

Reanalysis of Saturn's magnetospheric field data view of spin-periodic perturbations

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[1] Periodic perturbations with their period close to that of planetary rotation are observed in most of the magnetic field data from Saturn's magnetosphere. These data arise from the three spacecraft encounters with Saturn (Pioneer 11, Voyager 1 and 2). The long-held view that no planetary spin-periodic modulation was present in the magnetic field observations is thus not true. Here we present several new pieces of information obtained from a careful analysis of the magnetic field data in view of this peculiar periodic feature. First, by simple considerations of the magnetic field morphology, we argue that these perturbations cannot be directly due to the planetary intrinsic field. Also, we analyze by means of two-dimensional (2-D) hodographs the rotation of the magnetic field vector, expressed in an inertial planetocentric spherical polar coordinate system, and obtain a definitive argument against the possibility of a dipole tilt signature. In addition, we find that the inbound and outbound Pioneer 11 observations of the perturbations are nearly in phase (once the spatial distance is accounted for), indicating that this periodic feature is of a global nature. Finally, we discuss the fact that in the same data set, the magnetopause position in the dawn sector seems to be modulated in phase with the radial component of the perturbation magnetic field. *INDEX TERMS*: 2756 Magnetospheric Physics: Planetary magnetospheres (5443, 5737, 6030); 2740 Magnetospheric Physics: Magnetospheric configuration and dynamics; 5734 Planetology: Fluid Planets: Magnetic fields and magnetism; 6275 Planetology: Solar System Objects: Saturn; *KEYWORDS*: Saturn, magnetosphere, Pioneer, Voyager, periodicity, magnetic

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1. Introduction

[2] Saturn's magnetic field has been observed by only three flyby missions in the past, namely Pioneer 11, Voyager 1 and Voyager 2 (in 1979, 1980 and 1981, respectively), hence the spatial and temporal coverage have been rather limited. Models of the magnetic field, using all three data sets, showed the planetary intrinsic field to be mainly dipolar, with its polarity opposite to that of the Earth [e.g., *Connerney et al.*, 1984]. Two widely used models of Saturn's magnetic field ("Z₃ + ring current" [*Connerney et al.*, 1982, 1983] and "SPV" [*Davis and Smith*, 1990]), are both axisymmetric and have the dipole and rotation axes exactly aligned. These results are not questioned in this article, but are instead used as the background for the following analysis, which is motivated by a recent report of periodic perturbations with their period close to that of

planetary rotation, observed in the magnetic field data from Pioneer 11 and Voyager 2 [*Espinosa and Dougherty*, 2000]. The long-held view that no planetary spin-periodic modulation was present in the magnetic field observations is thus not true. The work presented here consists of a thorough examination of the data in order to characterize as much as possible this periodic feature that is challenging our understanding of Saturn's magnetosphere. Hereafter we show that the perturbations are present throughout the magnetosphere in the cases of Pioneer 11 and Voyager 1, and absent only from the Voyager 2 outbound pass magnetic field data. Then, by considering the magnetic field morphology, we argue that these perturbations cannot be directly due to the planetary intrinsic field. Besides, the analysis of the magnetic field rotation, by means of two-dimensional (2-D) hodographs of the field vector expressed in an inertial planetocentric spherical polar coordinate system, provides a definitive argument against the possibility of a dipole tilt signature. In addition, we obtain evidence that this periodic feature is of a global nature from the fact that the inbound and outbound Pioneer 11 observations of the perturbations are nearly in phase (once the spatial distance is accounted for). Finally, considering the same data set we propose that

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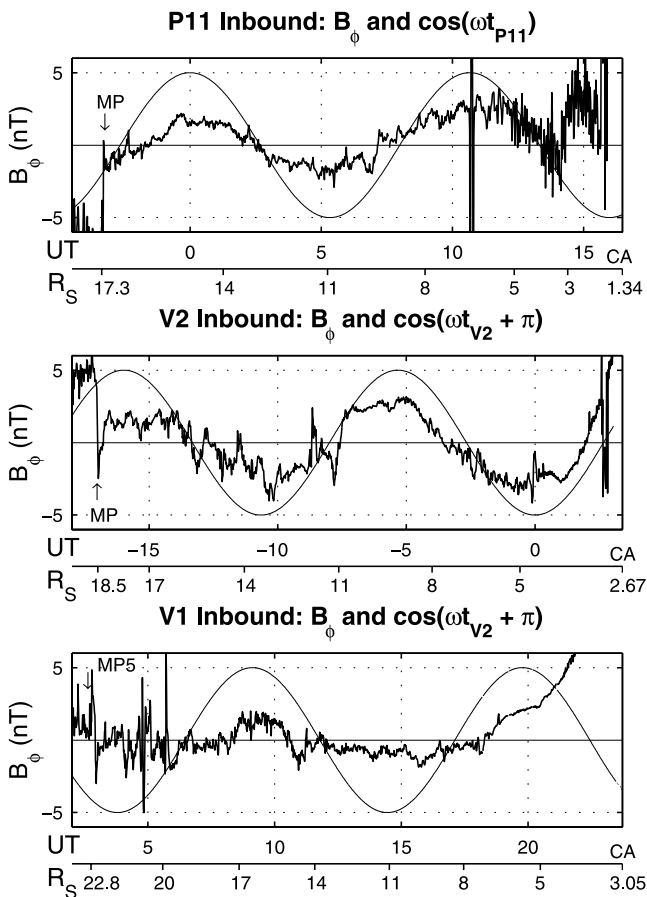


Figure 1. Azimuthal component of the magnetic field as a function of time (hours) and planetocentric distance ($1 R_S = 60,330$ km) for Pioneer 11, Voyager 2 and Voyager 1 inbound, from the MP crossing ($17.3 R_S$, $18.5 R_S$ and $22.8 R_S$, respectively) to CA ($1.34 R_S$ on 1 September 1979, $2.67 R_S$ on 26 August 1981 and $3.05 R_S$ on 12 November 1980, respectively). In the two top plots a sinusoidal function is superimposed, fitted on each occasion to the 48 s averaged data with a different phase, and with a period equal to the accepted planetary rotation period of 10 hr 39 min 24 s. In the case of Voyager 1, the sinusoid is extrapolated from the Voyager 2 time reference [Espinosa and Dougherty, 2001].

the magnetopause position in the dawn sector seems to be modulated in phase with the radial component of the perturbation magnetic field.

2. Observations

[3] To facilitate the qualitative study and the comparison between the observations from each mission, all the magnetic field data must be expressed in a suitable standard coordinate system. We use an inertial (i.e., not rotating with the planet) planetocentric spherical polar coordinate system, with the (\mathbf{r}) axis pointing away from Saturn to the spacecraft, the (θ) axis based on the rotation axis of the planet and the (ϕ) axis based on the direction of planetary rotation. In this system B_r , B_θ and B_ϕ are the radial, colatitudinal and azimuthal components of the magnetic field vector respectively. Accordingly, Figure 1 (adapted from Espinosa and

Dougherty [2001]) shows the inbound magnetic field measurements from Pioneer 11, Voyager 1 and Voyager 2 in this coordinate system, as function of time and planetocentric distance. The plots extend from the inbound magnetopause (MP) crossing (there was only one for Pioneer 11 and Voyager 2, and the last of five for Voyager 1 is shown here) to closest approach (CA) (cf. the figure caption for the respective distances).

[4] Since the models of Saturn's internal magnetic field are axisymmetric and have no dipole tilt, no B_ϕ is predicted by this source. However, the azimuthal component of the magnetic field measured by the Vector Helium Magnetometer (VHM) onboard Pioneer 11 and the Fluxgate Magnetometer (FGM) onboard Voyager 2 clearly present the spin-periodic perturbation from the inbound MP, to CA. In the two top plots a sinusoidal function is superimposed, fitted on each occasion to the data with a different phase, and with a period equal to the accepted planetary rotation period of 10 hr 39 min 24 s (obtained from the Voyager radio emissions data [Desch and Kaiser, 1981]). It is also clear that the signature in the Voyager 1 FGM measurements is much weaker, although possibly present from $19 R_S$ down to $8 R_S$, and then changes configuration ($1 R_S = 60,330$ km). Only the B_ϕ component has been shown. In fact, the B_r and B_θ components do not show spin-periodicities in any of the three inbound passes.

[5] A natural next step would be to organize the data with respect to the subspacecraft SLS longitude (Saturn Longitude System, as defined by Desch and Kaiser [1981]), and for instance carry out a phase comparison of the perturbation observed by the different spacecraft. This would seem appropriate if there is a source fixed with respect to the planet that would produce the observed modulation. Nevertheless, there are two problems preventing us from obtaining useful information, the longitude smearing, due to our level of knowledge and the second is the fact that the magnetosphere itself is not a rigid medium. The latter does not preclude periodicity but the phase may not be tightly preserved.

[6] The longitude smearing is due to the uncertainty placed on Saturn's rotation period, initially reported as ± 7 s [Desch and Kaiser, 1981]. Later reports of the rotation period deduced from the Ulysses spacecraft observations, suggest that it is not constant in time and may differ by 1% from that measured by Voyager [Galoiseau and Lecacheux, 2000]. In these circumstances, the cumulative uncertainty becomes rapidly too large for a secure SLS correlation between each spacecraft pass. For example, if we use the 10 hr 39 min 24 ± 7 s rotation period for an extrapolation between the Voyager 1 and Voyager 2 encounters, there is an uncertainty of more than 40° . It follows that the sinusoid shown in the bottom plot of Figure 1 is only indicative.

[7] For the outbound passes, an equivalent perturbation is evident only in the Pioneer 11 data, in the radial and azimuthal components of the field. We show this in Figure 2. The field is perturbed from CA to the first MP crossing (at $30 R_S$, hour 56). As done for the inbound data, a sinusoidal function is superimposed on each component with a period equal to the planetary rotation period and a phase difference of $\pi/2$. The fit is relatively good until about hour 43 ($\sim 22 R_S$), which means that the two components are in phase quadrature (this property will be analyzed in the next section). Afterward, B_r ,

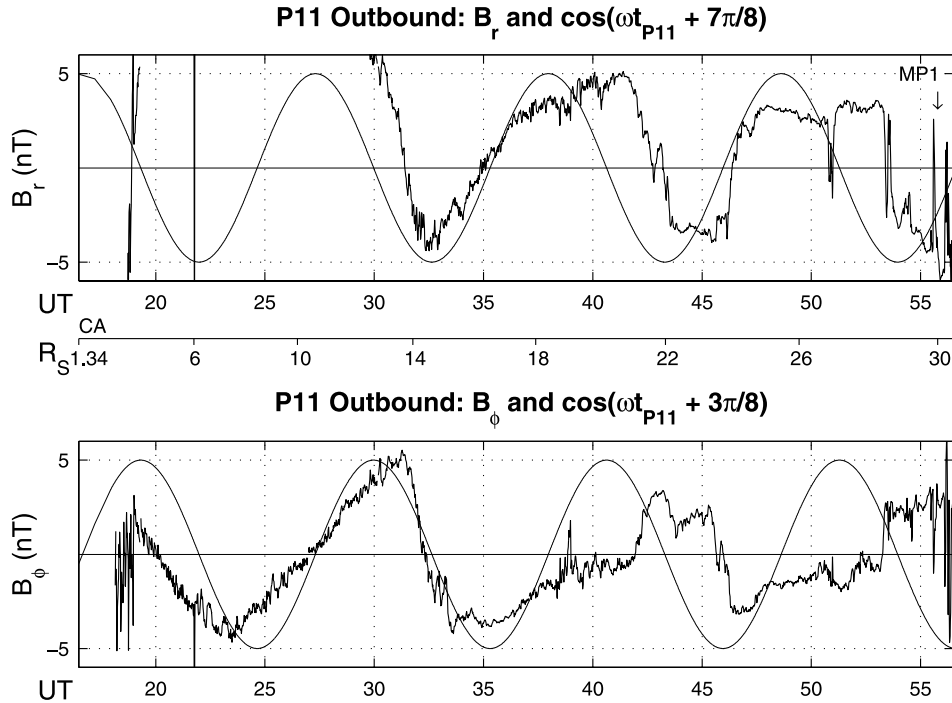


Figure 2. Radial and azimuthal components of the magnetic field as functions of time (hours) and planetocentric distance (R_S) for Pioneer 11 outbound, from CA to the first MP crossing (at $30 R_S$, hour 56). A sinusoidal function is superimposed to the 48 s averaged data, with a phase difference of $\pi/2$ between the two plots, and with a period equal to the accepted planetary rotation period of 10 hr 39 min 24 s [from *Espinosa and Dougherty, 2001*].

and B_ϕ appear to be rather in antiphase until the first outbound MP crossing [*Espinosa and Dougherty, 2001*].

[8] There is a further section of the outbound data displaying a similar spin-periodic perturbation, in the Voyager 1 observations. The modulation can be seen in the projection of the perturbation magnetic field onto the $(r - \phi)$ plane. We used the “SPV” model [*Davis and Smith, 1990*] to obtain an expression of the planetary intrinsic field (with its radial, colatitudinal and azimuthal components noted as mb_r , mb_θ and mb_ϕ , respectively) which was then subtracted from the observations. Thus $B_r - mb_r$ is the perturbed radial component and B_ϕ is the perturbed azimuthal component since mb_ϕ is zero. In Figure 3 we show the magnitude of the projected perturbation field, $\sqrt{((B_r - mb_r)^2 + B_\phi^2)}$, as a function of time and distance, for the whole outbound pass (i.e., from CA to the first MP crossing). The perturbation contains a spin-periodic variation almost throughout the magnetosphere.

[9] From the list of observations reported above, it turns out that only one section of magnetic field data from Saturn does not present a periodic perturbation with the period close to that of planetary rotation, that is the Voyager 2 outbound pass data. This substantially furthers the initial report of periodic perturbations in Saturn’s field by *Espinosa and Dougherty* [2000]. On its outbound pass, Voyager 2 was at relatively high southern latitudes (around 30°), as shown by a meridional projection of the flyby trajectory in Figure 4.

[10] Some of the features we show have been noticed before. *Connerney et al.* [1983] discussed the Voyager 1 observations around closest approach in the context of a

possible field-aligned current system, but the modulation shown in Figure 3 was not reported.

3. A Feature of the Planetary Intrinsic Field?

[11] Some information is now needed about the configuration of the magnetospheric field in order to determine if the spin-periodic perturbations can actually be a feature of the planetary intrinsic field or if they are of magnetospheric origin. In Figure 5, we use the Pioneer 11 outbound data and compare the observed colatitudinal component (shown in blue) to that in the $(r - \phi)$ plane (red plot), as well as to the perturbation field in that plane ($\sqrt{((B_r - mb_r)^2 + B_\phi^2)}$, green plot), obtained by subtracting only the planetary field. From about a distance of $16 R_S$ (\sim hour 35) until the first MP crossing, the component of the field in the $(r - \phi)$ plane is larger than B_θ . Moreover, around $20 R_S$ (\sim hour 41) the magnetic field vector lies essentially in the $(r - \phi)$ plane since B_θ is almost zero.

[12] Therefore the spin-periodic perturbation cannot be due to a wobbling of the planetary field because this would imply a large tilt angle. In addition, the observed and perturbation fields projected onto the $(r - \phi)$ plane (red and green curves), have similar amplitudes in the outer magnetosphere (say from $16 R_S$), ranging from 1 to 5 nT in that region. This precludes the signal being directly due to the planetary intrinsic field.

4. Analysis of the Field Rotation

[13] It was noted earlier and illustrated in Figure 2 that the radial and azimuthal components of the magnetic field observed by Pioneer 11 while outbound are in phase quad-

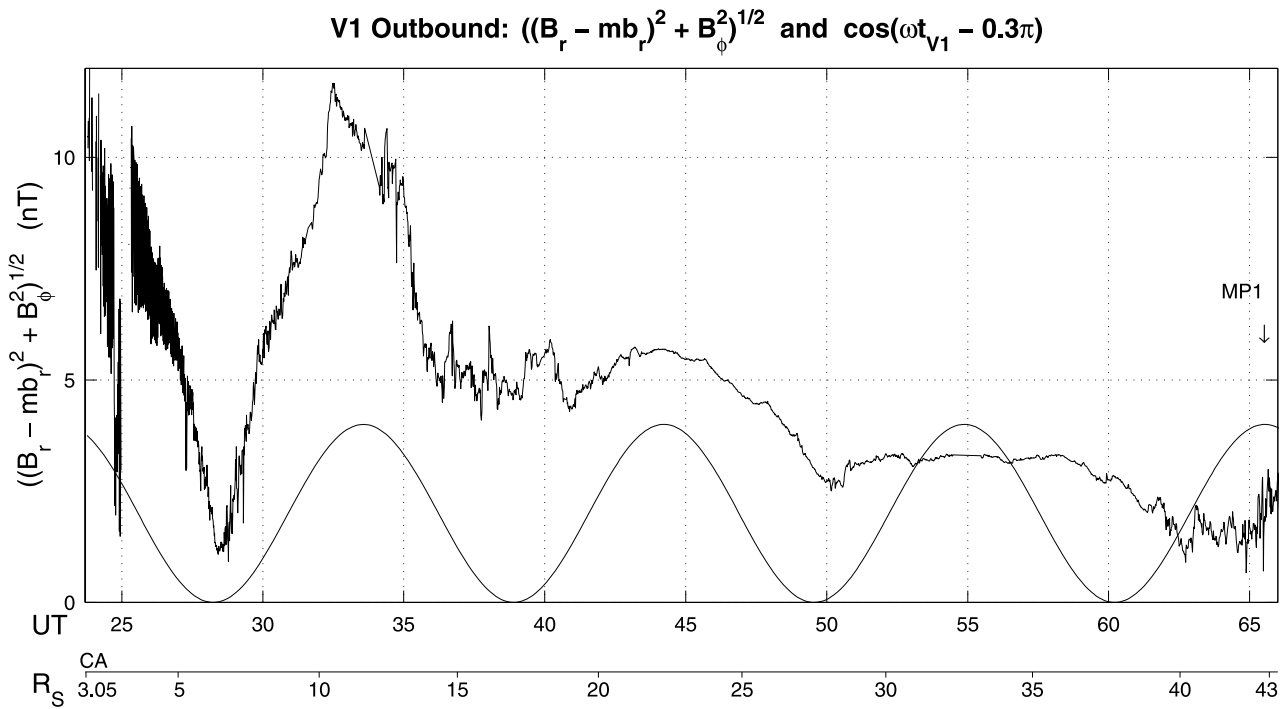


Figure 3. Projection of the perturbation magnetic field onto the $(r-\phi)$ plane as a function of time (hours) and planetocentric distance (R_S) for Voyager 1 outbound. A sinusoidal function is superimposed to the data, with a period equal to the accepted planetary rotation period. A modulation is noticeable throughout the outbound pass.

ture approximately from CA out to $22 R_S$. It turns out that if we consider the perturbation field (as previously, subtracting only the planetary field from the observations), we can show that an equivalent configuration is present in the inbound data. In Figure 6, a hodograph of the azimuthal component versus the perturbed radial component ($B_r - mb_r$, noted ΔB_r) is shown. The magnetic field vector completes a little more than one rotation as Pioneer 11 approaches Saturn from a distance of $17 R_S$ down to $5 R_S$ (\sim hours -3 to 12). The same exercise is carried out for the Pioneer 11 outbound data (from 7 out to $25 R_S$, \sim hours 23 to 47) and the perturbation field is

also used because the circular evolution is more evident. The field completes two rotations, shown separately for clarity and to emphasize that the perturbation is present in the middle and outer magnetosphere.

[14] A critical aspect of these observations, besides the period, is the sense of rotation of the magnetic field. With respect to the $(r - \phi)$ hodograph, we can note that the θ axis points into the page. This is equivalent to looking down from above the equator for most of the encounter, since Pioneer 11 was at north latitudes for most of the time. Therefore, in the inertial (nonrotating) spherical polar coor-

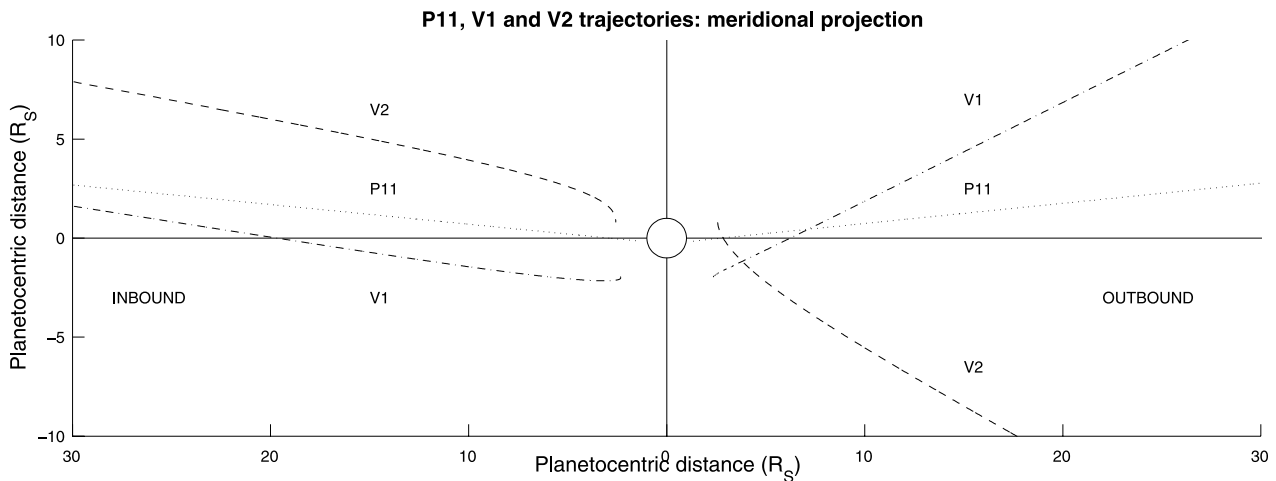


Figure 4. Meridional projection of the Pioneer 11, Voyager 1 and 2 flyby trajectories, in planetocentric distance. The negative values indicate Saturn's southern hemisphere.

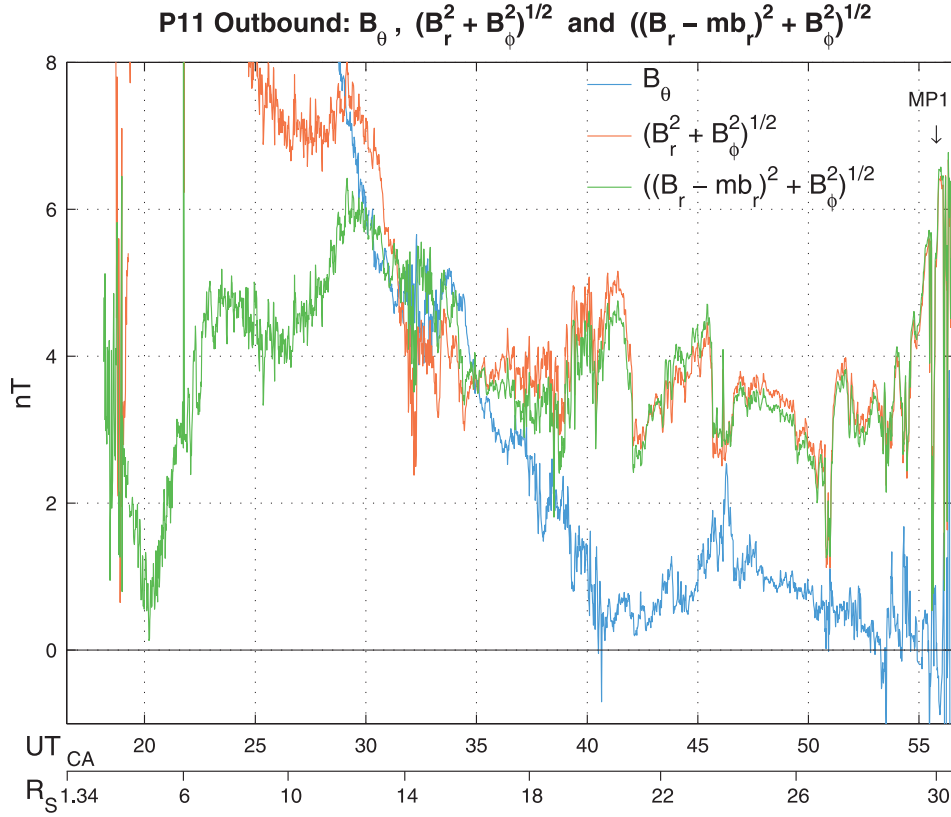


Figure 5. Pioneer 11 outbound magnetic field data as a function of time (hours) and planetocentric distance (R_S), from CA to the first MP crossing. The colatitudinal component is compared to that in the $(r-\phi)$ plane, as well as to the perturbation field in that plane ($\sqrt{((B_r - mb_r)^2 + B_\phi^2)}$). The perturbation cannot be directly due to the planetary intrinsic field (see text for details).

dinate system, the field rotates counterclockwise about the $-\theta$ axis, in other words B_r is $\pi/2$ phase ahead of B_ϕ .

[15] We regard the sense of rotation in the $(r-\phi)$ plane as a definitive argument against the possibility of a dipole tilt signature. A rotating tilted dipole would produce a clockwise sense of rotation in the same plane. In order to establish this point, we illustrate in Figure 7 a simple centered rotating tilted dipole. The sketches below show the magnetic field vector on a plane parallel and close to the rotational equator. We consider the plane to be above the equator, since all Pioneer 11 data were measured in Saturn’s northern hemisphere, except near closest approach (equator crossings at

$2.93 R_S$ inbound and $2.77 R_S$ outbound), as shown in Figure 4. In the side-view of the dipole, three field lines are represented, with one of them as a straight line since it is in a plane perpendicular to the viewpoint (the corresponding line behind the planet is superposed here, hence the vectors “2” for the front line and “4” for the back line). The vector magnetic field is then projected on the horizontal plane to obtain the top-view (middle, left panel). In other words, since a tilt angle would be equivalent to a horizontal dipole, the top-view in the fixed-frame shows the polar and equatorial fields associated with such a dipole. As the planet rotates, the sequence of vectors in the inertial frame will

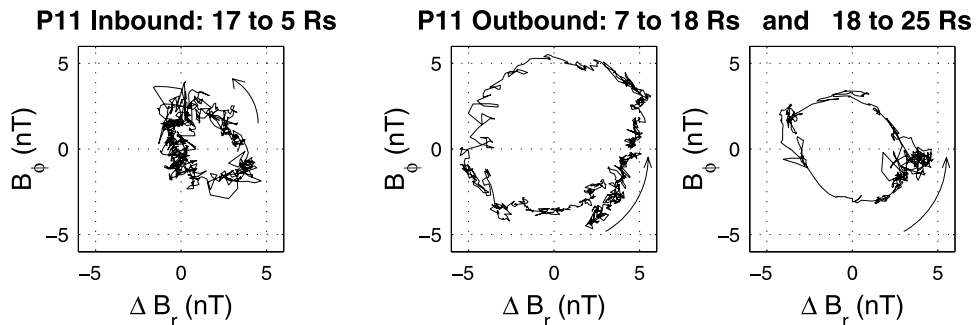


Figure 6. Hodographs of Pioneer 11 inbound and outbound magnetic field data. B_ϕ is plotted versus ΔB_r . The perturbation magnetic field completes at least one rotation while Pioneer 11 is inbound, and two while outbound. In the three instances, the field rotates counterclockwise about the $-\theta$ axis, and the curved arrows indicate the direction of increasing time.

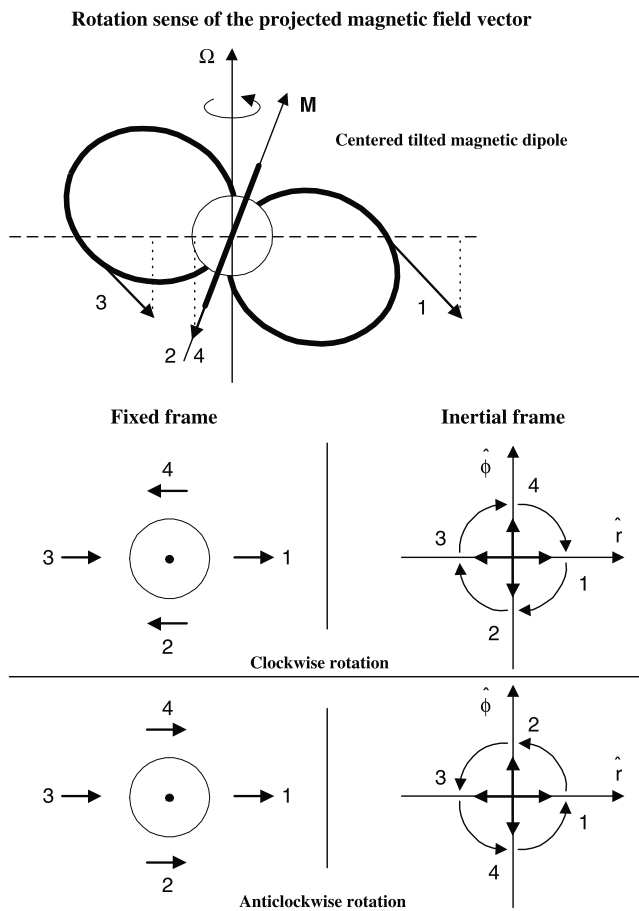


Figure 7. Centered tilted dipole and projection of the magnetic field vector on a plane parallel and close to the rotational equator. The rotation of the planet produces a clockwise rotation of the field projected onto the $(r-\phi)$ plane, as illustrated in the top-view. Also shown is the configuration that the projected field should have in order to obtain a counterclockwise rotation.

follow 1, 2, 3, 4. On a hodograph of $\hat{\phi}$, azimuthal direction pointing eastward, versus \hat{r} , radial direction pointing outwards (middle, right panel), one can see that the vector points successively outward, westward, inward and eastward, i.e., rotates clockwise and contrary to observation.

[16] Also shown is the configuration that the vector magnetic field projected on the $(r-\phi)$ plane should have at four different phases around the planet (i.e., in the fixed frame), if it is to rotate counterclockwise in the inertial frame, as illustrated in the $\hat{\phi}$ versus \hat{r} hodograph. Note that the directions of the fields in the fixed frame are inferred in this way and do not follow from any preconceived physical model. One can see that all four vectors are pointing toward the same general direction in a frame fixed to the planet (we will come back to this point in the Discussion).

5. Equatorial Projection of the Perturbation Field

[17] Another way of looking at the field data is to plot vectors along the trajectory. In Figure 8 we show an overall view of the magnetic perturbation along the spacecraft trajectory. The clearest spin-periodic signature was observed

during the Pioneer 11 encounter, and this is the one shown. Figure 8 shows the perturbation field (again obtained by subtracting only the model planetary field) observed by Pioneer 11 projected onto the equatorial plane along the spacecraft trajectory, from the inbound to the first outbound MP crossings. Some noisy data (amplitude greater than 20 nT) around closest approach were edited out for clarity. The counterclockwise rotation of the projected perturbation field is obvious and the cycloidal evolution results from the combination of the field rotation and the spacecraft motion.

[18] The tangent lines to the inbound and outbound portions of the Pioneer 11 trajectory, at large distance from the planet (say $30 R_S$), make an angle of about 77° . This angle is strikingly close to the phase difference angle of $3\pi/8$ radians (67.5°) between the sinusoidal functions fitted to Pioneer 11 B_ϕ inbound and outbound (cf. Figures 1 and 2). The agreement of the two angles is probably not a coincidence. They would be identical if the spin-periodic perturbations observed around noon (Pioneer 11 inbound) and near dawn (Pioneer 11 outbound) are in phase. This seems excellent evidence that this feature is of a global nature.

6. Modulation of the Magnetopause Position at Dawn

[19] There is one further feature we now show which also seems to indicate a strong planetary period imposition in the

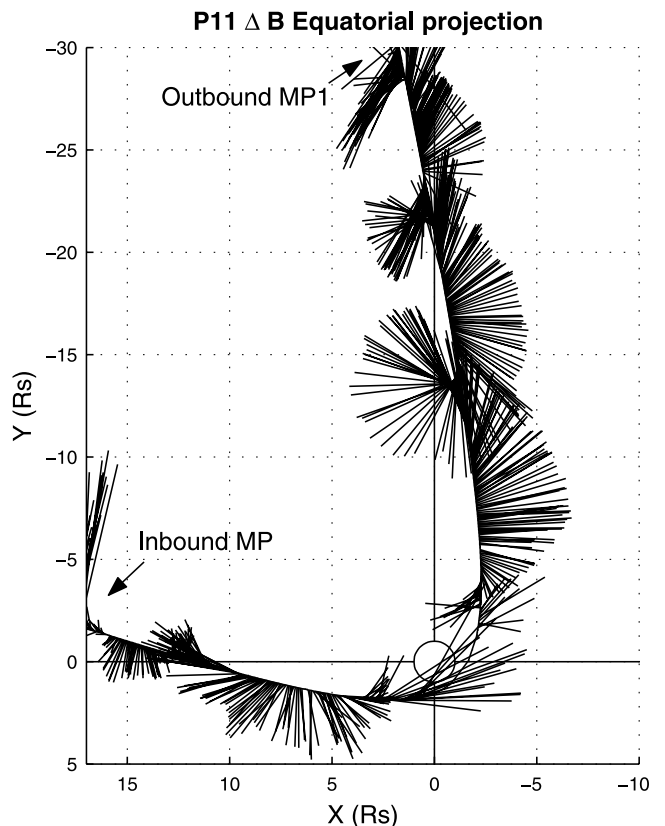


Figure 8. Perturbation field (5 min average) observed by Pioneer 11, projected onto the equatorial plane along the spacecraft trajectory, from the inbound to the first outbound MP crossings. Some noisy data (amplitude greater than 15 nT) around closest approach were edited out.

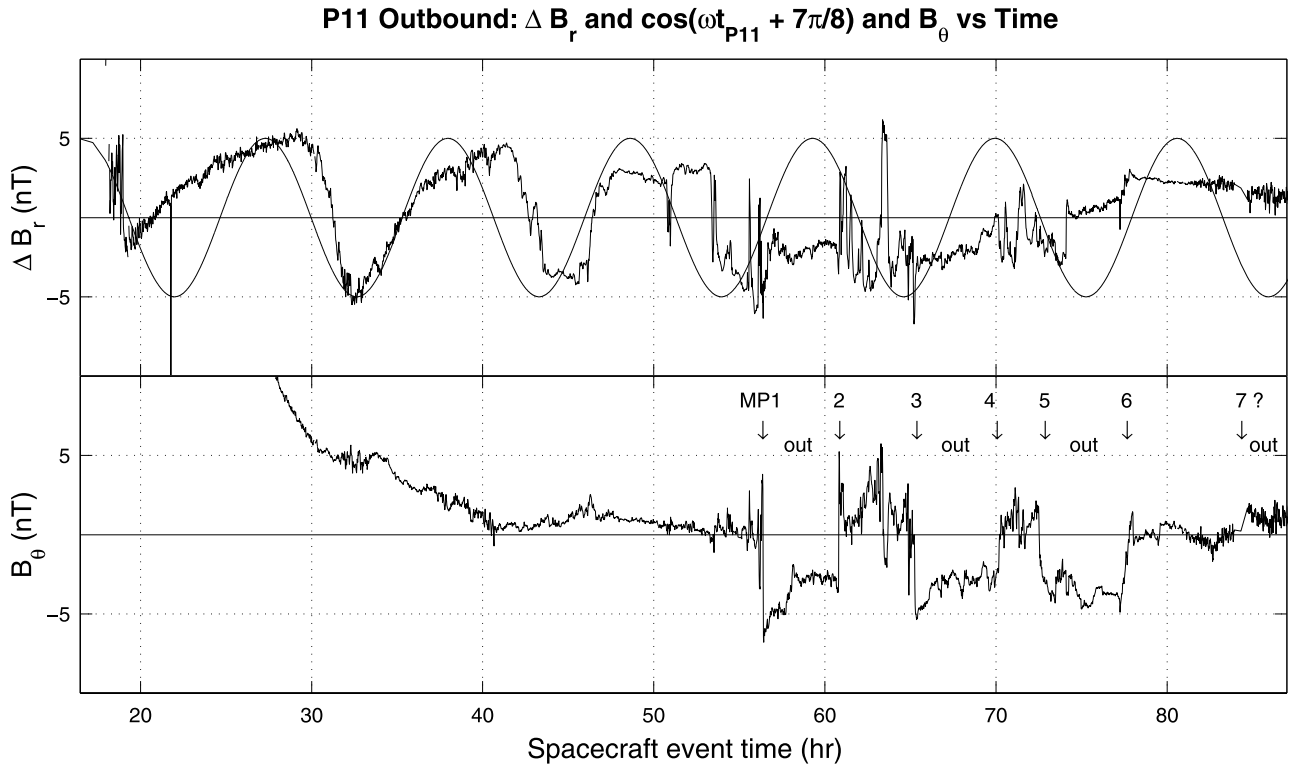


Figure 9. Colatitudinal and perturbed radial components of Pioneer 11 outbound magnetic field data versus time (hours). The perturbation observed in ΔB_r outbound is in phase with that observed in B_θ inbound, since the phase difference between the fitted sinusoids is $7\pi/8$ radians (see previous section). B_θ is similar to that in Figure 5, here the plot includes the outbound MP crossings (adapted from *Espinosa and Dougherty* [2001]).

outer regions of the magnetosphere. The MP crossings by Pioneer 11 during its outbound pass appear to be synchronized with the planetary rotation. In Figure 9, the colatitudinal and perturbed radial field components are plotted against time, for the period starting at CA and including the outbound MP crossings (adapted from *Espinosa and Dougherty* [2001]). The observations are now near dawn, hence the phase chosen for the sinusoid in the top plot is of $3\pi/8$ (cf. the previous section) plus $\pi/2$ (phase ahead of the sinusoid superposed to the B_ϕ component), that is $7\pi/8$ radians in total. The lower plot is used only to indicate the MP crossings.

[20] The sinusoid fits relatively well to ΔB_r while the spacecraft is inside the magnetosphere, therefore we can roughly predict the periods corresponding to a particular phase of the perturbation. Since Pioneer 11 flew outbound near the dawn meridian, the MP crossings give an indication of the boundary motions in that region. The first and third crossings are nearly coincident with predicted periods of negative ΔB_r , whereas the second and fourth crossings coincide with periods of positive ΔB_r . This correlation indicates that the spin-periodic perturbation modulates the position of the magnetopause at dawn, from within the magnetosphere. Since the boundary appears to move outwards during the periods of positive ΔB_r , that is when the magnetospheric field points away from the planet, one possibility is a variation of internal pressure due to the magnetic field and the plasma periodically “pushing” the boundary outwards. From the fifth crossing onward, there is no obvious correlation, but this could be possibly due to

the increasing solar wind control with distance from the planet.

[21] Therefore, from the phase information that we have thanks to the sinusoidal functions, we deduce that this possibly internally driven variation of the boundary position, determined from the Pioneer 11 data, is in phase with the magnetic field perturbation observed both inbound and outbound by the spacecraft.

7. Discussion

[22] We analyzed all Saturn’s magnetic field data in view of spin-periodic perturbations previously reported, while assuming the validity of the existing magnetic field models. That is, the planetary intrinsic field is mainly dipolar (with its polarity opposite to that of the Earth), and of special interest for the present study, the model field is axisymmetric, and in addition the dipole and rotation axes exactly aligned. In other words, no periodic modulation of the magnetic field with a period close to that of planetary rotation is predicted, hence the interest caused by the observation of such a feature, first reported by *Espinosa and Dougherty* [2000], in the Pioneer 11 and Voyager 2 magnetic field data. As detailed above, by a close reinspection of the Voyager data, we found that in fact, the only section of data that does not present any spin-periodicity is that from Voyager 2 outbound.

[23] Unfortunately, one cannot relate the phase signatures unambiguously to particular subspacecraft longitudes on the

planet. This is because of the uncertainty in the determination of the planet's rotation period, as mentioned in the section 2. On the other hand, we plan to study other data sets to obtain additional information, in particular observations taken simultaneously with the magnetic field data and which also present some spin-periodicity. The SKR emissions and the energetic particles data should be analyzed, since both contain the feature of interest [Carbary and Krimigis, 1982; Kaiser et al., 1984].

[24] The counterclockwise rotation of the perturbation magnetic field about the $-\theta$ axis is an important result because it definitely rules out the possibility of a dipole tilt to generate the spin-periodic modulation. Moreover, it is difficult to imagine a scenario involving such a rotation of the field, because it means that the field projected on a plane close to the rotational equator always points toward the same general direction in a corotating frame, as shown in Figure 7. If we assume the magnetic field frozen in to the plasma in such regions as the middle and outer magnetosphere, then the required configuration for the magnetic field implies super-corotating plasma when the field points eastward. This is in contradiction with the previous report of plasma subcorotation in those regions, in the cases of Voyager 1 and 2 [Richardson, 1986].

[25] From the equatorial projection of the perturbation field, we learned that, at least for Pioneer 11, the observations taken inbound and outbound are in phase (once the spatial distance is accounted for), which implies that the perturbation is global. Finally, the position of the magnetopause at dawn seems to be modulated in phase with the radial component of the perturbation field.

[26] In a second paper we speculate on the possible source of the perturbations and on a scenario accounting for them [Espinosa et al., 2003]. Here we will only point out that the signature is not always present and that may depend on external factors or location in latitude. One section of the data does not present any spin-periodic perturbation (Voyager 2 outbound). On this pass the spacecraft was at relatively high southern latitudes while outbound (around 30°). Moreover, Saturn's magnetosphere may have substantially expanded during the Voyager 2 encounter, as a result from the possible immersion of Saturn in the extended Jovian magnetotail [Behannon et al., 1983].

Either fact could be an element in the nondetection and should enter any final explanation.

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