Correlations between magnetic field and electron density observations during the inbound \textit{Ulysses} Jupiter flyby

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Abstract. The spacecraft \textit{Ulysses} flew through the Jovian magnetosphere during February 1992. This paper compares the magnetic field observations recorded during the inbound pass of the flyby with the electron density as derived from the URAP instrument. In general, it is expected that the density variations will anti-correlate with the magnetic field strength in order to maintain pressure balance, although there may be instances when a temperature or energy rise alone could balance the static stress. Furthermore, there is the possibility that a dynamic process could occur which would cause both the density and field magnitude to rise in unison. In the middle magnetosphere, anti-correlation is found to exist between the two data sets; however, in the outer magnetosphere (which was characterized by very disturbed fields) and in the transition region between the outer and middle magnetospheres, there is no simple relationship between the density and field. Examples of anti-correlation, temperature or energy increases and dynamic processes are found.

Introduction

The spacecraft \textit{Ulysses} flew past Jupiter in February 1992 on its journey to the polar heliosphere. During the inbound pass through the Jovian magnetosphere, the magnetosphere was found to be extended from that which was seen during the \textit{Voyager} and \textit{Pioneer 11} flybys. In particular, the outer magnetospheric region (broadly defined as the region beyond where the spacecraft made regular encounters with the equatorial magnetodisk, roughly beyond 70\textit{R}_\text{J} radial distance from the planet in the equatorial plane, where \textit{R}_\text{J} is the Jovian planetary radius = 71,400 km) was characterized by some very disturbed fields. This paper compares the magnetic field observations as recorded by the dual fluxgate/vector helium magnetometer (Balogh et al., 1992) and the plasma density as derived from the plasma frequency receiver of the radio wave instrument (URAP) (Stone et al., 1992a) onboard \textit{Ulysses}. The plasma density is derived from the plasma frequency (\textit{F}_\text{p} = 8.98/\sqrt{n_e}$, where \textit{n}_\text{e} is the total electron density in cm$^{-3}$) as identified from the URAP experiment. Frequency values below 0.57 kHz (\textit{n}_\text{e} of 0.004 cm$^{-3}$) are not recorded. The URAP sensor used in this study is the spin-plane electric field antenna (E,) which is connected to the plasma frequency receiver (PFR). The PFR sweeps the frequency range from 0.57 to 35 kHz in 32 logarithmically spaced frequency steps, with a corresponding separation of 14%. The threshold sensitivity is about 2 \textmu V per channel. A full spectrum is provided every 16 s. For a more detailed description of the instrument see Stone et al. (1992a). Averaged spectra (8), resulting in a 2 min time resolution, have been used in this study. The plasma frequency is identified from the low frequency cut-off of the continuum radiation, which is a strong electromagnetic emission observed inside the magnetospheric cavity during most of the flyby (Stone et al., 1992b), with an accuracy of about one or two PFR steps. This technique, already discussed and used for the plasma wave system data set onboard the \textit{Voyager} spacecraft (Gurnett et al., 1981) has provided for this study density values which are in very good agreement with the density values as derived from low-energy electrons observed by the plasma experiment (Phillips et al., 1993).

The magnetic field data have a maximum time resolution of 1 s, but in light of the URAP data resolution we have used 2 min averages for comparison purposes. Throughout the paper we use a right-handed polar coordinate system to display the magnetic field data in which the \textit{z}-axis is along the magnetic dipole axis of the planet. Data are presented in \textit{r}, \textit{\theta} and \phi components. The \textit{r} axis points radially outwards from the planet. The \textit{\theta}-component is measured positive from the \textit{z}-axis (i.e. increasing in the...
southward direction). The $\phi$ component makes up the orthogonal set and is positive in the sense of planetary rotation. The Jovian planetary magnetic dipole is tilted with respect to the rotation axis and thus the magnetic coordinate system takes account of any ordering that the planetary field imposes on the Jovian magnetosphere.

The Ulysses inbound pass

The initial reports of the Ulysses spacecraft flyby of Jupiter have been reported in Science (Smith et al., 1992 and succeeding papers). After encountering a variety of upstream phenomena associated with Jupiter, Ulysses entered the Jovian plasma environment proper on Day 33 (2 February 1992) when it passed through the bow shock. This was encountered inbound at a radial distance of 113\,$R_\oplus$ at 17:33 U.T. (Bame et al., 1992; Balogh et al., 1992). The first magnetopause crossing occurred 4 h later at a distance of 110\,$R_\oplus$ from the planet. The magnetosphere was much expanded from that seen by the previous Pioneer and Voyager flybys, with the furthest bow shock seen previously being that of Pioneer 10 at 98\,$R_\oplus$. The briefness of the magnetosheath crossing suggests that the magnetosphere had expanded substantially between the bow shock crossing and the first encounter with the magnetopause. There were also later brief multiple encounters with the magnetopause (Bame et al., 1992), all of which facts reaffirm the low rigidity of the magnetosphere established during earlier spacecraft flybys of Jupiter (Smith et al., 1976).

The spacecraft magnetic latitude varies as the planet rotates but remains small throughout the inbound pass. At the start of Day 34, when the spacecraft is over 100\,$R_\oplus$ from the planet, the range of magnetic latitude covered in a single planetary rotation is from $-5$ to $15^\circ$. The mean latitude rises as the spacecraft no longer encounters the projected magnetic equator and peak magnetic latitudes are of the order of 20°. On the basis of the magnetometer data, Balogh et al. (1992) categorize the dayside equatorial magnetosphere traversed on the inbound pass of Ulysses into three distinct magnetospheric regions: the outer, middle and inner magnetospheres, as originally proposed by Smith et al. (1976). In the inner and middle magnetosphere, the field is very regular and is marked by depressions in field strength roughly every 10 h produced by regular encounters with or approaches to the magnetodisk current sheet when the spacecraft is near its lowest values of magnetic latitude. In the inner region, the field is dominated by the planetary dipole, whereas in the middle region the field is primarily radial. The outer region is characterized by a very disturbed field which is predominantly in the $\theta$ (southward) direction. The outer region can exhibit large changes in field strength, some of which can be attributed to brief exits into the magnetosheath and others which resemble the magnetodisk current sheet crossings recorded closer in. A third category of field disturbance in the outer magnetosphere is described in a second report on the Ulysses magnetometer data from the Jupiter flyby by Haynes et al. (1993). This work identified isolated dips in field strength unique to the outer magnetosphere. They called the events field nulls. In the nulls, the field strength drops to values that can be lower than 0.2 nT. However, unlike the magnetodisk current sheet encounters found closer to the planet, throughout the events the field direction remains essentially in the $\theta$ direction. As indicated by Balogh et al. (1992) unlike that which occurs in the inner regions, there is no clear ordering of the data with magnetic latitude in the outer magnetosphere and current sheet nulls may be encountered anywhere in the latitude range traversed by the spacecraft.

The dayside Jovian magnetosphere

As a background to our study, let us review what is known of the dayside magnetospheric plasma and magnetic field. The three regions used by Balogh et al. (1992) to categorize the Ulysses magnetic field data can be fit into the currently accepted static picture of the dayside of the Jovian magnetosphere and the major plasma populations encountered there. The major plasma regions are the magnetosheath, the boundary layer, the magnetodisk with its central current sheet, and the inner magnetosphere, where the plasma is dominated by the presence of the Io torus and the field is dominated by the proximity to the planetary dipole. There is, then, a residual region which can be roughly identified as the off-equatorial magnetosphere where the plasma is sparse. Of the regions listed, the plasma density is highest in the inner equatorial magnetosphere in the Io torus. Outside the torus (which is not encountered in the data examined in the study reported here) the magnetosheath which contains the post-shock compressed solar wind plasma flowing around the planet has the highest plasma density.

The magnetopause marks the inner boundary of the magnetosheath and is marked most clearly by a decline in density rather than any sharp magnetic field feature. The magnetopause itself may be partially permeable to the external plasma, as just planetward of the magnetopause current layer there can be observed a region whose density is intermediate between the magnetosheath and the magnetosphere proper: the boundary layer (Sonnerup et al., 1981; Scudder et al., 1981; Bame et al., 1992). Once inside the magnetosphere proper, the region of highest density is found in the current sheet associated with the magnetodisk. Near the planet where the dipole field of the planet itself is relatively strong, the magnetodisk plasma merges with the high-density torus of plasma which encircles Jupiter and originates from the interaction between the magnetosphere and the volcanic moon, Io. As one moves closer to the planet, so the magnetodisk plasma becomes more clearly associated with the magnetic equator (i.e. low values of magnetic latitude as derived from the planetary dipole).

The confinement of plasma to the equatorial regions of the inner/middle magnetosphere is easily understood. The major source of ionized material (Io) does not move far from the magnetic equator and, furthermore, the relatively rapid rotation of the Jovian system means that as long as coupling between the ionosphere and the magnetosphere
is strong enough that magnetospheric corotation is maintained in the plasma frame of reference there is a net centrifugal force on the ionized material (Vasyliunas, 1983). The ionization and pickup process favours the creation of a plasma distribution with a strong pressure anisotropy transverse to the field, and in these circumstances there is a net magnetic mirror force acting on the plasma parallel to the field direction directed towards the weakest field region. The centrifugal force and the mirror force both act generally to push the plasma towards the equatorial region of magnetospheric flux tubes, but not necessarily towards exactly the same point. The parallel centrifugal force is zero at the point where a given flux tube is farthest from the rotation axis of the planet; the mirror force is zero where the field is smallest and the flux tube has largest cross-section. Far from the planet, the two are likely to equilibrate at the same point simply because the field configuration itself is largely controlled by the balance between the forces. Closer to the planet once the dipole component of the field becomes more important, the position of maximum plasma density may move away from the field line centrifugal equator (the most distant point from the rotation axis) to the magnetic equator (where the field magnitude is minimum), the size of the effect being dependent on the size of the plasma pressure anisotropy.

The farther one moves from the planet, the harder it is for the planet to impose corotation and the more complex may be the dynamical processes. Far from the planet, both thermal and rotational dynamical plasma stress can be as large as or larger than the magnetic field stresses exerted by the planetary field and the coupling between the plasma population and the planetary magnetic dipole becomes much looser. One simple effect is the winding up of the field identified by Smith et al. (1976) at distances where the field is unable to impose planetary corotation fully, but the identification of phenomena such as magnetic nulls by Haynes et al. (1993) in the outer magnetosphere suggests that matters are likely to be highly dynamic and more complex. In particular, the existence of the entire outer magnetospheric region where there is no magnetodisk and the equatorial field is primarily southward shows the existence of a large region where the magnetic dipole latitude has little influence on the magnetospheric structure.

It follows that, although we have a good idea of the internal dynamics of the plasma in the inner and middle magnetosphere, there remain many unanswered questions, concerning in particular what happens in the outer regions where it is very difficult for corotation to be imposed. The Ulysses spacecraft inbound pass, with its extended passage through the outer magnetosphere offers a new opportunity to investigate these issues.

Overview of the Ulysses data

Figure 1 shows an overview plot of the magnetic field data for the four days (Days 34–37, 1992) used in the study presented here. Three components, as well as the field magnitude, are shown. Throughout Days 34 and 35, the spacecraft is in the outer magnetosphere with $B_z$, the southward field, being dominant. Towards the middle of Day 35, significant radial components occur in bursts, and by the beginning of Day 36 the radial and $\theta$ components are of the same order. Here, then, is the transition region between the outer and the middle magnetospheres. Note that the radial component may be positive or negative and that the scale on which the sense switches is much more rapid than the planetary rotation period of 10 h. At this time, then, although the reversals may be evidence of a magnetodisk current, the current is not rigidly fixed in magnetic latitude. After about 06:00 U.T. on Day 36,
the radial field component \( B_r \) begins to dominate and continues to do so right through to the end of Day 37. The \( B_n \) and \( B_b \) components show a fairly regular 10 h variation locked in phase to the regular dips in the \( B_r \) component. Here the magnetodisk current is dominating the field structure. The current sheet encounters, marked by the dips in \( B_r \), occur where the spacecraft passes through the lowest magnetic latitudes as the planet rotates beneath it. By this time the spacecraft is in the middle magnetosphere.

Figure 2 shows an overview plot for the electron density derived from the URAP instrument where the log of the density is shown. The most immediate features are the high values of density encountered towards the end of Day 34 and the beginning of Day 35. These correspond to encounters with the magnetosheath and a boundary layer region, as we shall see. Otherwise the outer magnetosphere is characterized by background electron densities of less than 0.01 cm\(^{-3}\) with fluctuations superposed which peak at several times that value. The threshold density value of 0.004 cm\(^{-3}\) can be easily seen in the latter part of the plot. On Days 36 and 37, the 10 h periodicity resulting from regular crossings or approaches to the magnetodisk current sheet can be clearly seen. A cursory comparison of Figs 1 and 2 reveals that these density enhancements correlate with the points where depressions in the field indicate the presence of the magnetodisk current.

In the following sections, we carry out a comparison between the magnetic field and the electron density data on the inbound pass in more detail. This type of detailed correlation between the electron density and the magnetic field measurements in the Jovian magnetosphere has not been carried out before. Following the \textit{Voyager} 1 flyby, Bridge \textit{et al.} (1979) noted that, where regions of enhanced density were observed at regular intervals on the inbound pass, the magnetic field strength was seen to be low: in a survey of the plasma electron environment of Jupiter it was observed (Scudder \textit{et al.}, 1981; Belcher, 1983) that the \textit{Voyager} 2 inbound pass data showed electron density enhancements during the plasma sheet encounters which were well correlated with depressions in field strength. A recent paper by Ansher \textit{et al.} (1992) has examined sharply defined density structures in the plasma sheet as observed by \textit{Voyager} 1. The simplest expectation is that the density variations should anti-correlate with the magnetic field strength, as, we have noted, seems evident on Days 36/37. This is not the only scenario. Drop-outs in the field imply that the field pressure decreases and to make up the total pressure deficit, the gas pressure must rise: this is the basis for the belief that the plasma density might also rise. However, a rise in temperature or mean energy alone could also balance the static stress. Furthermore, there is the possibility that the changes in field and electron density recorded by the spacecraft instruments are associated with a dynamic process in which static stress balance is not maintained. For example, a local dynamic compression of the plasma in which the electrons were effectively frozen to the magnetic field would cause both density and field magnitude to rise together. In what follows, we shall establish that all three possibilities outlined here can occur in the Jovian magnetosphere.

\textbf{Days 34/35: the outer magnetosphere}

Figures 3a and b show Day 34, where \( B_n \) and \( \log (n_e) \), and \( |B| \) and \( \log (n_e) \) are plotted on the same time scale. On Day 34, the spacecraft is in the outer magnetosphere and the \( B_n \) and \( B_b \) components (seen in Fig. 1) are much smaller than \( B_r \). The dominant component of the field is (largely) positive throughout, although noticeable features of the plot are the variety of dips occurring in both \( B_r \) and the field magnitude, \( |B| \). The dips correspond largely, but not exclusively, to increases in plasma (total electron) density. During the first half of the day, the density
increases are relatively small compared with the density difference between the magnetosheath and the magnetosphere proper as occurs during the latter part of the day, and it is not clear that the anti-correlated field and plasma variations are in any way connected with the magnetopause. Many of the dips in $B_0$ resemble the field null event identified by Haynes et al. (1993), although the example described in detail there came from closer to the planet.

Nulls are a fairly common outer magnetospheric phenomenon at Jupiter; Leamon et al. (1993) have shown
that nulls were recorded by both Voyager and Pioneer spacecraft, as well as by Ulysses. The field in the null events described in the above papers is predominantly in the southward direction. The dominant $B_\parallel$ component either does not reverse in the event or reverses only briefly in the weak field region near the very centre of the event. Examples of nulls which fit the descriptions given by Haynes et al. (1993) and Leamon et al. (1993) which do not contain a field reversal are at 06:40 and 08:45 U.T. (denoted by arrows in Fig. 3a and b). These authors quote a characteristic time for a null event of order 5 min. In the data shown in the figure there are null-like events associated with the broader depressions in the field strength, although not shown, follows the $B_\parallel$ component quite closely) between 01:00 and 01:45 U.T. and between 02:00 and 04:00 U.T. Within the depressed regions, there are individual null events (for example around the minimum in $B_\parallel$ at 01:45 U.T.). The extended depressed field regions thus seem more complex than the simple isolated field null regions encountered closer to the planet. In the first region (01:00-01:45 U.T.), despite the $B_\parallel$ component decreasing when the field magnitude decreases, there is actually a concurrent increase in the radial component (which also briefly reverses).

The assumption made by Haynes et al. (1993) that the nulls were a spatial structure either swept over or traversed by the spacecraft seems reasonable. It follows that the decline in field pressure in the centre of events must be taken up in some way by mechanical stress. The depressed field region is marked by a general increase in density well matched with where the depression in strength occurs. However, there is no one-to-one relationship between field and density. The temperature of the material within the low-field region must be variable if pressure balance is to apply. For reference, one may note that for a plasma of density 0.01 cm$^{-3}$ to hold off a field of 4 nT by simple pressure balance, the mean thermal energy would be of the order of a few keV. If, in contrast, dynamical processes are balancing the stress, flow velocities would be as high as the Alfvén speed, which for a proton plasma would be of the order of 10$^3$ km s$^{-1}$. The field structure in the depressed field regions is more complex than the simple sketch given by Haynes et al. (1993) implies. It is likely that the field forms loops, evidence for which is given by the fact that in the centre of the depressed field region at around 03:00 U.T., there is a period of the order of 30 min where $B_\parallel$ is reversed (i.e. there is a large northward field). The peak negative value of about $-1.8$ nT which is larger than in any other null event detected by Ulysses. Within the reversed field region the density is very marginally enhanced ($n_e \approx 0.01$ cm$^{-3}$). It might be thought that the depressed regions reported here correspond to an exit from the magnetosphere. This possibility seems unlikely, as unambiguous magnetosheath reentries do occur and the densities encountered there are more than 10 times higher than this value. Furthermore, the magnetopause current layers detected in association with the high-density magnetosheath encounters do not contain field nulls.

Between 04:00 and 10:00 U.T., there are other isolated null events, the number depending on what threshold is chosen for definition. Isolated dips in field strength (06:40 U.T., three up to 08:30 U.T. and a deep null at 09:00 U.T.) are all associated with minor enhancements in density. At 10:00 U.T., Ulysses encounters a further extended region of depressed field strength. Both $B_\parallel$ and the field strength are depressed for an extended period of $\approx 1.5$ h. The magnitude, although variable, is of order 1 nT throughout the event. Once again, within the region, there are large isolated drops in magnitude on a time scale of a few minutes, all being generally similar to the nulls reported by Haynes et al. (1993). The field only regains its former value of 4 nT some time after 12:00 U.T. Throughout the period from 10:00 to 12:00 U.T., as a general rule the plasma density rises where the field drops, but there is not a systematic relationship. The maximum density encountered is of the order of 0.03 cm$^{-3}$, an order of magnitude lower than the magnetosheath values encountered both previously and later. In the centre of the period near 10:30 U.T., a reversal in $B_\parallel$ component is detected, although the maximum northward field is of order 1 nT, smaller than the earlier maximum value. Once again a rough guide to the nature of the plasma in the enhanced density regions can be derived by invoking pressure balance: the required thermal energy would be of the order of 3 keV in the nulls.

During the second half of the day, once again the field and plasma density signatures seem coupled with a field null occurring at 13:00 U.T. (shown by an arrow in Fig. 3a and b) and a corresponding peak in $n_e$ of the order of 0.04 cm$^{-3}$. Later on in the day, the plasma density increase is much larger (by more than an order of magnitude, peak values are of the order of 0.2 cm$^{-3}$) than any of the examples earlier in the day. The most noticeable feature in the magnetic field is the region from about 17:45 to 19:30 U.T. where the field develops a distinct northward component. However, in sharp contrast with the previous instances of northward field encounters (at 02:00 and 10:00 U.T.), there is no reduction in magnetic field strength and there are no signs of any nulls here. The density rises very significantly through this region which has been independently identified by the plasma instrument (Bame et al., 1992) as the magnetosheath. The density in this region exceeds the density anywhere else, and we thus concur with the plasma instrument identification and suggest that the northward field region where the density is highest is the magnetosheath. This magnetopause crossing is rather complex, with $n_e$ increasing from about 17:00 U.T. as the $B_\parallel$ component increases before dropping sharply at 17:30 U.T. The density value has a peak at about 0.1 cm$^{-3}$ and then there is a shoulder region, denoting some sort of boundary layer. There then follows a long decrease in $B_\parallel$, of about half an hour which is the actual magnetopause crossing. Once in the sheath the peak values of the density are of order 0.2 cm$^{-3}$, the highest we have seen thus far.

Between 19:30 and 19:45 U.T. the spacecraft reenters the magnetosheath, there is an inward magnetopause crossing and the field back inside is very like it was preceding the boundary layer, and is remarkably quiet: the density here is at about half of its sheath value but very much (about 10 times) greater than it was previously in the magnetosheath. This long boundary layer with high density, of the order of 0.06 cm$^{-3}$, remains until the next
sheath encounter about 8 h later. Note that in the boundary layer, when $B_z$ and $|B|$ dip, there are corresponding peaks in $n_e$ on top of the boundary layer. As we noted above, the field strength does not change significantly in the vicinity of what we would now identify as an outbound magnetopause crossing, nor does it vary much when the spacecraft reenters the southward field direction at around 19:30 U.T. and the density drops a little. We interpret this signature as the inbound magnetopause crossing. Once again, the field strength does not change much within the magnetopause. Minimum variance analysis (Sonnerup et al., 1981) of both the magnetopause entry and exit have been carried out using 1 min average data, as well as high-resolution 1 s data. The results are almost identical for both data sets, since the crossings are slow enough to allow clear identification of the maximal variance direction. The analysis of the outbound magnetopause does not yield an unambiguous normal, only a maximal variance direction is clearly identified (as the two smaller eigenvalues are comparable). The maximal variance direction lies in the $(\theta, \phi)$ plane (see Fig. 4, a plot of $B_\theta$ vs $B_\phi$). Thus the data could be consistent with a roughly radial normal.

This implies that there is a normal field of order 1 nT threading the magnetopause and directed toward the planet. Analysis of the subsequent reentry yields a similar result. Again, the two smaller eigenvalues are of similar order and thus the identification of the normal direction is difficult. The major change in field is in the $(\theta, \phi)$ plane, and there is a radial field of order $-1$ nT. The field configuration at the two boundary crossings is that of a rotational discontinuity and thus consistent with reconnection taking place at the magnetopause. The negative radial component means that the field threading the boundary is directed towards the planet, a configuration that would imply the neutral line was to the North of the spacecraft.

On reentry to the magnetosphere at about 20:00 U.T., the magnetic field data reveals a southward field which is remarkably steady. However, the plasma density is very different from the value before the magnetospheric exit. There is a further exit into the magnetosheath field at 01:00 U.T. on Day 35 (Fig. 5a and b) and until that exit there is relatively high density ($0.1 \text{ cm}^{-3}$), to be contrasted with $n_e \approx 0.2 \text{ cm}^{-3}$ in the magnetosheath and $n_e \approx 0.01 \text{ cm}^{-3}$ in the magnetosphere prior to exit. We thus concur with the plasma team that there is a boundary layer which lies between the two sheath encounters on Days 34/35. The spacecraft remains in this boundary layer for about 4 h. On other encounters with the magnetopause, similar regions of intermediate density are seen (see also Bame et al., 1992), but none of such a long duration. It seems likely that the magnetopause is moving inward between 20:00 and 24:00 U.T., and it is thus that the spacecraft remains in the layer for so long. The magnetopause encounters at 01:30 and 03:00 U.T. are similar to the previous pair, exhibiting a field rotation with a steady negative radial component throughout. The magnetosheath field strength is however smaller ($\approx 2$ nT) than the interior field ($\approx 5$ nT), in contrast to the earlier encounter. It is tempting to relate its behaviour explicitly to the field configuration within the thick magnetopause current layer which is appropriate for magnetic reconnection to be occurring between the magnetospheric and interplanetary fields.

The two data sets for the following day (Day 35) are seen in Fig. 5a and b, where $B_z + 4$ nT is plotted in b, so as to easily distinguish between the data. There is another outbound magnetopause crossing at about 01:00 U.T. of duration about 30 min, where again $B_z$ is negative, $B_\theta$ drops out and becomes slightly negative and there is no deep minimum in $|B|$. Within the sheath region 01:15-02:45 U.T., there are a number of nulls in $|B|$ with no detectable features in the density in contrast with nulls seen later inside the magnetosphere. Following reentry to the magnetosphere at around 03:00 U.T. on Day 35 the density returns to the earlier very low values ($n_e \ll 0.01 \text{ cm}^{-3}$).

**Fig. 4.** A plot of $B_\theta$ vs $B_\phi$ for the outbound magnetopause crossing on Day 34, where the field components are in nT.
There is a boundary layer of intermediate density ($n_e \approx 0.01 \text{ cm}^{-3}$) for the first 50 min that the spacecraft is in the southward (planetary) field. The field strength inside the magnetopause is once more fairly steady, but there is now a radial component ($\lesssim 2 \text{ nT}$). The major component is still $B_r$, and as Fig. 5a shows, some insignificant depressions in field are associated with small increases in density. The next major feature in the magnetometer data is the large dip in field strength at about 10:55 UT (marked by an arrow in Fig. 5a). This is a null event discussed by Haynes et al. (1993). The field strength increases on each side of the null by the order of 20%.
The field increases are associated with increases in plasma density. However, in the centre of the field null itself the density decreases. The density in the centre is of the order of 0.01 cm$^{-3}$. The plasma in the field null must have sufficient energy to counter the external field pressure. Using a value of 8 nT for the external field, one obtains a rough estimate of the thermal energy in the centre of the order of 20 keV. In other words, the plasma in the null has a temperature considerably in excess of the temperature of the plasma in the previous null regions and also considerably higher than the temperature indicated for the plasma in the magnetodisk current sheet detected later in the inbound pass. It is hard to avoid the conclusion that some local dynamic heating process is associated with this event.

During the second half of the day, the radial component of the field is becoming more significant, particularly towards the end of the day. At 13:00 and 13:30 U.T. (denoted by arrows in Fig. 5a), there are small drop-outs in $B_r$ which are seen to be compensated by peaks in $n_e$ of the order of 0.015 cm$^{-3}$. There are two further field nulls at 15:50 and 15:50 U.T. (again marked by arrows in Fig. 5a); density peaks of 0.02 and 0.01 cm$^{-3}$ are seen in association. At 16:30, 17:00 and 17:20 U.T. (all denoted by arrows in Fig. 5a), there are further field drop-outs which are again matched in anti-phase by $n_e$ with values of 0.01–0.02 cm$^{-3}$ occurring.

At 19:00 U.T. there is a large drop-out in $B_n$ of about 20 min duration, after which $B_r$ is rather more important and often dominant. We thus deduce that the spacecraft is now entering the middle magnetosphere where the magnetodisk current dominates the equatorial field. Despite the large change in $B_n$, the corresponding change in $B_r$ means there is little net change in $B$. There is also no clear change in $n_e$ throughout the region. At 20:00 U.T. we encounter a large density increase. Both $B_n$ and $B_r$ reverse sign in the vicinity, but the plasma density is highest where $B_n$ drops out in a region where $B_r$ is positive. This is arguably an encounter with the outer edge of the magnetodisk, but more work is required to elucidate the precise field geometry. The density peak at 21:50 U.T. corresponds to a value of 0.04 cm$^{-3}$, and that at 20:20 U.T. to a value of 0.08 cm$^{-3}$. At 21:00 U.T., there is a further current sheet crossing, with $B_r$ becoming negative. In this region $n_e$ is best ordered by comparison with the derivative $dB_r/dr$ as one would expect in a region dominated by the presence of the magnetodisk. For the rest of the day, $n_e$ anti-correlates with $B_r$. At 03:55 U.T. there is a null in $B_r$ across which $B_n$ changes sign and within which the density peaks at a value of 0.02 cm$^{-3}$. $B_n$ does not fully reverse (as it does in later current sheets). We conclude that the spacecraft is grazing the magnetodisk at this point.

**Day 36: the start of the middle magnetosphere**

At the start of Day 36, the spacecraft is some 70R$_J$ from the planet. The plots in Fig. 7 show that $B_n$ dominates for the first 4 h of the day, and thereafter $B_r$ becomes the same order of magnitude, until after about 06:00 U.T. it becomes the dominant component. Thus, according to the criteria outlined in the Introduction, we are moving through the transition region between the outer and middle magnetosphere into the middle magnetosphere proper where the field is dominated by the magnetodisk current.

Figure 6a and b shows plots of the southward and radial field components, $B_r+2$ nT and $B_r+5$ nT (for ease of viewing), together with the electron density log ($n_e$) derived from the URAP data. The 4 h of the transition region at the start of the day contain complex field signatures that will probably repay further investigation. At 00:15 and 00:30 U.T. there are null events in the field, but unlike the ones encountered earlier, there is a significant radial field outside the null. Both the radial and $\theta$-components of the field decrease noticeably and also change sign within the centre of the first null. In the second only $B_r$ changes sign. In each event, the density peaks at a value of order 0.02 cm$^{-3}$.

At about 01:45 U.T. there is a sharp negative spike in $B_r$, but there is only a minor dip in field strength because of the size of the radial component. $B_n$ in fact remains the dominant component until about 03:00 U.T., but inspection of Fig. 6b shows that, despite the fact that until 06:00 U.T. $B_n$ is not dominant the plasma density variation correlates much more clearly with the radial component than with $B_n$. The density rises whenever there is a gradient in $B_n$ and the correlation is sustained throughout the remainder of the day as the radial component becomes more and more dominant. The lack of correlation with features in $B_n$ is particularly evident at the time of the drop-out in $B_n$ just prior to 07:00 U.T. The drop-out corresponds to a local minimum in density.

The reversals in $B_n$ can be interpreted as crossings of the magnetodisk and the density enhancements correspond to the location of the current carrying plasma. However, the current sheet is likely to be very distorted at the times of the reversals in $B_n$. Two pieces of evidence point to the spacecraft crossing a series of warped current sheets. Firstly, as the crossings are encountered on scales of hours over a period of two planetary rotations, there is no relation between the latitude of the spacecraft and the magnetodisk current sheet crossings. Secondly, the $B_n$ component regularly changes sign when the radial component reverses. This suggests that the current sheet is strongly tilted in the meridian.

From 04:00 U.T. onwards, the field strength drops very significantly in the $B_r$ reversal regions. Thus, the density enhancements can be identified as a diamagnetic effect. In the sheet regions, the density rises as high as 0.1 cm$^{-3}$. However, as in the outer magnetosphere, a general correlation between field structure and density behaviour does not yield on closer examination any detailed onetoone correlation. For example, the 10:15 and 11:15 U.T. current sheet crossings are associated with barely detectable density signatures, and as a result the temperature must be rather high or dynamical processes must balance the magnetic stress at this time. At the 10:15 U.T. crossing for example, a highly anisotropic field-aligned beam of energetic ions up to $\approx 200$ keV were observed by the HiScale instrument (Sarris, 1993, personal communication).

Magnetodisk current sheet crossings in which $n_e$ anti-correlates with the field strength dominate the latter half of the day. The spacecraft passes through a local minimum
in magnetic latitude shortly after 15:00 U.T. The double encounter with a current sheet and density enhancements is near the minimum. The density peaks are of the order of 0.06 cm$^{-3}$, higher by a factor of 2 than the values in the outer magnetosphere. However, the field external to the sheet is of the order of 7 nT, and the net result is that the thermal energy is deduced to be of the order of a few keV, and is similar to that derived earlier. Despite the occurrence near the minimum latitude, the presence of a large $B_z$ component which changes sign as the radial
component changes sign at 17:30 U.T. indicates that the current sheet is still warped in shape at this time.

**Day 37: the middle magnetosphere**

The spacecraft starts Day 37 some $53.5R_J$ from the planet. Figure 1 shows that the spacecraft is now firmly within the middle magnetosphere, the radial component is the completely dominant field component and the field structure is dominated by the periodic current sheet crossings which are now occurring shortly after the spacecraft passes through the minimum in latitude as the planet rotates. The data can be seen in Fig. 7 for $B_r + 5$ nT and log ($n_e$). The first current sheet encounter takes place between about 01:00 and 04:00 U.T. (10 h after the previous one). The spacecraft enters a region where the field is radially towards the planet, in which the density is high on the other side of the reversal. The lack of symmetry suggests that the spacecraft does not fully exit the current sheet. The maximum density is about 0.1 cm$^{-3}$. Ten hours later, multiple sheet encounters are detected. The multiple nature of the encounter implies that the sheet is still not a rigid disk structure, but is undergoing some form of dynamic process. The spacecraft only marginally detects a reversed radial field near the minimum in latitude ($3\phi$). The density anti-correlates with the radial field strength. Ten hours later, at about 22:00 U.T., the spacecraft appears to brush the sheet. Once again, there are multiple encounters with the density and the radial field component anti-correlating.

**Conclusions**

We have reported a comparison of the magnetic field measurements made on the Ulysses spacecraft inbound pass through the outer regions of the jovian magnetosphere and the electron density as determined from the URAP radio and plasma wave instrument on the same spacecraft. The data reported here were recorded as the spacecraft moved from a distance of 108 to $34R_J$ from the centre of the planet over 4 days. This preliminary comparison certainly suggests that further comparison will be worthwhile, particularly in elucidating what the structure is and which processes govern the outer edge of the magnetodisk and outer magnetosphere.

There is no simple uniform relationship between $n_e$ and $|B|$ that holds throughout Days 34-37. Good order is achieved by the end of the period where, on Day 37, the spacecraft is in the middle magnetosphere and making regular encounters with the magnetodisk and its allied plasma sheet. Here the electron density rises as the field falls as the spacecraft approaches the current sheet region. At the centre where the field strength disappears, the number density is of the order of 0.1 cm$^{-3}$. By Day 37, the spacecraft is moving between $53.5$ and $34R_J$. Although at this distance the magnetodisk current structure is encountered as the spacecraft passes through the lowest magnetic latitudes, there is still evidence that the structure is not static, as evidenced by the coupled field and density disturbances seen on each side of the sheet encounters and which are likely to be due to oscillations of the sheet.

On Day 36, the regular current sheet encounters start appearing in both the field and density data. Initially, the
encounters seem not to be associated with any preferential magnetic latitude and we conclude that the outer magnetodisk is likely to be highly distorted in shape. This distortion of the magnetodisk was discussed by Behannon et al. (1981) in the context of the magnetotail, with a number of models being put forward to describe its shape. The first 6 h of Day 36 marked what we regard as the transition between the outer and middle magnetospheres, during which time the B, and B components are rivalling for predominance. Here drop-outs in the field strength can sometimes be associated with radial field configurations where the field reverses, and sometimes with pre-dominantly North–South fields. The former are no doubt encounters with the distorted outer edge of the current sheets, whilst the latter are instances of the events identified by Haynes et al. (1993) as field nulls. There may be some direct connection between the two types of events (as Haynes et al. speculate). The nulls may be evidence of material breaking off from the outer edge of the magnetodisk and detaching from the planet. If this were so, one clearly expects the density to rise in the centre of events, and for the bulk of events this is so. However, there are circumstances where the field and density change in phase, an effect that is most easily understood if dynamical changes are under way. Interestingly, the centre of the null event reported in detail by Haynes et al. is an instance where the density drops as the field drops out. We concluded that the thermal energy would have to be of the order of 20 keV for pressure balance (Krimigis et al., 1981) and there is an implication that substantial heating (or acceleration) would have to have occurred in the formation of the event. Elsewhere pressure balance arguments suggest that thermal energies should be lower ($\approx 1$ keV).

Null field events largely associated with density enhancements are the dominant feature of much of the outer magnetosphere. Embedded within the outer magnetospheric data examined here is a lengthy encounter with the magnetosheath and a relatively thick boundary layer. The density in the sheath and boundary layer is substantially higher than anywhere else in the outer magnetosphere. We concluded that the boundary layer could have been formed by magnetic reconnection between the planetary field and the interplanetary field.

The work should be regarded as only a first pass through the data. It is clear that comparison of the two data sets has opened up various questions; we expect to continue with other multi-instrument studies of the Ulysses Jovian flyby data.

References


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