97, 1972.

Lanczos, C., Linear differential operations, 564 pp., D. Van Nostrand Company, Ltd., London, England, 1971.

Lawson, C. L., and R. J. Hanson, Solving least squares problems, 340 pp., Prentice-Hall, Inc., Englewood Cliffs, NJ, 1974.

Ness, N. F., M. H. Acuña, R. P. Lepping, L. F. Burlaga, K. W. Behannon, and F. M. Neubauer, Magnetic field studies at Jupiter by Voyager 1: Preliminary results, Science, 204, 982-987, 1979.

Smith, E. J., L. Davis, Jr., and D. E. Jones, Jupiter's magnetic field and magnetosphere, in Jupiter, ibid., pp. 788-829, 1976.

Smith, E. J., L. Davis, Jr., D. E. Jones, P. J. Coleman, D. S. Colburn, P. Dyal, C. P. Sonnet, and A. M. A. Frandsen, The planetary magnetic field and magnetosphere of Jupiter: Pioneer 10, J. Geophys. Res., 79, 3501-3513, 1974.

Van Allen, J. A., D. N. Baker, B. A. Randall, and D. D. Sentman, The magnetosphere of Jupiter as observed with Pioneer 10: 1. Instrument and principal findings, J. Geophys. Res., 79, 3559-3577, 1974.

Wiggins, R. A., The general linear inverse problem: Implication of surface waves and free oscillations for earth structure, Rev. Geophys. Space Phys., 10, 251, 1972.

		(1979.2) V1 17 ev	(ϵ)	P11 O_4(GSFC)[A]	(2σ)[B]	(1974.9) P11 15 evs[B]	P11 SHA 23[C]	MODEL CURRENT SHEET[D]	
1	g_1^0	4.208	(.032)	4.218	(.030)	4.068	4.092		
2	g_1^1	-.660	(.004)	-.664	(.019)	-.668	-.705		
3	h_1^1	.261	(.005)	.264	(.024)	.243	.231		
4	g_2^0	-.034	(.028)	-.203	(.023)	-.093	-.033		
5	g_2^1	-.759	(.030)	-.735	(.039)	-.672	-.699		
6	g_2^2	.483	(.018)	.513	(.048)	.502	.537		
7	h_2^1	-.294	(.058)	-.469	(.037)	-.498	-.531	NA	
8	h_2^2	.107	(.018)	.088	(.037)	.119	.074		
9	g_3^0	—	(—)	-.233	(.060)	-.111	-.113		
10	g_3^1	—	(—)	-.076	(.083)	-.316	-.585		
11	g_3^2	.263	(.114)	.168	(.080)	.220	.283		
12	g_3^3	-.069	(.054)	-.231	(.082)	-.250	.067		
13	h_3^1	—	(—)	-.580	(.104)	-.476	-.423		
14	h_3^2	.695	(.108)	.487	(.108)	.380	.120		
15	h_3^3	-.247	(.054)	-.294	(.068)	-.228	-.171		
16	R_0	—						5	R_J

17	R_1	56				50	R_J
18	D	3.1	N/A	N/A	N/A	2.5	R_J
19	I	185				225	S/F
20	θ_0	6.5				9.6	DEG
21	ϕ_0	206.				202.	DEG

1965 System III ϕ Positive East
Schmidt normalized spherical harmonic coefficients, Gauss

A. Acuña and Ness (1976): Rotated to 1965 System III
B. Connerney (1981)
C. Smith et al. (1976: Rotated to 1965 System III
D. Connerney et al. (1981)

FIGURE CAPTIONS

FIGURE 1. A cross-section of the model current disc.

FIGURE 2. Comparison of modeled perturbation magnetic field (dashed) with that observed for Voyager 1 (spherical coordiantes are used). In this presentation the model internal field has been subtracted from the observations; the total field at closest approach (C.A.) is ∼ 3330 nT.

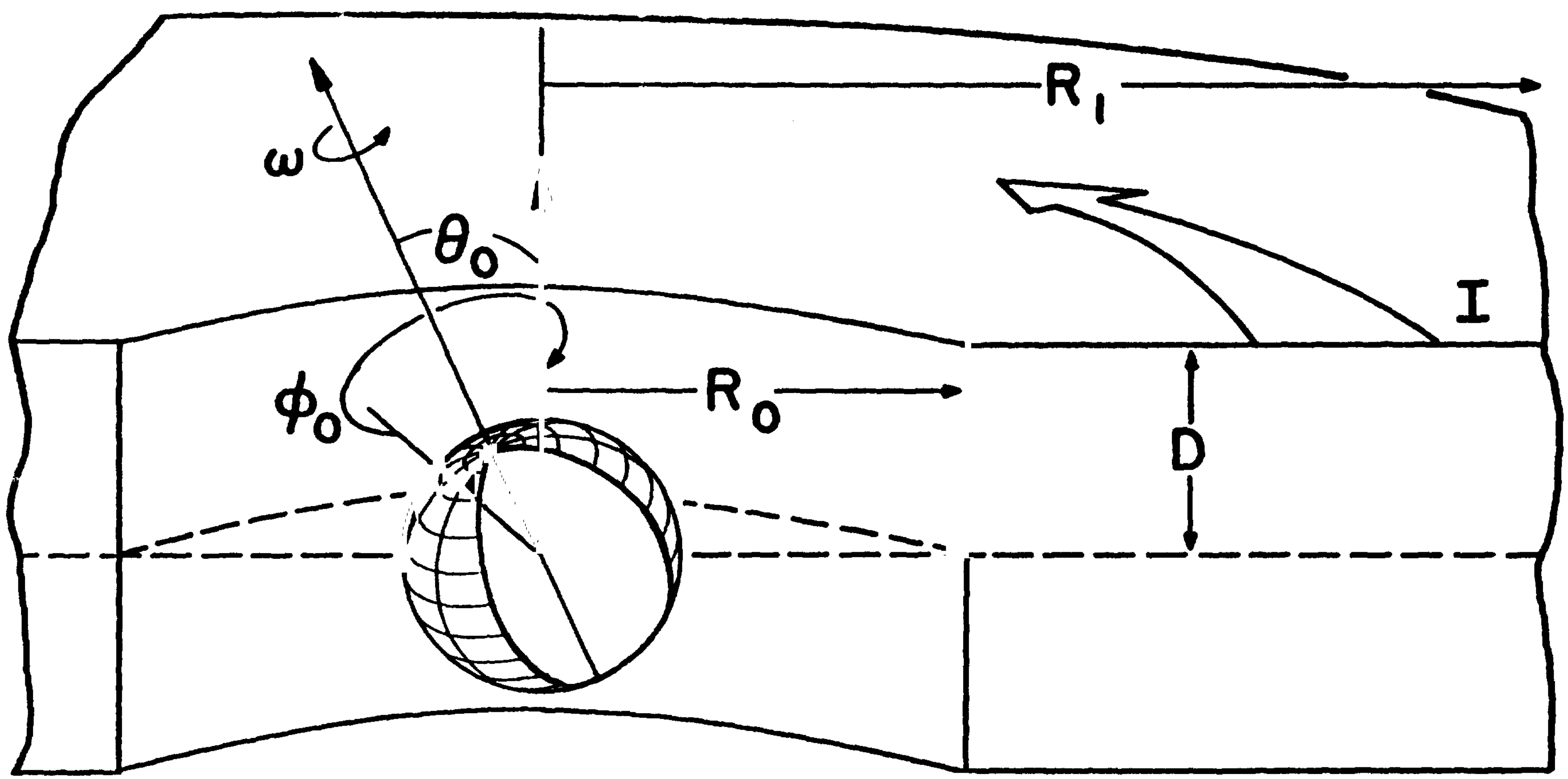

FIGURE 1

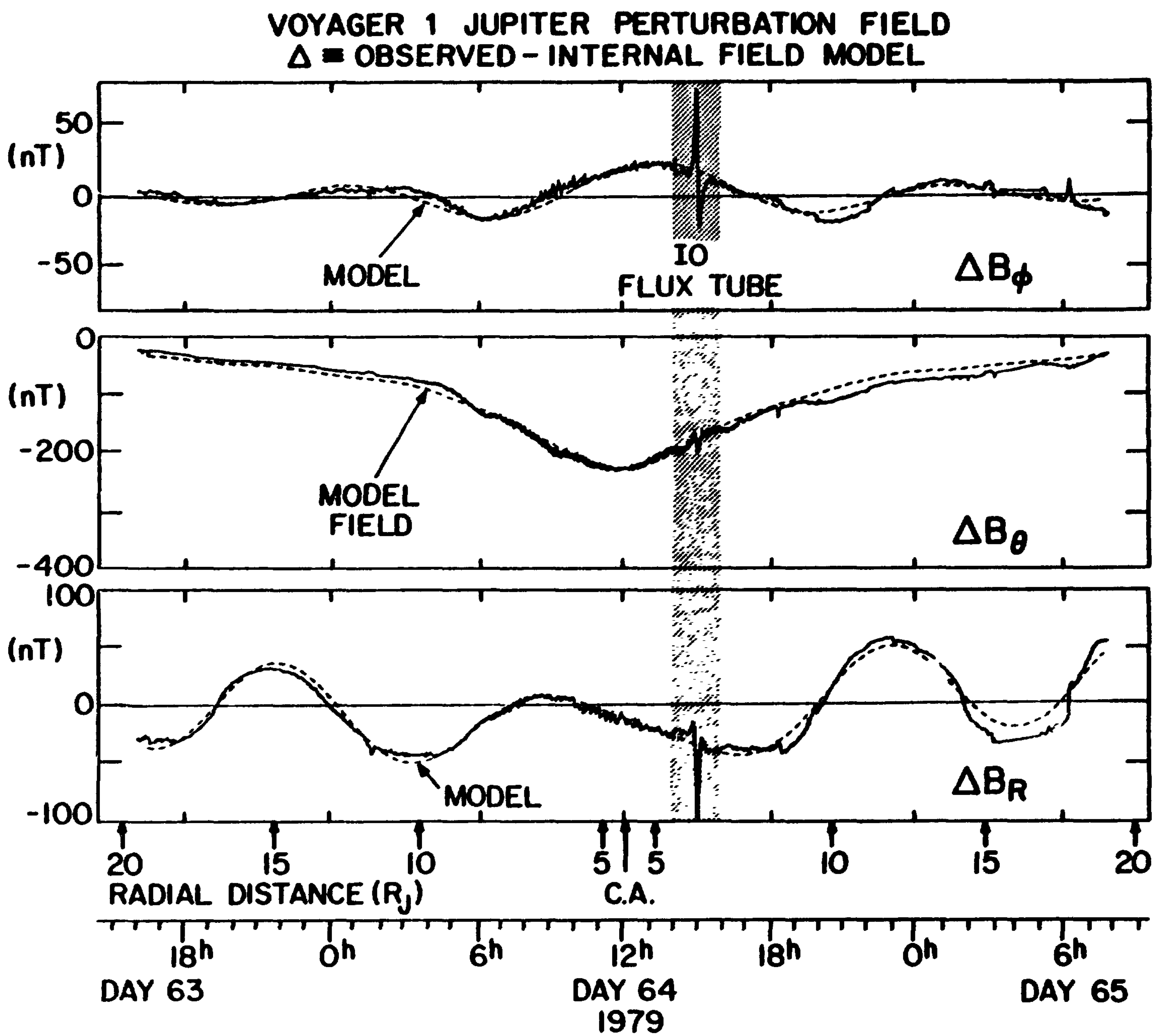
VOYAGER 1 JUPITER PERTURBATION FIELD
Δ ≡ OBSERVED - INTERNAL FIELD MODEL
50
(nT)
0
-50
MODEL
IO
FLUX TUBE
ΔBφ
0
(nT)
-200
-400
MODEL
FIELD
ΔBθ
100
(nT)
0
-100
MODEL
ΔBR
20
15
10
5
5
10
15
20
RADIAL DISTANCE (RJ)
C.A.
18h
0h
6h
12h
18h
0h
6h
DAY 63
DAY 64
1979
DAY 65

FIGURE 2