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PLASMA WAVE OBSERVATIONS FROM THE ULYSSES SPACECRAFT'S FAST HELIOGRAPHIC LATITUDE SCAN

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ABSTRACT

Plasma wave observations obtained by the Ulysses spacecraft in 1994 and 1995 over a heliographic latitude range of -70 to +70° show significantly different wave characteristics inside and outside the streamer belt. Langmuir wave bursts are most commonly found in magnetic holes, especially in fast solar wind. The intensities of ion-acoustic-like waves are reduced at high latitudes. Low frequency electrostatic wave levels show variations that may correlate with solar wind velocity. The maximum levels of whistler waves are correlated with magnetic field magnitude.

INTRODUCTION

The highly-inclined, elliptical orbit of the Ulysses spacecraft around the Sun has a perihelion at 1.3 AU and an aphelion at 5.4 AU. As a consequence, the perihelion pass covers -70° to +70° of heliographic latitude in less than 8 months (see Figure 1); Ulysses is the first spacecraft to provide in situ observations at these high heliographic latitudes. Furthermore, this rapid South-to-North pass through the interplanetary medium, known as the "fast latitude scan", provided observations that are nearly independent of radial distance and evolution of the solar cycle. The Unified Radio and Plasma Wave Investigation (URAP) on Ulysses measures electric fields from DC to 940 kHz and magnetic fields from 0.22 to 450 Hz (Stone *et al.*, 1992; MacDowall *et al.*, 1996a). These observations extend the exploration of the solar wind plasma wave environment initiated by wave instruments on the Helios, Voyager, ISEE, and other spacecraft. In this paper, we present in situ wave data of 10-minute time resolution for the fast latitude scan interval. The data from approximately -20° to +20° correspond to the interval when the heliospheric current sheet repeatedly intercepted the Ulysses spacecraft (Balogh *et al.*, 1995). The intensity and variability of the wave activity, as well as the solar wind and magnetic field parameters, usually differ significantly inside and outside the streamer belt because of the much larger number of discontinuities in and near the streamer belt and because of intrinsic differences between fast and slow solar wind.

Plasma waves observed in the frequency ranges of the URAP instruments are typically divided into three classes: Langmuir waves, ion-acoustic-like waves, and whistler waves (c.f., Gurnett, 1991), although it is recognized that this classification scheme is overly simplistic. Indeed, there remain numerous questions about the source mechanisms and evolution of most of the plasma wave modes occurring in the solar wind. Ulysses measurements can play a key role in improving the understanding of these waves because of the wide range of plasma parameters observed as the spacecraft pursues its elliptical orbit over the poles of the Sun.

WAVES AT THE ELECTRON PLASMA FREQUENCY (f_{pe})

The electrostatic fields observed at approximately f_{pe} are generally assumed to be Langmuir waves. As seen in Figure

2(a), the intensities of the electric fields at ~f_{pe} are frequently much higher outside of -20° to +20° than inside. (Note that the wave activity for panels (a) and (b) in Figure 2 does not correspond to constant frequencies. In order to relate the observed waves more directly to characteristic frequencies of the plasma, panel (a) in Figure 2 uses the wave data obtained at the frequency closest to the electron plasma frequency; panel (b) uses the frequency $f_{pe}/3$. The values of f_{pe} used for this purpose have been derived from the electron thermal noise spectrum observed by the URAP radio receiver (Meyer-Vernet and Perche, 1989, Hoang *et al.*, 1996)). The plasma frequency in the streamer belt is usually much higher than at high latitudes; compare the plot of plasma density (panel (e), which is derived from the observed f_{pe} data). The probability of wave activity greater than 5×10^{-6} V $Hz^{-1/2}$ occurring outside of the streamer belt is more than 3 times the probability inside the streamer belt (MacDowall *et al.*, 1996a). Although Langmuir waves are often caused by the electrons associated with type III bursts or with shocks, the Langmuir wave activity at high heliographic latitudes is almost exclusively associated with magnetic holes or other magnetic field discontinuities (Lin *et al.*, 1995; 1996a). In the fast latitude scan data (Figure 2(a)) there are only two short intervals of Langmuir waves that are unambiguously associated with electron streams producing type III radio bursts (bursts of Langmuir waves occurring at approximately 7°). Shocks are also few in number during this interval; the latitudes of the shocks observed at Ulysses are indicated on Figure 2 by dashed lines (R. J. Forsyth, private communication). As suggested by the greater likelihood of bursty wave activity at high latitudes, magnetic holes are more common in the fast (high-latitude) solar wind, although they also occur in the streamer belt (Winterhalter *et al.*, 1994; Balogh *et al.*, 1995).

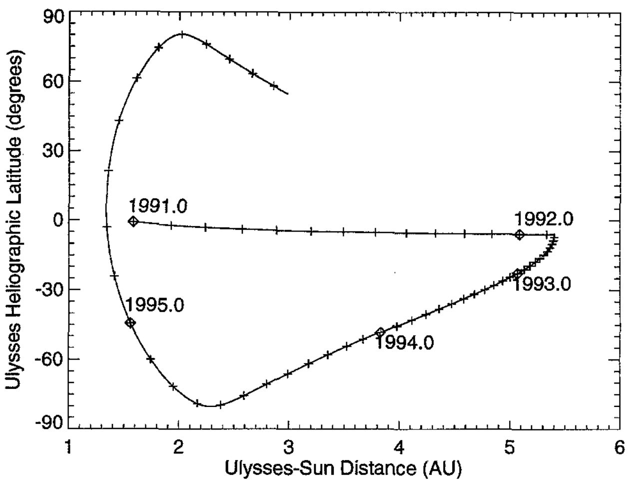

Fig. 1. Position of Ulysses as a function of distance from the Sun (AU) and heliographic latitude (degrees). Tick marks indicate the start of each month; diamonds indicate the start of each year.

The detailed explanation of the generation of Langmuir waves inside magnetic holes is not yet available, although it seems certain that it depends on unusual characteristics of the electron distribution function in magnetic holes. It has been noted by MacDowall *et al.* (1996b) that conservation of magnetic moment could produce "anti-loss cone" electron distributions inside magnetic holes. Southwood and Kivelson (1993) have discussed similar consequences for ions in magnetic holes. Meyer-Vernet and Hoang (1996) have suggested that the resulting "anti-loss cone" distribution would also generate low frequency waves, which might be Doppler shifted into the f_{pe} regime. Furthermore, magnetic holes are also associated with electrostatic and electromagnetic waves at lower frequencies (Lin *et al.*, 1995).

WAVES AT APPROXIMATELY $f_{pe}/3$

As seen in Figure 2(b), the waves at $f_{pe}/3$ show a behavior very different from those at f_{pe} (presented in Figure 2(a)). The most intense wave activity occurs inside the streamer belt, and the observed levels are modulated as the spacecraft flies through fast and slow speed streams. The waves in this frequency range (typically 0.2-0.5 f_{pe}) are most often proposed to be ion acoustic waves that are Doppler shifted into the frequency range of observation by the solar wind velocity. It can be seen that the average wave intensity is alternatively higher and lower in the streamer belt, compared to that at high latitudes. The comparison of Figures 2(b) and 2(a) indicates that ion-acoustic-like wave occurrence is controlled by parameters significantly different from the Langmuir wave regime. It is expected that the temperature ratio T_e/T_p should play a key role because ion-acoustic waves are rapidly damped unless $T_e/T_p \gg 1$. Indeed, it has been shown elsewhere (Gurnett *et al.*, 1979, Hess *et al.*, 1996) that the intensity or occurrence probability of these waves is correlated with T_e/T_p. Nevertheless, the levels of wave activity remain quite high when $T_e/T_p \lesssim 1$, strongly suggesting that they are not the ion-acoustic mode (MacDowall *et al.*, 1996).

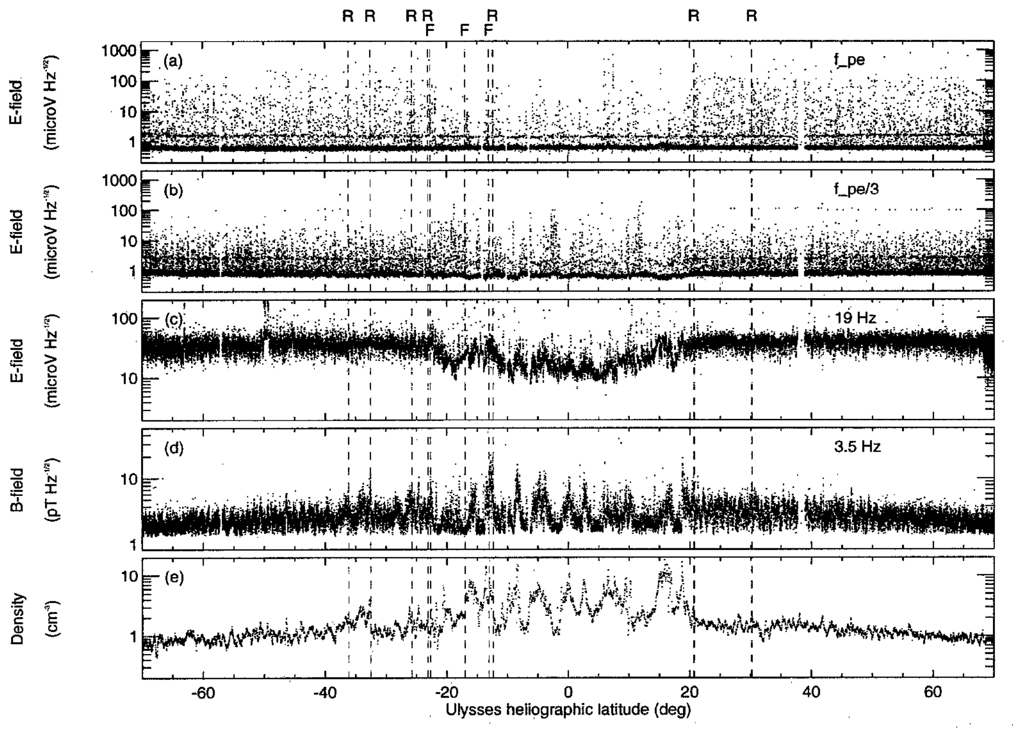

Fig. 2. Plots of wave data (10 min time resolution) from the Ulysses fast latitude scan for heliographic latitudes from -70 to +70°. Dashed lines indicate the occurrences of forward and reverse shocks, labeled F and R, respectively.

ELECTROSTATIC AND ELECTROMAGNETIC ULF WAVES

In Figure 2(c), the 19 Hz electric field data show a rapidly fluctuating signal level, in the restricted range from about 2 to 6×10^{-5} V $Hz^{-1/2}$, while the spacecraft is outside of the streamer belt. The 19 Hz electric field undergoes a profound change during the passage through the streamer belt. Note that outside of the streamer belt, the 19 Hz signal shows relatively small variations with only occasional events occurring above the typical signal level. Inside the streamer belt, there is a gradual decrease, modulated by passages through the current sheet. There are some similarities in the evolution of this signal level and the variation of the solar wind velocity. The conventional assumption might be that the 19 Hz signal is the electric component of whistler mode activity. It is likely that these variations depend on a combination of solar wind velocity and density (Lin *et al.*, 1996b). Further analysis is required to understand both the long-term trends and the short-term variability of this wave activity.

The 3.5 Hz search coil data in Figure 2 (d) show a high level of correlation with the magnetic field magnitude (not shown), as reported previously by Lengyel-Frey *et al.* (1994; 1996). As Ulysses passes through the streamer belt, the large variations in density and the associated changes in "frozen in" magnetic field result in variations of 3.5 Hz magnetic field that is alternately higher and lower than that observed outside the streamer belt. Outside the streamer belt, the magnetic field data show a highly variable, but otherwise structureless, signal level.

It has been proposed by Gary *et al.* (1994) and Scime *et al.* (1994) that the whistler heat-flux instability is the likely source of heat flux regulation in the solar wind. The variations in whistler wave levels observed during the fast latitude scan deserve examination from that perspective. Indeed, Lin *et al.* (1996b) present wave and electron data correlations that are consistent with this mechanism playing a key role in heat flux regulation.

Finally, it is significant that the 6-year orbit of Ulysses around the Sun will bring the spacecraft over the solar poles in 2000-2001 at approximately the maximum in the solar cycle. At that time, the wave activity observed by URAP should be substantially different from the activity levels reported in this paper. Solar radio bursts are expected to occur more frequently and with greater intensity. Waves associated with IP shocks and coronal mass ejections will also be more common. It will be particularly interesting to observe the impact of enhanced solar activity on waves in the high-latitude solar wind.

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REFERENCES

Balogh, A., E. J. Smith, B. J. Tsurutani, D. J. Southwood, R. J. Forsyth, and T. S. Horbury, The Heliospheric Magnetic Field over the south Polar Region of the Sun, *Science,* **268**, 1007 (1995).

Gary, S. P., E. E. Scime, J. L. Phillips, and W. C. Feldman, The Whistler Heat Flux Instability: Threshold Conditions in the Solar Wind, *J. Geophys. Res.,* **99**, 23, 391 (1994).

Gurnett, D. A., Waves and Instabilities, in *Physics of the Inner Heliosphere*, eds. R. Schwenn and E. Marsch, pp. 135-157, Springer-Verlag, Berlin (1991).

Gurnett, D. A., E. Marsh, W. Pilipp, R. Schwenn, and H. Rosenbauer, Ion Acoustic Waves and Related Plasma Observations in the Solar Wind, *J. Geophys. Res.*, **84**, 2029 (1979).

Hess, R. A., D. Lengyel-Frey, R.J. MacDowall, and B. J. Goldstein, Ion Acoustic Waves Observed by Ulysses near Interplanetary Shocks, *J. Geophys. Res.,* submitted (1996).

Hoang, S., N. Meyer-Vernet, K. Issautier, M. Maksimovic, and M. Moncuquet, Latitude Dependence of Solar Wind Plasma Thermal Noise: Ulysses Observations, *Astron. Astrophys.*, submitted (1996).

Lengyel-Frey, D., W.M. Farrell, R.G. Stone, A. Balogh, and R. Forsyth, An Analysis of Whistler Waves at Interplanetary Shocks, *J. Geophys. Res.,* **99**, 13325 (1994).

Lengyel-Frey, D., R. A. Hess, R. J. MacDowall, R.G. Stone, N. Lin, *et al.*, Ulysses Observations of Whistler Waves at Interplanetary Shocks and in the Solar Wind, *J. Geophys. Res.,* in press (1996).

Lin, N., P.J. Kellogg, R.J. MacDowall, A. Balogh, R.J. Forsyth, *et al.*, Observations of Plasma Waves in Magnetic Holes, *Geophys. Res. Let.,* **23**, 3417 (1995).

Lin, N., P. J. Kellogg, R. J. MacDowall, B. T. Tsurutani, and C. Ho, Langmuir Waves Associated with Discontinuities in the Solar Wind: a Statistical Study, *Astron. Astrophys.*, in press (1996a).

Lin, N., P.J. Kellogg, R.J. MacDowall, E.E. Scime, J.L. Phillips, *et al.*, Low Frequency Plasma Waves in the Solar Wind: from Ecliptic Plane to the Solar Polar Regions, *Adv. Space Res.*, submitted (1996b).

MacDowall, R.J., R.A. Hess, N. Lin, G. Thejappa, A. Balogh, and J.L. Phillips, Ulysses Spacecraft Observations of Radio and Plasma Waves: 1991-1995, *Astron. Astrophys.*, submitted (1996a).

MacDowall, R.J., N. Lin, P.J. Kellogg, A. Balogh, R.J. Forsyth, and M. Neugebauer, Langmuir Waves in Magnetic Holes: Source Mechanism and Consequences, *Proceedings, Solar Wind 8*, in press (1996b).

Meyer-Vernet, N. and S. Hoang, Anti-loss Cone Instabilities and Application in Magnetic Holes, *Geophys. Res. Let.*, submitted (1996).

Meyer-Vernet, N. and C. Perche, Tool Kit for Antennae and Thermal Noise near the Plasma Frequency, *J. Geophys. Res.*, **94**, 2405 (1989).

Scime, E. E., S. J. Bame, W. C. Feldman, S. P. Gary, and J. L. Phillips, Regulation of the Solar Wind Heat Flux from 1 to 5 AU: Ulysses Observations, *J. Geophys. Res.,* **99**, 23,401 (1994).

Southwood, D. J., and M. G. Kivelson, Mirror Instability: 1. Physical Mechanism of Linear Instability, *J. Geophys. Res.*, **98**, 9181 (1993).

Stone, R.G., J. L. Bougeret, J. Caldwell, P. Canu, Y. DeConchy, *et al.*, The Unified Radio and Plasma Wave Investigation, *Astron. Astrophys. Supp. Ser.*, **92**, 291 (1992).

Winterhalter, D., M. Neugebauer, B.E. Goldstein, E.J. Smith, S.J. Bame, *et al.*, Ulysses Field and Plasma Observations of Magnetic Holes in the Solar Wind and their Relation to Mirror-mode Structures, *J. Geophys. Res.*, **99**, 23,371 (1994).