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doi: 10.1016/S0273-1177(03)00331-4

HELIOSPHERIC LANGMUIR WAVE OBSERVATIONS FROM THE ULYSSES SPACECRAFT

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ABSTRACT

Langmuir waves are electrostatic plasma oscillations produced by unstable electron beams in the solar wind and elsewhere. Typical electron sources are solar flares, shocks, and magnetic holes. In t his paper, we present an overview of the Langmuir waves observed by Ulysses during both its solar minimum and solar maximum orbits. Langmuir waves in magnetic holes are a major component of the total Langmuir wave population; they occur preferentially in fast solar wind and are observed by Ulysses to be most intense within 2 AU of the Sun.

INTRODUCTION

Instabilities in the solar wind support a number of plasma wave modes, including Langmuir waves, ion-acoustic waves, whistler mode waves, etc. (see MacDowall and Kellogg (2001) and references therein.) Here, we focus on Langmuir waves, which are narrow band, electrostatic waves, whose characteristic frequency is the electron plasma frequency, $f_{pe} \approx 9N_e^{1/2}$, where f_{pe} is in kHz and N_e is the electron number density in cm^{-3}. The sources of these instabilities include electron beams from solar flares, acceleration at interplanetary (IP) shocks and planetary bow shocks, and unstable distributions formed in magnetic holes. The latter are decreases in magnetic field amplitude, which have been shown to be locations conducive to the excitation of Langmuir waves (Lin et al., 1995). Figure 1 shows a Langmuir wave event studied by Thejappa and MacDowall (2002); the top panel shows electric field wave data from the Ulysses radio and plasma (URAP) wave investigation (Stone et al., 1992), the bottom panel shows magnetic field amplitude from the Ulysses magnetometer (Balogh et al., 1992). At 10:35 UT, a short duration magnetic hole may be seen in the magnetic field data. Associated with it is a burst of Langmuir waves, seen in the URAP data. From 6:45 to 7:45 UT, a longer interval of Langmuir waves occurs. Thejappa and MacDowall (2002) describe an unsuccessful search for the source of these Langmuir waves. The relevant electrons may occur in an energy range (~1 to 40 keV) not observed by Ulysses, but the solar or interplanetary source of the electrons is not observed. A large solar flare starting at about 5:35 UT occurs too late for the

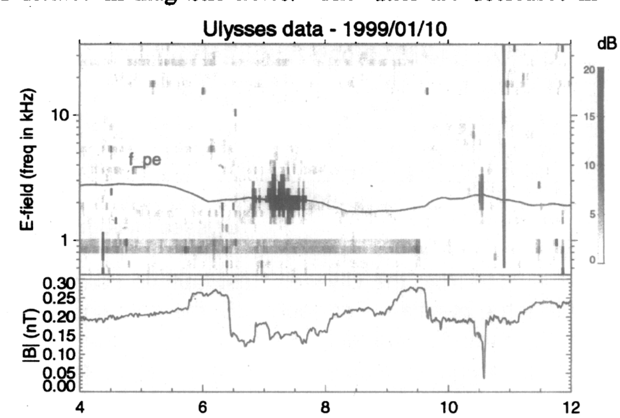

Fig. 1 – (Top) Ulysses wave electric field data, showing two intervals of Langmuir wave activity on January 10, 1999. (Bottom) Ulysses magnetic field amplitude, with magnetic hole at 10:35 UT. (See text for details.)

Adv. Space Res. Vol. 32, No. 4, pp. 479–483, 2003

Printed in Great Britain
0273-1177/$30.00 + 0.00

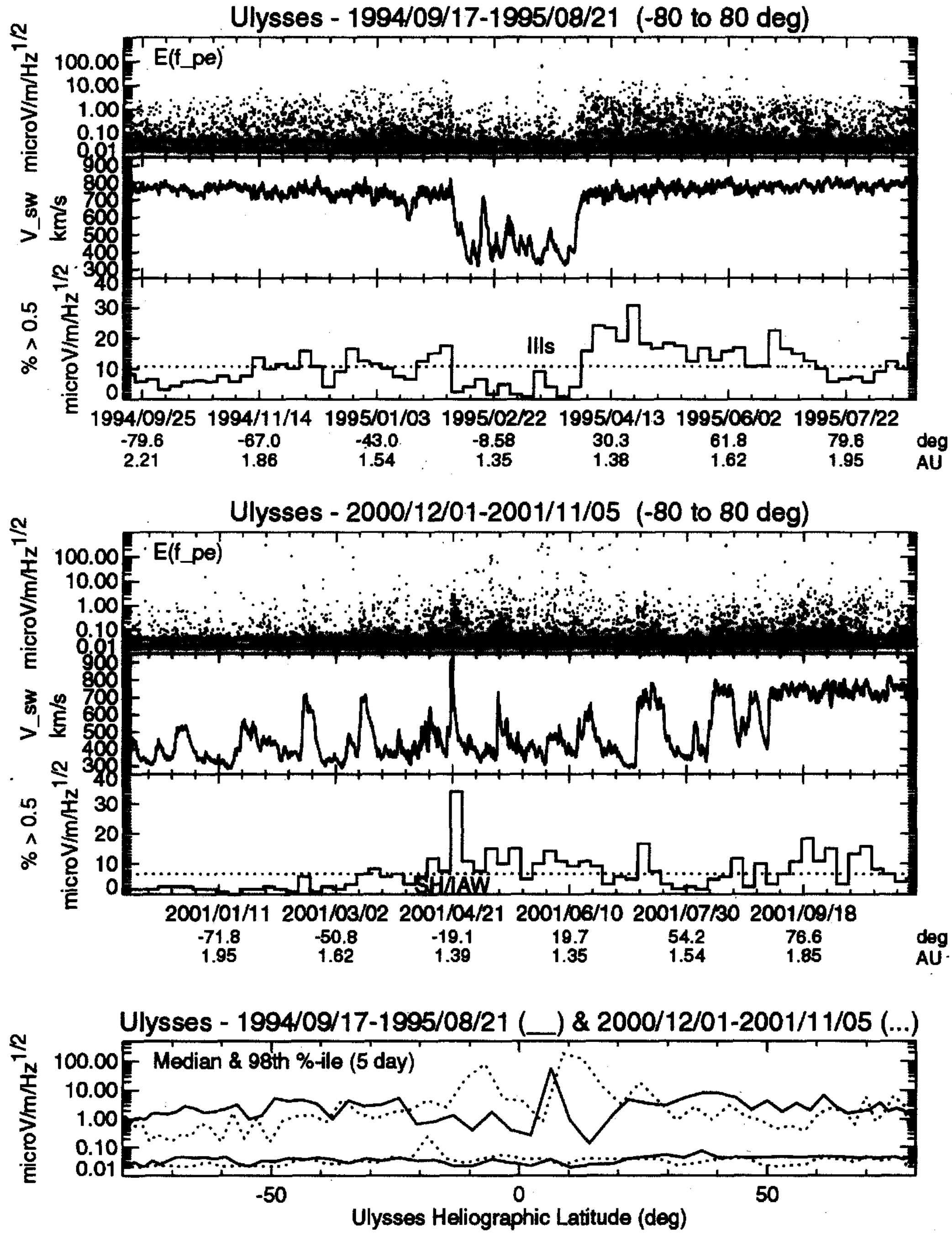

Fig. 2 – Data from the Ulysses "fast latitude scans" in 1994-1995 (top three panels) and 2000 -2001 (middle three panels). For each FLS, the data cover the intervals when Ulysses traveled from -80° to +80° heliographic latitude. From the top, data are 1 -hour electric field maximum values for the frequency channel including the plasma frequency f_{pe} , solar wind velocity, and percentage of electric field 1-hour maxima exceeding 0.5 10^{-6} V/m/$Hz^{1/2}$ for 5-day data windows, followed by the same parameters for the second FLS. The top six panels are plotted as a function of t ime. In the bottom panel, the median and 98^{th}-percentile values for the same electric field maximum data (5-day windows) are plotted as a function of Ulysses heliographic latitude.

electrons to propagate to Ulysses at the time of the Langmuir wave onset. The waves cannot be associated with an IP shock, none of which intercept the spacecraft for several days before or after Jan. 10, 1999, and the magnetic field data indicate that no magnetic holes occurred during the interval. We note that the magnetic field magnitude and components (not shown) are more variable during this interval, but such variations are not typically associated with Langmuir waves. It would be informative to survey a large number of occurrences of Langmuir waves without obvious solar or interplanetary source associations using a spacecraft with complete electron spectral coverage, because there is still much to be learned about Langmuir waves in the solar wind.

OBSERVATIONS

Langmuir wave occurrence throughout the Ulysses mission demonstrates that different regions of the heliosphere are dominated by different sources of electron instability with consequent variations in Langmuir wave statistics. Changes in the global structure of the heliosphere throughout the solar cycle also play a significant role.

Figure 2 presents data from the two Ulysses "fast latitude scans"; these segments of the highly- elliptical Ulysses orbit occur as the spacecraft descends from the highest southern heliographic latitudes, passing through low latitudes, and rapidly ascends to the highest northern latitudes. The top three panels contain data from the first Ulysses fast latitude scan (FLS), which occurred near solar minimum. The top panel shows 1-hour maximum values of the electric field in the frequency channel including f_{pe}. The electron plasma frequency is calculated from the Ulysses SWOOPS ion data ($N_e \approx N_p + 2 N_\alpha$, where N_p and N_α are the number densities of protons and alphas, respectively). The second panel shows 1-hour averages of solar wind velocity V_{SW}, also from SWOOPS (Bame et al., 1992). In the third panel, the percentage of electric field values (top panel) greater than 0.5 10^{-6} V/m/Hz$^{1/2}$ is shown for 5-day windows. The 0.5 10^{-6} V/m/Hz$^{1/2}$ level, hereafter "the limit", is chosen because it selects of the order of 10 percent of the data and also for compatibility with MacDowall et al. (2001). The percentage of points exceeding the limit is approximately three times higher in fast solar wind than in slow wind. In the fast solar wind, the percentages decrease noticeably with increasing Sun-Ulysses range. The vast majority of these Langmuir wave bursts occur in magnetic holes; exceptions occur on March 14- 15, 1995, when electrons from solar flares intercept the spacecraft, exciting Langmuir waves a nd intense type III bursts (plot labeled IIIs).

The next three panels show data from the comparable interval of the second Ulysses FLS, close to solar maximum. It is notable that the majority of peak electric field values are less intense than for the first fast latitude scan, with the exception of the interval between approximately ± 20° heliographic latitude. At these low latitudes, there are more shocks than at solar minimum, which contributes to the occurrence of Langmuir waves. Also, around April 21, 2001, high V_{SW} associated with a fast interplanetary shock and coronal mass ejection (ICME) causes intense ion acoustic waves to be shifted up to the plasma frequency (interval labeled SH/IAW). During the second fast latitude scan the solar wind velocity is typical of solar maximum; it is only when Ulysses reaches >70° N. heliographic latitude that it enters an extended interval of fast solar wind (McComas et al., 2001). Therefore, the percentage of peak values exceeding the limit is low except during shocks, some ICMEs, a nd intervals of fast solar wind, which may be seen in the correlated variation of V_{SW} and the electric field percentages.

The panel at the bottom of the figure shows the median and 98th-percentile values for 5-day intervals of the 1-hour maximum electric field data as a function of *heliographic latitude*; note that the time intervals are the same as in the upper panels. The median values are not significantly different from background levels because Langmuir waves are bursty and do not occur continuously. The 98th-percentile values again suggest that Langmuir wave bursts are somewhat more intense throughout most of the heliosphere during solar minimum than solar maximum. Most of these Langmuir wave events are believed to occur in or at the edge of magnetic holes.

A more complete manner for assessing the statistical characteristics of Langmuir waves along the orbit of Ulysses is shown in Figure 3. The top 3 panels correspond to the Ulysses solar minimum orbit (1992-1998); the bottom 3 panels correspond to the interval of the Ulysses solar maximum orbit (1998- 2004) for which URAP plasma wave data are available. (The relatively short interval from launch in October 1990 to Jupiter encounter in February 1992 has been excluded due to space limitations.) In addition to solar wind velocity data and percentage of electric field values greater than the 0.5 10^{-6} V/m/Hz$^{1/2}$ limit, the complete distribution of Langmuir wave amplitudes is indicated using the color scale at the bottom of the figure. Thirteen-day data intervals are used for Figure 3. Key Ulysses-Sun ranges and solar heliographic latitudes are indicated. There are two types of features imposed on an approximately constant background: short duration (<13 day) features and the longer duration increases when Ulysses nears perihelion (labeled A, B, C, and D).

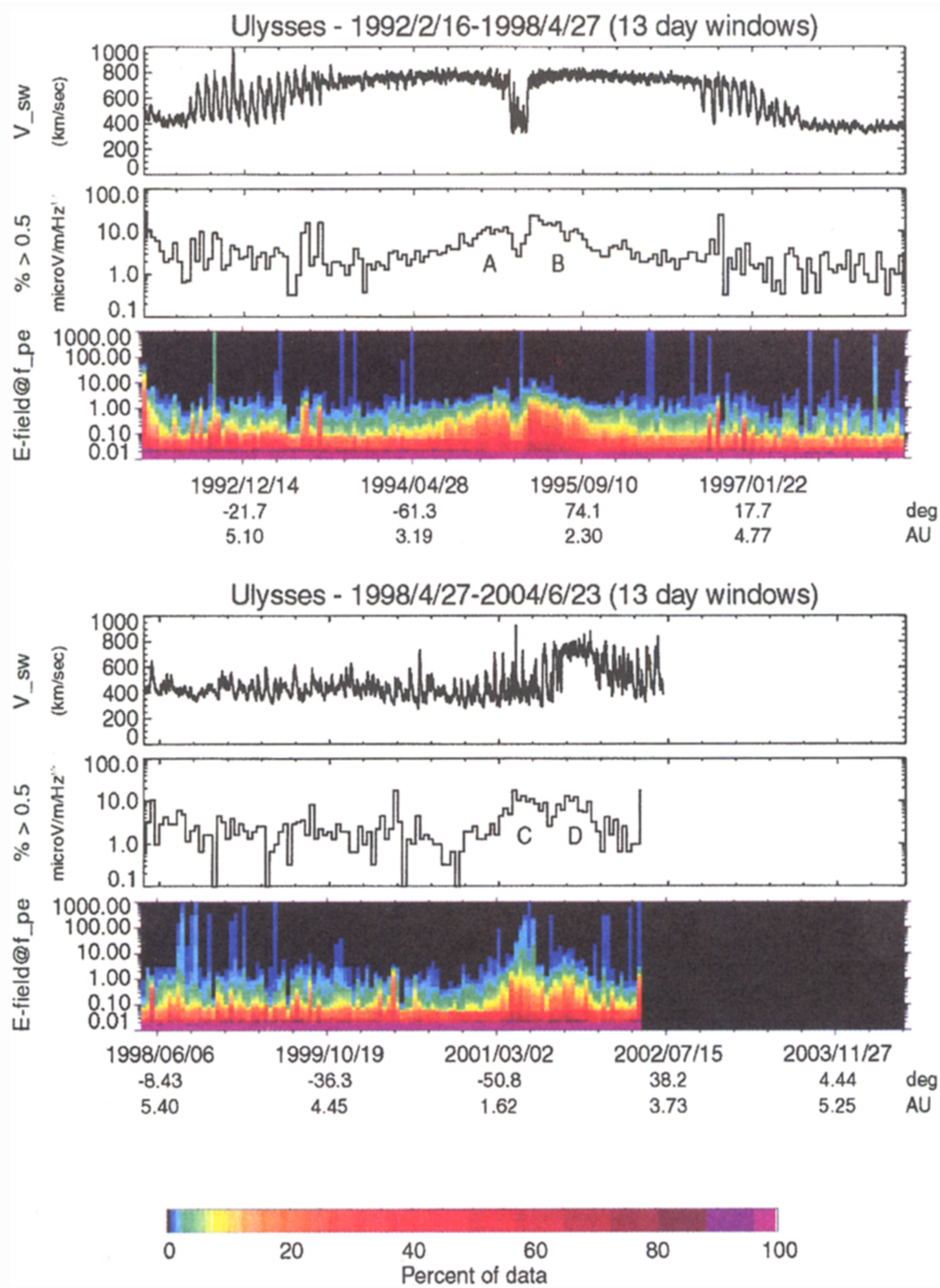

Fig. 3 – (Top panels) Ulysses data from the entire solar minimum Ulysses orbit (1992-1998); (bottom) same format for the Ulysses solar maximum orbit (1998 -2004). Data are solar wind velocity, percentage of electric field 1-hour maxima exceeding 0.5 10^{-6} V/m/Hz$^{1/2}$, and complete distribution (percentages given by color scale) of electric field 1-hour maxima as a function of time and electric field amplitude. Electric field data are binned in 13-day windows.

A number of the short duration features extend only to ~10^{-6} V/m/Hz$^{1/2}$; many of these are Langmuir waves occurring upstream of IP shocks. A few events show fractions of a percent of the peak electric fields extending above 10^{-4} V/m/Hz$^{1/2}$, these are either Langmuir waves associated with solar flare electrons or contamination from ion acoustic waves in ICMEs. It is noteworthy that these intervals have significantly different percentage E- field distributions than do the shocks (as seen in the color variations). During the two perihelion passes, there appear to be four gradual enhancements in the Langmuir wave event amplitude. Three of these – A, B, and D – are intervals when V_{SW} is fast (>700 km/sec) and the spacecraft was within ~2 AU of the Sun. As described above, Langmuir waves in magnetic holes are common in this environment. These intervals show that the amplitude of the Langmuir wave electric field falls off significantly with distance from the Sun (evident in all four plots of electric field); similar decreases with increasing distances are observed for Langmuir waves associated with solar flares (Gurnett et al., 1978). Interval C is different in that a small fraction of the Langmuir wave amplitudes extend above 10^{-4} V/m/Hz$^{1/2}$; this is at least partly due to a number of flare -associated electron beams during this interval. Additional analysis of this interval using high resolution magnetic field to identify all magnetic holes is required to partition the wave activity among the various sources. Such a study will help to answer questions about the relative occurrence probabilities of magnetic hole-associated Langmuir waves in slow and fast solar wind.

DISCUSSION

The dominant sources of Langmuir waves in the outer heliosphere are shocks and magnetic holes. Near and inside 1 AU, flare electron beams contribute to the Langmuir wave population. In fast solar wind, ion acoustic waves in ICMEs may be Doppler-shifted to or above f_{pe}, causing confusion with Langmuir waves (MacDowall and Kellogg, 2001). For each of these sources, the distribution of electric field amplitudes appears to be different, as suggested by Figure 3. Additional analysis is required to fully explain the electric field distribution of Langmuir waves in magnetic holes as a function of radial distance.

ACKNOWLEDGMENTS

The Ulysses URAP investigation is a collaboration of NASA Goddard Space Flight Center, the Observatoire de Paris, the University of Minnesota, and the Centre d'etude des Environnements Terrestre et Planetaires.

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Manuscript received 3 December 2002, revised 28 February 2003, accepted 28 February 2003