LANGMUIR WAVE ACTIVITY: COMPARING THE *ULYSSES* SOLAR MINIMUM AND SOLAR MAXIMUM ORBITS

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Abstract. We examine the occurrence and intensity of Langmuir wave activity (electrostatic waves at the electron plasma frequency) during the solar minimum and solar maximum orbits of *Ulysses*. At high latitudes during the solar minimum orbit, occurrences of Langmuir waves in magnetic holes were frequent; in the second orbit, they were less common. This difference, in comparison with observations from the first *Ulysses* fast heliolatitude scan, suggests that Langmuir wave activity in magnetic holes is enhanced in solar wind from polar coronal holes.

In November 2000, the *Ulysses* spacecraft reached the highest southern heliographic latitude (−80.2°) of its second orbit around the Sun. Comparison of data from the solar maximum portion of the solar cycle to those of the previous, solar minimum orbit facilitates understanding of processes in the solar wind. In this paper, we examine Langmuir wave activity during the solar minimum and maximum orbits.

Langmuir waves are electrostatic plasma oscillations whose frequency is approximately the electron plasma frequency (f_{pe} (kHz) $\sim 9\, n_e^{1/2}$ (cm^{-3})). They are produced by instabilities involving fast electrons, such as those accelerated by solar flares or interplanetary shocks. They may also occur when a continuous source of energetic electrons is disrupted, creating unstable electron distribution functions. This mechanism may be the source for Langmuir waves in magnetic holes (Lin *et al.*, 1995), which are significant decreases in the magnitude of the magnetic field (Winterhalter *et al.*, 1994, and references therein); however, the mechanism is not well understood. An example of Langmuir waves and their correlation with magnetic holes is shown in Figure 1. Here, we present observations of such Langmuir waves as observed by the Plasma Frequency Receiver (PFR) of the *Ulysses* Unified Radio and Plasma Wave (URAP) investigation (Stone *et al.*, 1992).

During the first ‘fast’ heliolatitude scan (late 1994 to mid-1995) made by the *Ulysses* spacecraft, it was possible to study the occurrence of magnetic holes in the solar wind from −80° to +80° heliographic latitude. Winterhalter *et al.* (2000) found that at ∼30° north and south latitude the hole count rate dropped to ∼10%

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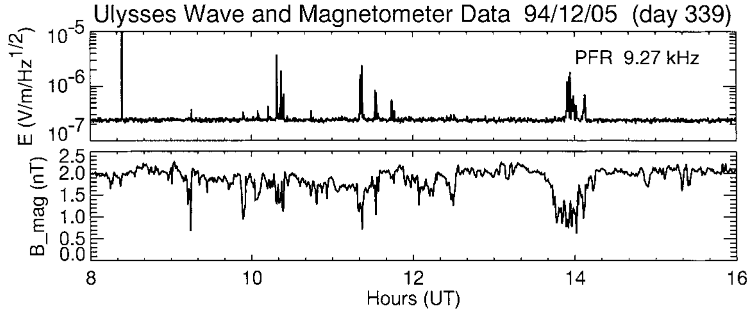

Figure 1. Ulysses example of correlated Langmuir waves and magnetic holes.

of that in the low latitude region and stayed constant at this level to near the poles. In making this comparison, the number of magnetic holes was normalized by the solar wind velocity (V_{SW}) to account for the larger volume of solar wind moving past the spacecraft when V_{SW} is larger. On the contrary, the Langmuir wave activity observed by the PFR increased significantly in the fast solar wind (MacDowall *et al.*, 1996). It is, therefore, interesting to examine the *Ulysses* data from the solar maximum orbit (through 2000) to determine if the same latitudinal variations occur, providing clues to the understanding of waves in magnetic holes.

In Figure 2, we show data from the PFR, as well as V_{SW} from the *Ulysses* SWOOPS instrument (Bame *et al.*, 1992). The top three panels correspond to the southern segment of the solar *minimum* orbit; repeated passes through well-defined corotating interaction regions are evident in V_{SW} (middle panel), as the spacecraft moved from low to high southern latitudes. By 1994, *Ulysses* was continuously in the fast solar wind from the southern polar coronal hole. The PFR data (top panel) are peak values during 1-hour intervals for the observing frequency closest to f_{pe} (derived from the SWOOPS ion densities). Receiver voltages have been divided by 35 m (one-half of the dipole antenna length) to obtain electric field. In the third panel, the fraction of peak values exceeding 0.5 μV m^{-1} Hz$^{-1/2}$ is plotted (26 day intervals). This limit was chosen so that only wave activity significantly greater than the background signal was selected, thereby rejecting the background levels due to receiver and spacecraft noise. The 26-day intervals smooth the effects of solar rotation, such as Langmuir waves at shocks upstream and downstream of corotating interaction regions. The dotted line is the mean value for the panel. Note that the fraction of peak values exceeding 0.5 μV m^{-1} Hz$^{-1/2}$ increased steadily beginning in late 1993, as *Ulysses* moved closer to the Sun and to higher latitudes. Several 'peaks' in this plot are due to broadband wave activity in magnetic clouds (labeled MC; they are presumed to be ion-acoustic waves (MacDowall and Kellogg, 2001; Thejappa and MacDowall, 2001)). The short wavelengths of the ion-acoustic waves permit their detection frequencies to be Doppler-shifted to f_{pe} or higher by fast solar wind.

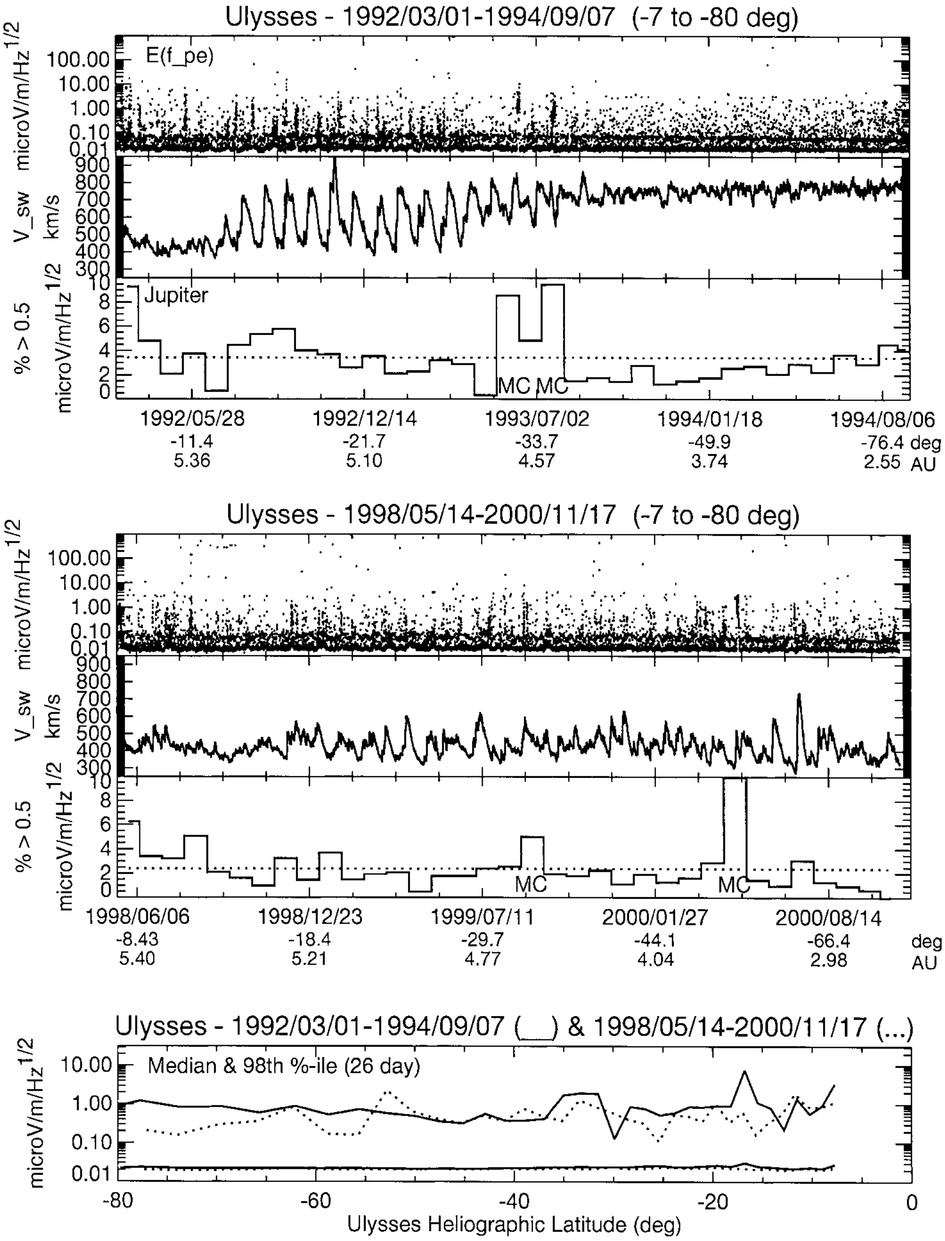

Figure 2. Ulysses Langmuir wave and solar wind velocity data for the intervals March 1, 1992 to September 7, 1992 and May 14, 1998 to November 17, 2000. (Detailed discussion in text.)

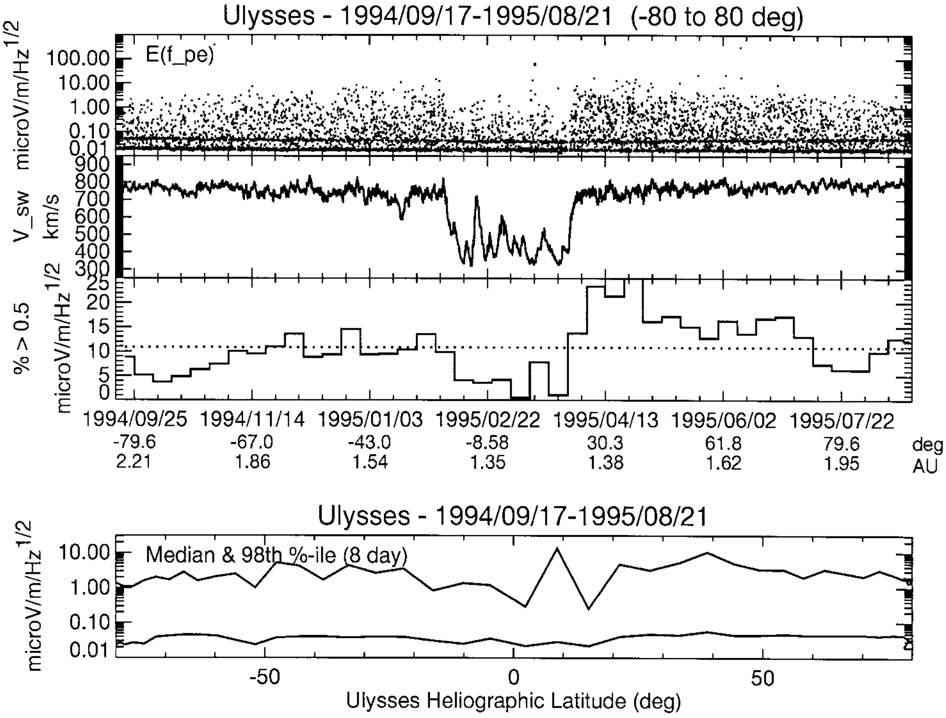

Figure 3. Ulysses Langmuir wave and solar wind velocity data for the interval September 17, 1994 to August 21, 1994. Note that the window interval for the histogram and bottom panels is 8 days. (Detailed discussion in text.)

The next 3-panel plot in Figure 2 shows similar data for the southern segment of the solar *maximum* orbit; the lack of fast solar wind from a polar coronal hole is evident. Throughout this interval, the sources of Langmuir waves are either shocks or magnetic holes. The fraction of peak values exceeding 0.5 μV m^{-1} Hz$^{-1/2}$ is lower, ~0.025 compared to 0.035 for the solar minimum orbit. In the bottom panel, medians and 98th-percentile values for each 26-day interval are plotted as a function of heliographic latitude. Because the wave activity is bursty and not continuous, the median serves as a good indication of the background level for the PFR. The 98th-percentile represents the peak electric fields because it excludes occasional intense noise signals caused by the instrument or the spacecraft. Note that the 98th-percentile values are comparable until the spacecraft approaches ~3 AU from the Sun (latitudes higher than ~60°), where the data values for the solar *minimum* orbit begin to increase to higher levels. This increase to higher electric field levels is apparently due to an increased occurrence probability for Langmuir waves in magnetic holes when *Ulysses* is closer to the Sun *and* in fast solar wind. Figure 3, where similar data are plotted for the first *Ulysses* fast latitude scan (FLS), is essentially a continuation of the time series for the solar minimum orbit. It shows that the 98th-percentiles continued to increase closer to the Sun,

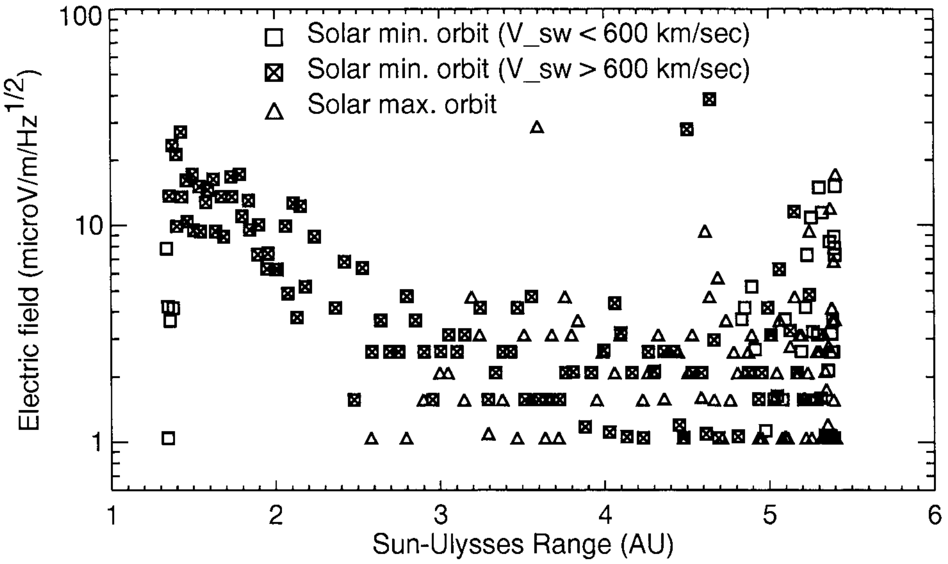

Figure 4. Electric field values (98th-percentile in 8-day intervals at f_{pe} as a function of *Ulysses* distance from the Sun.

reaching ~5 (10) μV m^{-1} Hz$^{-1/2}$ in the southern (northern) hemisphere. (There was no significant ion acoustic wave occurrence at f_{pe} in the FLS data, possibly because of the lack of magnetic clouds during the short time that *Ulysses* was near perihelion.) The fraction of peak values greater than 0.5 μV m^{-1} Hz$^{-1/2}$ was small in the slow solar wind at low latitudes; one 26-day interval was enhanced due to intense Langmuir waves from solar flare electrons.

A reasonable explanation for these results can be deduced from Figure 4, where the electric fields from the time intervals in Figures 2 and 3 are plotted versus the distance of *Ulysses* from the Sun. Here the 98th-percentile values were calculated for 8-day intervals. Different symbols indicate field values that are associated with the solar minimum or maximum orbits and with average V_{SW} for the interval being greater or less than 600 km s^{-1}. There are no occurrences of average V_{SW} greater than 600 km s^{-1} for the solar maximum orbit (see Figure 2). Considering first the values for the solar minimum orbit with V_{SW} <600 km s^{-1}, we find that these data occurred only at distances greater than 4.8 AU from the Sun or less that 1.4 AU from the Sun. These data do not show a significant trend with distance and have large scatter at a given distance. For the solar maximum orbit, there is a suggestion that the peak fields *increased* with increasing distance. This is quite surprising, since the peak Langmuir wave fields for type III radio bursts, for example, decrease with increasing distance from the Sun (Gurnett *et al.*, 1978). For the data with V_{SW} >600 km s^{-1}, this is indeed the case; the majority of field values greater than 10 μV m^{-1} Hz$^{-1/2}$ occur at distances from the Sun of 1.4 to 2.2 AU, whereas the fields beyond 2.5 AU are substantially smaller, with an increase near 5 AU.

Physical considerations suggest that a trend of decreasing field with increasing distance should occur, like that identified by Gurnett *et al.* (1978). In the *Ulysses* case, this effect is compensated because the spacecraft's highly elliptical orbit causes it to remain near 5 AU for much of the orbital period, greatly increasing the likelihood of detecting large and small events in this region. Conversely, *Ulysses* spends very little time inside 2 AU. Therefore, both the solar maximum orbit and the solar minimum orbit ($V_{SW} < 600$ km s^{-1}) observations do not show the expected decrease with increasing distance from the Sun. An analysis of Langmuir wave probability distributions as a function of distance and solar wind speed is required to better understand the consequences of the *Ulysses* orbit. The *enhanced* electric field levels closer to the Sun when $V_{SW} > 600$ km s^{-1} indicate that a strong source of Langmuir waves must exist in this region. When available, occurrence statistics of magnetic holes for the solar maximum orbit will be compared to the solar minimum results and will indicate whether the increase in Langmuir wave occurrence and intensity in the fast solar wind is due exclusively to the number of magnetic holes or to some aspect of the generation mechanism for the Langmuir waves. It is very likely to be the latter cause, based on the determination (Winterhalter *et al.*, 2000) that the rate of magnetic hole occurrence decreased, whereas the Langmuir wave occurrences increased in fast solar wind (MacDowall *et al.* 1996). Some characteristic(s) of the fast, uninterrupted solar wind from polar coronal hole flows may hold the key to understanding Langmuir waves in magnetic holes.

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