ULF Wave Observations in Jupiter’s Magnetosphere

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ABSTRACT

In previous work we have examined magnetometer data from the Ulysses Jupiter flyby, and in particular middle magnetosphere observations in the vicinity of the magnetodisk. Waves transverse to the background magnetic field were found in the heavy ion gyrofrequency regime, a signature of Ion Cyclotron (IC) waves. We examined the dayside and high latitude duskside high resolution 1 sec data. Wave signatures were observed on several occasions both close to the magnetic equator and at some distance from it. Lower mass ion signatures were observed further away from the planet and the heaviest mass ion signatures appear closer to the Io torus although still at some distance from it. IC waves and their propagation properties can be used as a diagnostic of the particle species in a multicomponent plasma. Here we present polarization analysis of a portion of the Ulysses magnetometer wave observations in the middle Jovian magnetosphere during the inbound pass and close to plasma sheet approaches. The analysis show transverse waves in the heavy ion gyrofrequency regime with left-hand polarization in some cases and right-hand polarisation in others. We discuss these results in terms of polarization reversal properties of ULF waves propagating in a multicomponent plasma. © 2001 COSPAR. Published by Elsevier Science Ltd. All rights reserved.

Introduction and Method

There are several neutral atoms and ions present in the Jovian magnetosphere, arising from Jupiter’s moons, possibly through sputtering from high energy particles. Atoms become ionised and are then transported outwards and become part of the plasma sheet. The magnetospheric material are mainly sulfur and oxygen ions such as $O^+$, $S^{4+}$, $S^{3+}$, $O^{+}$, $S^{2+}$, $S^{+}$, $SO_2^+$, also Na$^+$, K and, possibly icy materials are present along with solar wind particles and ions from the Jovian ionosphere (see e.g. Bagenal (1994)), making the magnetospheric plasma a multicomponent one. In a cold multicomponent plasma the dispersion relation for IC waves shows that such waves occur below the gyrofrequency of the heaviest ion in the distribution and for limited bands of higher frequencies. If the mass-to-charge ratios of ions in a multicomponent plasma are not known, they can be found from a knowledge of the ion gyrofrequency resonances and additional characteristic frequencies (Smith and Brice (1964)). The crossover frequency is such an additional frequency, at which the phase speed of the L and R wave modes have the same phase velocity. For oblique propagation waves become linearly polarized at the crossover frequency. They reverse their natural polarization from left to right (or vice versa) as the wave frequency transverses the crossover frequency (Rauch and Roux, 1982).

In Petkaki and Dougherty (2000) we revisit the Ulysses magnetometer data of the middle magnetosphere and searched for wave signatures. We presented an overview analysis of the Ulysses magnetometer data obtained during both the inbound and outbound passes. We found signatures of waves transverse to the background field and close to gyrofrequencies of ions abundant in the Jovian middle magnetosphere. Signatures are found during days 36, 37, 38 of the inbound Ulysses pass and 41, 42 of the outbound pass. In this paper we present polarization analysis of the Ulysses magnetometer data inside the middle Jovian magnetosphere, of wave signatures occurring during the inbound pass of the spacecraft and close to the plasma sheet at distances of $\sim 46$ to $\sim 34 \, R_J$ from the planet (along the magnetic equator). Some of the wave signatures show left-hand polarization and some right-hand polarization. The presence of waves with both polarizations could be explained if the waves reverse their polarization when they transverse the crossover frequency between consecutive ions as they travel along the magnetic field lines, the efficiency of the reversal...
Ulysses Flyby of Jupiter in Magnetic Coordinates, day 36 to 38

Fig. 1. Ulysses Trajectory inside the Jovian Magnetosphere shown here in magnetic coordinates. Jupiter lies in the origin of the axes of the coordinate system. Horizontal axis is along the magnetic equator where the plasma sheet lies. Perpendicular axis is along the magnetic dipole axis. Units are in Jovian radii. The numbers next to the curve correspond to the beginning of the day of 1992 that the spacecraft was in the Jovian Magnetosphere. Dark marks on Days, 36, 37, 38, inbound are the wave events that we found. Crosses and circles denote time intervals of one hour.

depending on the angle of propagation to the magnetic field (Rauch and Roux, 1982).

High resolution Ulysses magnetometer data is of one second resolution. In analysing the data we introduce a running window average of 120 seconds, stepping every second. From the Jovian system III coordinates we transfer the data into field aligned coordinates (FAC). We define Z as along the background field which is essentially in the radial direction in the middle magnetosphere. X is in the meridian (north-south direction) and Y is then closing the system of coordinates (Petkaki and Dougherty, 2000a). Any transverse waves will appear as disturbances in the X and Y directions, and any compressional waves will appear as disturbances in the Z direction. We fast Fourier transform the data and compute the dynamic power spectrum using standard routines. In the power spectra plots we overplot the gyrofrequencies of ions with mass per unit charge of 16 (O+, S+++), 23 (Na+), 32 (S+), 39 (K+), 48 (SO+), and 64 (SO;). Doppler shift of the waves due to the motion of the spacecraft in the middle Jovina magnetosphere plasma is not important. In order to identify the type of waves occurring, polarization analysis of the waves is an important tool. Polarization analysis of waves when a spectrum of wave frequencies is present can be inconclusive. For this we filter out fluctuations and thereby obtain quasi-monochromatic waves. We filter the transverse components using a band-pass filter centered on the frequency of the peak with highest power in the power spectrum. Hodograms of the filtered components of B_z and B_y show the polarization of the waves in the specific frequency range and in the plane perpendicular to the direction of B_z. We use standard MATLAB routines to design band-pass, elliptic filters, with 0.1 decibels of ripple in the passband and a stopband of 20 decibels down.
Observations and Results

Ulysses flew by Jupiter during February 1992 with its inbound trajectory being in the late morning sector and the outbound trajectory being in the dusk sector, south of the planetary equator at high latitudes. Ulysses observations in this region show periodic depressions in field strength, detected about every 10 hours, produced by encounters with or approaches to the magnetodisk (Balogh et al., 1992). We examine high resolution (one second) data from the Ulysses vector helium magnetometer taken during day 37 of the Jupiter flyby, that is over radial distances of 46 to 34 $R_J$ inbound. Several IC events were found. A summary plot of the results is shown in Figure 1 where part of Ulysses trajectory inside the Jovian magnetosphere is shown. Events are present close to the magnetodisk which lies close to the magnetic equator but also at some distance from it.

During day 37 Ulysses had three current sheet encounters, at distances between 53 and 34 $R_J$. The second current sheet encounter on day 37 takes place between 11:00 and 12:30. Just before the encounter around 10:00 wave activity is observed. The spacecraft is at distance 45.5 $R_J$ from the planet and along the magnetic equator and 2.8 $R_J$ from the planet and along the magnetic rotation axis. The highest power in transverse components is 20 nT$^2$/Hz. Wave activity starts at 09:51 and goes on to 10:15. Peaks are found near ratios 32, 16, and 8. At ratio 32 the compressional component peaks with the transverse components. The highest power corresponds to mass/charge ratio of 16 (Fig. 2). After the current sheet encounter at
Fig. 3. Power spectrum of magnetic field data in Field Aligned coordinates $B_x$ (continuous curve), $B_y$ (bold curve), $B_z$ (dashed dotted curve), and magnetic field magnitude $B_m$ (continuous line on top of the $B_z$ curve) of day 37 from 13:20 to 13:38. The vertical lines denote the gyrofrequencies of mass/charge ratios 48, 32, 16, 14, 8 and 32/5.

13:21-13:37, the $B_x$ component shows high power at a frequency of $\sim 6$ mHz (ratio 32), at $\sim 15$ mHz (ratio 16), and at $\sim 20$ mHz (ratio 8). $B_y$ peaks at the same frequencies but with significantly less power. The spacecraft is at a distance $42 R_J$ from the planet and along the magnetic equator and $9.6 R_J$ from the planet and along the magnetic rotation axis. The highest power in transverse components is $40 nT^2/Hz$ (Fig. 3).

We proceed with the polarisation analysis of the events. In the event of day 37, 09:50-10:08 UT the wave amplitude maximum is close to $\sim 8$ mHz. We filtered the data using a bandpass filter of 6.5-9.8 mHz which is centered around $\sim 8$ mHz. The hodogram of the filtered components of $B_x$ and $B_y$ shows lefthand (LH) elliptical polarisation for longer than 5 wave periods (Figure 4). In the event of day 37, 13:20 to 13:38 UT the wave amplitude maximum is close to a frequency $\sim 6.5$ mHz. We filtered the data using a bandpass filter of 5.5-7.2 mHz which is centered around $\sim 6.5$ mHz. The hodogram of the filtered components of $B_x$ and $B_y$ shows righthand (RH) elliptical polarisation for longer than 5 wave periods (Figure 5).

For field aligned wave propagation in a cold plasma, the two possible electromagnetic wave modes are either LH or RH circularly polarised (Smith and Brice, 1964). In the more general case of oblique propagation the fluctuating electric field vector $\epsilon$ of each permitted wave mode contains both LH and RH polarised components. When a plasma contains more than one ion species, a set of characteristic crossover frequencies, $\omega_{CR}$, exist for which the RH and LH modes propagate at the same parallel phase velocity. These occur between each adjacent pair of gyrofrequencies, $\Omega_c$, at a frequency controlled by the fractional ion charge.

![Power Spectrum of Bx, By, Bz, Bm components](image-url)
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Fig. 4. Hodograms of the filtered components of $B_x$ and $B_y$, day 37, 09:55-10:08 UT of Ulysses Flyby of Jupiter. The wave shows left-handed polarisation in the frequency band 6.5-9.8 mHz.

densities (Petkaki and Dougherty, 2001). Waves may be generated with LH polarization (for non-relativistic particles) and for propagation at an angle they change polarization (Rauch and Roux, 1982). They become linearly polarised at each $\omega_{CR}$. Each wave mode exhibits a natural reversal of its predominant polarization as the wave transverses the crossover condition owing to propagation within an inhomogeneous plasma. The presence of transverse waves close to the $\Omega_e$ of ions resident in the Jovian magnetosphere with RH polarisation could mean two things. Either that the waves were generated by relativistic negatively charged ions or that the waves as they propagate through the inhomogeneous Jovian plasma they transversed the $\omega_{CR}$ and they have reversed their polarisation. We introduce in Eq. 3 of Thorne and Moses (1985) the ion compositions of the eleven ions from Keppler et al. (1992) and solve the equation to find the crossover frequencies for the local magnetic field strength. The ions are $\text{Fe}^+$, $\text{Si}^+$, $\text{Mg}^+$, $\text{Na}^+$, $\text{Ne}^+$, $\text{O}^+$, $\text{N}^+$, $\text{C}^+$, $\text{He}^+$, and $\text{H}^+$. The $\omega_{CR}$ between $\text{Na}^+$ and $\text{Ne}^+$ is $\omega_{CR} = 8$ mHz, during the event on day 37, $\sim 10:00$ UT which has wave frequency also close to 8 mHz. The wave is LH polarised so it has not transversed a $\omega_{CR}$. The propagation of the wave at this frequency could suggest that $\text{Ne}^+$ is not present in the plasma sheet at this location since there should exist a stopband close to the $\Omega_e$ (8.1 mHz) of this ion. Of course this interpretation changes if the waves are created from pickup ions. During the event $\sim 13:00$ UT, the wave frequency is $\sim 6.5$ mHz but the peak is very wide. Several ion $\Omega_e$ are in the same frequency range (Fig. 3). It is not straightforward to make conclusions about the presence or not of different ions. For further discussion of these phenomena see also Petkaki and Dougherty (2001).
Fig. 5. Hodograms of the filtered components of $B_z$ and $B_y$, day 37, 13:20-13:38 UT of Ulysses Flyby of Jupiter. The wave shows righthand polarisation in the frequency band 5.5-7.2 mHz.

REFERENCES


