The fluctuating magnetic field in the middle jovian magnetosphere: initial Galileo observations


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Abstract

The region of the jovian magnetosphere from 10–24 planetary radii is a region of strong, nearly dipolar, magnetic field through which the plasma added to the Io torus must pass as it convects and diffuses outward to the magnetodisk region and ultimately to be lost down the tail. Magnetic fluctuations can be used to diagnose the processes present in this plasma. Herein we examine magnetic fluctuations at frequencies below 0.04 Hz observed in the middle magnetosphere on a single pass of the Galileo spacecraft. These frequencies are generally well below the ion gyro-frequencies in this portion of the magnetosphere. Near perijove, about 10.7 R_J on this orbit, the equatorial region is not more disturbed than off the equator, but it is quite disturbed at the outer edge of this dipolar region near 24 R_J where the magnetic field becomes weak. These fluctuations are quasi-periodic, strongly compressional, and incoherent resembling somewhat the mirror mode. Conversely, the region off the equator is quiet in this outer portion of the middle magnetosphere. In the quasi-dipolar region there are irregular transverse fluctuations everywhere Galileo travels. Compressional transient events are also observed that may mark flux tube interchange. An unusual structure that could be due to the outward convection of Europa’s wake is also seen. In toto, these fluctuations indicate that the middle magnetosphere is a very dynamic region.

1. Introduction

Jupiter’s magnetosphere is unique in having a very strong source of plasma deep within it. The mass added to the magnetosphere by this source, the moon Io, cannot build up indefinitely. It will either be lost out the ends of the flux tubes or will undergo radial transport and eventually be lost down the tail. At Io where the mass is initially added to the magnetosphere, the ion distribution becomes highly anisotropic at least for SO_2, and copious waves are generated that can scatter these ions (Kivelson et al., 1996; Huddleston et al., 1997; Warnecke et al., 1997). However, more than 20 Io radii away from Io these ion cyclotron waves disappear and there is very little wave activity to scatter the particles from the equatorial region. Thus the ion density is believed to build up until outward forces such as the plasma pressure and the centrifugal force are sufficient to power outward transport of the mass loaded flux tubes (Pontius et al., 1986; Pontius and Hill, 1989; Southwood and Kivelson 1987; 1989; Yang 1994). This process, originally applied to the rotating dense plasmasphere in the Earth’s magnetosphere by Richmond (1973), is called the interchange instability.

Evidence for interchange has been found in the torus by Galileo (Kivelson et al., 1997a). This process in fact may help power the standing hydromagnetic waves in this region discovered by Glassmeier et al. (1989) in the Voyager 1 magnetic field observations. We do not expect the interchange process necessarily to be steady, nor do we expect the radial transport to be loss-free.

Fluctuations in the magnetic field are both diagnostic of the processes occurring therein and may also be agents for particle scattering. Since the region to be traversed in moving from Io ultimately to the magnetotail is very large, even low amplitudes of fluctuations may be important. Five spacecraft have traversed this region prior to Galileo: Pioneer 10 and 11, Voyager 1 and 2, and Ulysses. The observations of the first four of these missions have been summarized by Khurana (1993) and Glassmeier (1995). Based on the Pioneer 10 and 11 observations, Kivelson (1976) showed that Jupiter’s magnetosphere can be divided into three regimes of ULF wave behavior. There is a turbulent boundary layer just inside the dayside and dawn magnetopause at all observed latitudes where the field is extremely disordered with perturbation amplitudes of between 5–10 nT, comparable to that of the background magnetic field. In the radial range 10–35 R_J, the equatorial region was disturbed and the high latitude...
region was quiet. Khurana and Kivelson (1989) confirmed this picture using the Voyager 1 and 2 magnetometer data and further examined the correlation between the plasma and field fluctuations. While the fluctuations in both field and plasma were correlated, the wave periods were much shorter than expected for field-aligned standing waves. Ulysses flew by Jupiter at generally high latitudes and observed only one 60-min interval of waves at near 60 R_J. These waves were linearly polarized, with about 6 min periods, transverse to the magnetic field with a peak-to-peak amplitude of 0.5 nT (Tsurutani et al., 1993; Krupp et al., 1996). Ulysses also encountered irregular fluctuations near the current sheet. Dougherty et al. (1997) have discussed one of these at 35 R_J in terms of ion cyclotron waves.

Keeping in mind the objective of both diagnosing processes present and determining the amplitude of waves responsible for particle scattering, we examine the nature of the fluctuations seen on Galileo’s second orbit of Jupiter on which it encountered Ganymede as shown in Fig. 1. This pass was chosen because it includes a significant amount of real time system (RTS) magnetic observations at a rate of once per 12 s. Unfortunately, the low downlink capability of the Galileo mission has required that the telemetry bits be carefully apportioned and the majority of these bits are used during the satellite encounters, leaving few bits for the rather long periods of ‘cruise’ through the magnetosphere proper. Over most of the magnetospheric portion of the orbits either there are no data gathered, or data are averaged over about 30 min from the memory readout system. When RTS are obtained it is usually at a rate of once every 24 s. The RTS data do not have sufficient temporal resolution to resolve ion cyclotron frequencies near 10 R_J where the sulfur ion cyclotron period is about 5 s but does have sufficient resolution near 20 R_J where the ion cyclotron period ranges from about 40–160 s as the spacecraft moves from high latitudes across the equator. However, the RTS data can readily resolve any field-aligned standing modes whose periods are expected to range from 20,000–100,000 s over the range 10–20 R_J (Khurana, 1993).

Figure 2 shows the magnetic field measured on this pass beginning at 28 R_J at 0800 UT on September 5, 1996 continuing in to 10.7 R_J at 1345 UT on September 7, 1996 and returning to 26 R_J at 1200 UT on September 9. The coordinate system is radially outward (B_R), southward along the rotational axis (B_u), and azimuthal in the direction of corotation (B_f). In this region the rotation of the planet is most evident in the radial component, that is outward in the northern hemisphere and inward in the southern hemisphere. Also evident is the strengthening of the B_u component with decreasing radial distance, so that near periapse the B_u component is the dominant component over the entire ±1° latitude band whereas at the outer edge of the region the radial component is dominant everywhere except right at the crossing of the equator. In this report we examine the regions near the equator and off the equator, both at the outer edge of the middle magnetosphere and deep in the middle magnetosphere, near 11 R_J.

2. The outer edge of the middle magnetosphere

Figure 3 shows the magnetic measurements from 1330–2330 UT on September 5, 1996 as Galileo moved from 26 R_J to 23 R_J. In accord with previous measurements it is evident that the equatorial region is noisy and that the high latitude regions are not (Kivelson, 1976; Khurana and Kivelson, 1989). The fluctuations are clearly largest where the magnetic field is weakest. Figure 4 shows a blowup of the second current sheet crossing from 2100–2205 UT on September 5. In this plot both the average magnetic field and the trend have been removed so that the waves can be more easily observed. The waves have a significant compressional component. At low frequencies as shown in Fig. 5 the compressional component and transverse components have similar powers. Above 4 mHz the transverse component dominates. In some aspects these waves are similar to the mirror mode waves seen in the Io wake (Russell et al., 1998) and in the magnetosphere of comet Halley (Russell et al., 1987) but these waves are more strongly compressional. The wave period range from 5–8 min and the amplitude gradually rises and falls as the magnetic equator is crossed. The oscillations exhibit little coherency as the relative amplitudes and phases of the signals change randomly over the
Fig. 1. Magnetic field measurements obtained by Galileo from 0939 on September 4, 1996 at a radial distance of 17 RJ to 0199 on September 8, 1996 at a radial distance of 15 RJ. The spacecraft passed through a closest approach to Jupiter of 0.6 RJ at 0226 UT on September 6. The measurements are in a coordinate system with $B_R$ measured radially outward, $B_u$ measured southward and $B_c$ measured in the direction of corotation.

Fig. 2. Magnetic field measurements obtained by Galileo from 0400 on September 5, 1996 at a radial distance of 28 RJ to 1200 on September 9, 1996, at a radial distance of 26 RJ. The spacecraft passed through a closest approach to Jupiter of 10.7 RJ at 1337 UT on September 7. The measurements are in a coordinate system with $B_R$ measured radially outward, $B_u$ measured southward and $B_c$ measured in the direction of corotation.

Fig. 3. Magnetic field measurements in the $R\phi\psi$ system for the period 1345–2245 UT on September 5, 1996, showing two crossings of the current sheet 26 and 23 RJ.
Fig. 3. High-pass filtered magnetic components in the $R\theta\phi$ coordinate system for the period 2100–2205 UT on September 5, 1996. The corner frequency of the filter is at 0.0009 Hz.

Fig. 4. Power spectral density of the signals seen in Fig. 3. The compressional spectrum is calculated from the magnitude of the field. The transverse spectral density is the trace of the spectral matrix minus the compressional power. The power shown has been summed over seven original frequency estimates from the Fast Fourier Transform.

Fig. 5. Power spectral density of the signals seen in Fig. 4. The compressional spectrum is calculated from the magnitude of the field. The transverse spectral density is the trace of the spectral matrix minus the compressional power. The power shown has been summed over seven original frequency estimates from the Fast Fourier Transform.

interval. The spectrum is quite steep, also reminiscent of the spectrum seen in the Io wake. Calculations of cross-spectra (not shown) also exhibit low coherence in agreement with the visual appearance of the data. The minimum variance direction points in the azimuthal direction so that the fluctuating field is mainly, but not completely, in the magnetic meridian.

The behavior at lowest latitudes is in strong distinction to that at higher latitudes in this region. Figure 6 shows the detrended magnetic field from 1700–1900 UT on September 5. The signals are very weak, about 0.1 nT rms in $B_r$ and mainly transverse to the field. The power spectrum in Fig. 7 verifies the weakness of these waves. The various peaks in the spectrum at 8 mHz and above may be aliased spin frequency harmonics.

3. The region near perijove

Perijove on this pass occurred at a distance of 10.67 $R_J$ at 1345 UT on September 7, 1996. Figure 8 shows the magnetic field measurements during the period of time 0700–1900 UT surrounding perijove. The $B_r$ component of the field is strong, $\sim 220$ nT, and steady throughout this entire period while the radial component and azimuthal component periodically reverse as the tilted magnetic dipole axis rotates every 10 h. The $B_\phi$ and $B_R$ components are 90° out of phase here, and not 180° as in the current sheet region where the phase lag is due to the bending back of the field out of the meridian plane. Here the phase lag is due to the tilt of the magnetic meridian relative to the local jovigraphic meridian. It is clear even
on this coarse resolution plot that the magnetic field is highly disturbed. The most obvious features are the compressional disturbances near 0900 and 1100 UT that appear to be almost wake-like in appearance and conjugate to each other lying equidistant from the equator crossing. The wake-like nature of the disturbance comes from the two enhanced field intervals separated by a weak field interval between them. There is very little disturbance in the azimuthal direction. When these two disturbances are seen Galileo is about 1.3 R\_J above (and below) the magnetic equator, 1.2 R\_J outside the orbit of Europa and 4.3 R\_J inside the orbit of Ganymede. We do not expect the field line through Galileo at a L-shell of 11.2 R\_J to approach that of Ganymede that at a minimum lies at an L-shell of 15 R\_J. Thus, this disturbance must be associated with Io or Europa. Io is almost 20° ahead of Europa as seen on two Galileo orbits later (Kivelson et al., 1997b), we believe this disturbance most likely represents the radially convected plume or wake of Europa. There seems to be a slight disturbance at 1430 UT and again at 2200 UT that could also be extended Europa disturbances. We note that the maximum L-value of Europa during a Jovian rotation is about 10.0 R\_J and the minimum L-value on this orbit was about 10.8 R\_J. At the times of these observations Galileo was at L-values of 11.2 and 10.9 R\_J. Europa was at the same System III longitudes 9.5 h earlier when Europa was at L-values of
Fig. 7. Magnetic measurements in the R\(\theta\phi\) system for the period 0700–1900 UT on September 6, 1995, when Galileo moved from 10.7 RJ through closest approach at 09.6 RJ and back out to 10.0 RJ. Thus these disturbances, if associated with Europa, represent a significant radial displacement of the material, (at least 0.8 RJ) and correspond to an outward velocity of about 3 km/s. If they are not associated with Europa, or Io, then we know no plausible mechanism to explain these features. In any event we can use the increase in the field strength to estimate the beta of the plasma to be 0.25 under the assumption that the field maximum at 0900 UT is an evacuated flux tube.

Fig. 8. Magnetic measurements in the R\(\theta\phi\) system for the period 0700–1900 UT on September 7, 1996, when Galileo moved from 11.4 RJ through closest approach at 10.7 RJ and back out to 11.1 RJ.

9.5 and 9.6 RJ, respectively. Thus these disturbances, if associated with Europa, represent a significant radial displacement of the material, (at least 0.8 RJ) and correspond to an outward velocity of about 3 km/s. If they are not associated with Europa, or Io, then we know no plausible mechanism to explain these features. In any event we can use the increase in the field strength to estimate the beta of the plasma to be 0.25 under the assumption that the field maximum at 0900 UT is an evacuated flux tube.

The equatorial noise in this region is not as intense as it is at the outer edge of the dipolar region. This is illustrated in Fig. 9 that shows the high-pass filtered records from 1440–1640 UT. (The change in amplitude of the high frequency noise on the \(B_\phi\) component at 1545 UT is due to the change of the 12 s rate to 24 s and the consequent change in the period of the aliased spin tone). The noise is in fact lowest in the vicinity of the current sheet crossing at 1540 UT. The power spectrum corresponding to these data is shown in Fig. 10 over the period from 1440–1545 when the data rate is once per 12 s. At high frequencies the noise is slightly greater transverse to the magnetic field. At low frequencies it is mainly compressional. Although the waves are much less intense here than near the equator at 25 RJ, the compressional power is similar in shape suggesting that the same (mirror) mode waves may be present here also.

In contrast to the equatorial noise, the high latitude noise is very much transverse. Figure 11 shows two h of high-pass filtered magnetic measurements at 10.7 RJ from 1145–1345 UT when Galileo was at its highest (negative) magnetic latitude. The waves are almost 10 nT amplitude peak to peak in the components and only about 2 nT peak to peak in the magnitude of the field. This behavior is confirmed in Fig. 12 that shows the compressional and transverse power spectra of these fluctuations. The transverse power is much greater than the compressional power at all frequencies, quite in contrast to the behavior shown near the equator in Fig. 10.

Non-oscillatory fluctuations are also occasionally seen in this region. Fig. 13 shows two hours of detrended magnetic field with the average field (~200 nT) removed for the period from 0440–0640 UT as Galileo moved from 11.9 to 11.4 RJ. The magnetic field at 0530 and 0540 has two sharp positive impulses. Similar but smaller negative impulses are seen at 0605, 0618 and 0623 UT. The positive impulses may represent empty or nearly empty flux tubes similar to those found in the Io torus. If so, then this suggests that the plasma beta of the surrounding (lower magnetic field strength) plasma here is about 0.07. Such less-dense tubes should move inward toward Jupiter. The negative-going spikes on the other hand suggest that these tubes contain plasma with a higher beta and thus a higher density and/or temperature. These spikes indicate the presence of small scale features in the transport process. This inference is in contrast to
that drawn from the disturbance that appears to be due to the outward convection of the Europa wake. That event suggests a large scale, rather steady circulation pattern.

4. Discussion and conclusions

The magnetic field observations of fluctuations in the middle magnetosphere by the Galileo orbiter extend our understanding of the fluctuations in this region in important ways. There appears to be a measurable level of ambient fluctuations everywhere from 10.7 $\text{R}_J$ to 25 $\text{R}_J$, the outermost distance studied in this overview. The one exception to this statement is in the region well above and below the magnetodisk current sheet that is often referred to as the lobe, in analogy to the low-density lobes in the Earth’s magnetotail. Here the signals lie close to the noise level of the magnetometer. The waves in the current layer in this outer part of the quasi-dipolar magnetosphere where the field strength becomes weak appear to be mirror mode waves. This mode becomes unstable when $P_\perp/P_\parallel > 1 + 1/\beta_\perp$. We would expect that the atmospheric loss cone helps maintain an overall $P_\perp/P_\parallel > 1$ in the dipolar magnetosphere region and that the lowest threshold for instability would occur in the neighborhood of the current sheet where $\beta_\perp$ is large. By itself the small size of the atmospheric loss cone should not cause much anisotropy, but pitch angle scattering could with time broaden the hole in the particle distribution around the magnetic field direction. The clues that these fluctuations are indeed mirror mode structures are that the structures are quasi-periodic i.e., they all have roughly the same dimensions but they are not regularly spaced, that they are strongly compressional structures appearing to be
The high pass filtered magnetic field in R/φ coordinates for the period 1145-1345 UT on September 7, 1996, when Galileo was at a distance of 10.7 R_J and near maximum negative magnetic latitude. The corner frequency of the high pass filter was 0.0009 Hz.

Fig. 11. The power spectra of the signals shown in Fig. 11.

Fig. 12. The power spectra of the signals shown in Fig. 11.

'holes' in a stronger background magnetic field, and that they have a very steep spectrum with most power at long wavelengths. This mode is important because it provides a mechanism for scattering ions from the equatorial regions. This enhances particle losses to the atmosphere.

The presence of similar fluctuations, albeit at a lower level, at smaller radial distances indicates that this mechanism works over a wide radial range even though it is strongest in the outer regions. At the lower altitudes in fact the equator seems to be quieter than the off-equatorial regions. These off-equator fluctuations are strongly transverse to the magnetic field and as such contribute to pitch angle scattering.

The appearance of what appears to be a segment of the wake of Europa two jovian radii outside the orbit of Europa, while at first surprising, is consistent with plasma observations on Pioneer 10 and possibly on Voyager 2 (Intriligator and Miller, 1982). In order to be seen at Galileo, the wake would have to remain intact as it corotated with Jupiter for almost 10 h at a minimum assuming that the 'plume' we encountered had encircled Jupiter only once. This corresponds to a radial convection velocity of about 3 km/s. If the plume circled Jupiter several times before reaching Galileo, it could have a radial velocity some submultiple of this value. We might not expect the plume to be continuous as the production of the plume is probably greatest when Europa is in the plasma sheet. Thus we cannot simply count the number of plume encounters as a function of radial distance to deduce the radial velocity. At times the plasma may be too weak to have a magnetic signature.

Intriligator and Miller (1982) observed plasma enhancements at radial distances just external to Europa’s orbit and deduced from their spacing a radial velocity of 0.37 km/s. They also deduced a velocity of 1 km/s from similar data on Voyager 2. Assuming that the Europa plume is also not always detectable by the plasma
detectors these estimates are mutually consistent. The lowest inferred velocity 0.4 km/s is most probably typical of this region of space.

Overall, the nature of the magnetic fluctuations suggest a very dynamic middle magnetosphere. The appearance of various structures in the magnetic field suggest the presence of significant radial transport both on a small scale, flux tube level and more globally. The structure that resembled the wake of Europa was seen on several occasions during the Galileo passage. Pulses and dips in the field suggest the presence of underdense and over-dense tubes of plasma. Such non-uniformities in the rapidly rotating jovian magnetosphere will lead to radial transport, due to the buoyancy of the lighter flux tubes. The motion of the over-dense flux tubes into lower field strength regions will lower the perpendicular energy of the particles, decreasing their pitch angles and leading to increased ion precipitation.

Acknowledgments

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