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LOW FREQUENCY MAGNETIC SIGNALS ASSOCIATED WITH LANGMUIR WAVES

Paul J. Kellogg*
Departement de Recherche Spatiale, Observatoire de Meudon, Meudon

K. Goetz, N. Lin, S. J. Monson
School of Physics and Astronomy, University of Minnesota, Minneapolis

A. Balogh and R. J. Forsyth
The Blackett Laboratory, Imperial College of Science and Technology, London

R. G. Stone
Goddard Space Flight Center, Greenbelt

Abstract. With the URAP experiment on Ulysses, we have observed low frequency signals with a magnetic component in close time correlation with electrostatic Langmuir waves at the plasma frequency. In most, if not all, of these cases, the Langmuir waves are part of a Type III solar burst. We investigate this effect and show that the low frequency waves are in the whistler mode and are most likely due to nonlinear effects involving Langmuir waves.

Introduction

The unified radio and plasma experiment (URAP) on Ulysses measures electric fields in the range from 1 MHz down to the spin frequency and magnetic fields from 448 Hz down to the spin frequency, 1/12 Hz. This complete coverage has shown that there are signals with a low frequency magnetic component (less than 10 Hz) in close time correlation with Langmuir waves which are at the plasma frequency (5-20 kHz). The low frequency signals also have an electric component. Figures 1 and 2 show selected frequency ranges for examples of such observations. The event of Figure 1 occurred on Day 195 (1991), when Ulysses was 3.61 A.U. from the sun, while that of Figure 2 occurred at about 1 A.U. Figure 1 presents better data for analysis, while the event of Figure 2 more clearly demonstrates the time correlation. We here analyze and try to understand these events.

Experiment Description

The URAP experiment analyzes the signals on four antennas--two electric and two magnetic. There is one electric and one magnetic antenna aligned along the spin axis, and one electric antenna, Ex, and one magnetic antenna, By, perpendicular to the spin axis, the Z axis being the spin axis of the spacecraft (always directed toward the earth). The Ex antenna consists of two monopoles of length 35.2 m each; with a spacecraft diameter of 2.6 m, this gives a tip-to-tip length of 73 m. The Ez antenna has a length of 7.5 m, but an effective length of about 2 meters when base capacitance is taken into account. In this paper we will usually report the electric signals as volts at the receiver input. Roughly speaking, this can be converted to field strength by dividing by an effective length of 36 m for the x antennas and 2 m for the z antenna. A more accurate calibration for the low frequencies is not known at the present time, since at the very low frequencies the antennas are resistively coupled to the plasma and to the spacecraft in a way which we have had insufficient experience. These antennas feed circuits which analyze the signals in various frequency bands. For the data reported here, the signals between 570 Hz and 35 kHz are analyzed by the plasma frequency receiver (PFR). Each receiver consists of a four pole filter whose center frequency is swept two times per telemetry frame by switching resistances and capacitances in the filter circuits. The frequencies lower than 570 Hz are analyzed in two bands by an on board digital Fourier transform (16 point). In the higher band, 10-448 Hz, 40 Fourier analyses are averaged before telemetry, while in the lower band, .22 Hz to 5.3 Hz, each Fourier transform is telemetered. Each Fourier analysis is windowed by an approximately triangular window to reduce leakage. The resulting Fourier transform gives a rather wide band pass of about 29% of the center frequency. A full description of the entire experiment is given in Stone et al. [1992].

The event of 1991, Day 195, occurred when Ulysses was at a distance of 3.61 astronomical units from the sun. The Langmuir waves beginning at about 1100 were apparently produced by the electrons which had earlier produced a Type III burst. When Ulysses is at 3.61 A.U., the standard Archimedes spiral (solar wind speed 400 km/s) has a length of 8.02 A.U. and turns through 215 degrees in reaching Ulysses. The Type III burst must have originated on the far side of the sun therefore. For a Type III burst on the far side, the high frequency omissions will be occulted by the sun and inner corona, and will only reach Ulysses at an attenuated amplitude through scattering [Lecachoux et al., 1989]. A Type III burst with weak or no signal from 1 MHz down to 300 kHz occurred shortly before 0345 and is the only strong Type III with missing high frequencies in a six hour period. Emissions beginning at 300 kHz are clearly seen and decrease in frequency to about 30 kHz where the emissions ended. However, an extrapolation of the onset times to the local plasma frequency of about 8 kHz shows that the Type III burst would have reached Ulysses at about 1100, had it continued. The transit time corresponds to

*Permanent Address: School of Physics and Astronomy, University of Minnesota, Minneapolis, MN 55455 USA

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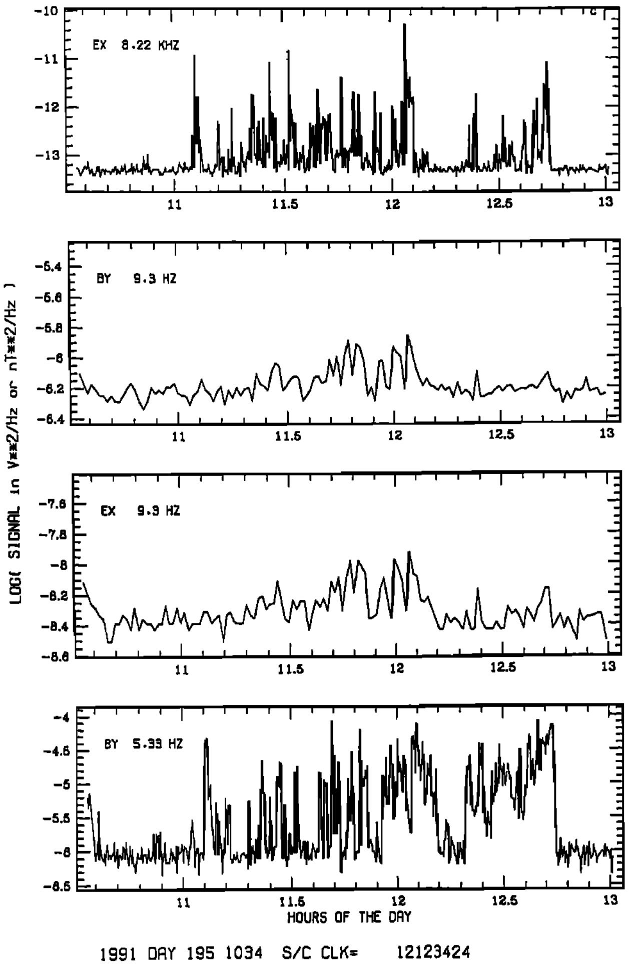

Fig. 1. Signals at several selected frequencies for the event on 1991 Day 195 (14 July). The top panel shows the signal Ex at the plasma frequency, averaged over 16 sec.; the 2 central panels show Ex and By at 9.3 Hz, the only frequency for which both E and B are above the noise, and the bottom panel shows By at 5.3 Hz, a more typical By signal.

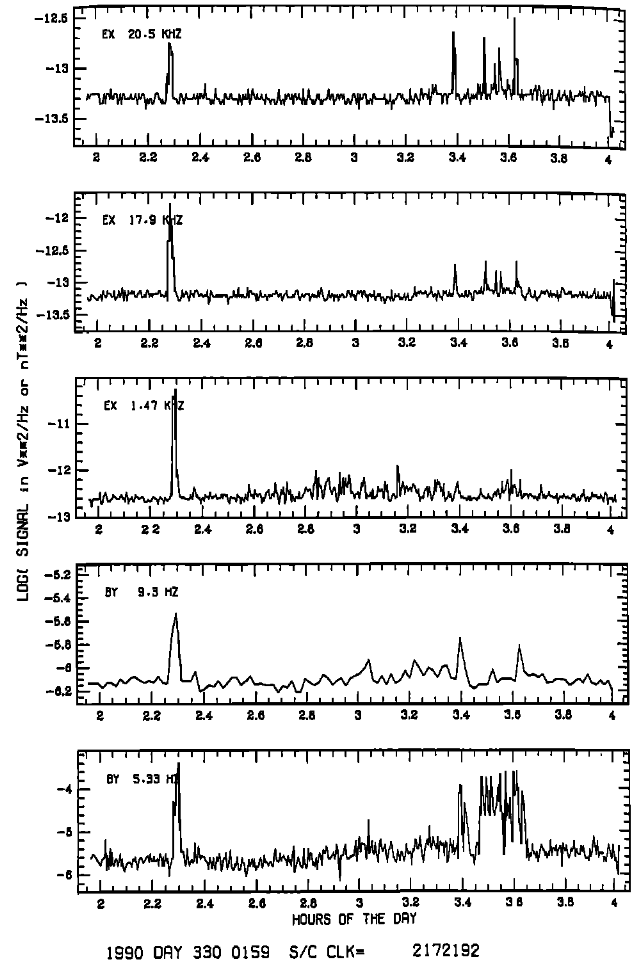

Fig. 2. Signals at several selected frequencies for the event on 1990 day 330 (26 Nov.). This event also showed electric signals in the kHz range, usually identified as ion acoustic waves.

electrons of 6 keV energy, velocity c/6.5, which are typical values [Lin et al., 1981; Kellogg, 1986; Dulk et al., 1987. This sequence of events where a Type III burst stops at a certain frequency but Langmuir waves, indicating energetic electrons, occur somewhat later, is fairly common in the Ulysses data.

Essentially simultaneously with these Langmuir waves we see low frequency electric and magnetic signals in the 10 Hz channels. Magnetic signals extend down to the lowest frequencies which we observe. Presumably the electric signals do also, but the signal to noise ratio is worse in the 6 Hz to 0 frequency band and the electric signals are buried in the noise. In Figure 3 we show a spectrum of the magnetic signals. The spectrum is steeply rising toward low frequencies. The dashed line gives the noise level of the instrument, obtained from a slightly later period on the same day, and the solid line gives the observed spectrum, which then rises toward low frequencies and is sharply cut off above 10 Hz.

We first show that the magnetic signals are in the whistler mode. During the relevant period, the interplanetary magnetic field was about 1 nT and approximately radial toward the sun, giving an electron cyclotron frequency varying between 25 and 29 Hz, and a simplified analysis because the measured components of E and B are then perpendicular and parallel to the ambient field, and to the solar wind. At 10 Hz the ratio of Ex to the By component of magnetic field (again assuming that the effective length of the x antenna is 36 meters) is (in SI units) 1.4 x 10^6 m/s, and the cB/E = 215. For a whistler the dispersion relation is approximately (there are significant modifications above $\Omega_e/2$ due to electron thermal motion):

$$k^2c^2/\omega^2 = \omega_p{}^2/\omega(\Omega_e\cos\theta - \omega) \qquad (1)$$

The motion of the solar wind past the spacecraft not only changes the observed frequency of the waves, but also transforms some B into E through the Lorentz transformation.

Calculations for a whistler propagating nearly parallel to B, using eq. (1) and its associated eigenvectors and taking into account Doppler shift and Lorentz transformation, gives a plasma frame frequency of about 5 Hz, and cB/E = 400. We interpret this as showing that E is measured to be about two times larger than it would be for quasiparallel propagation, and showing that there is a significant admixture of whistlers near the resonance cone. Our ignorance of a proper antenna effective length is not likely to change this result, since the true effective length should be shorter than the one we have taken. Of course, we are not measuring all three components of the electric and/or of the magnetic fields,

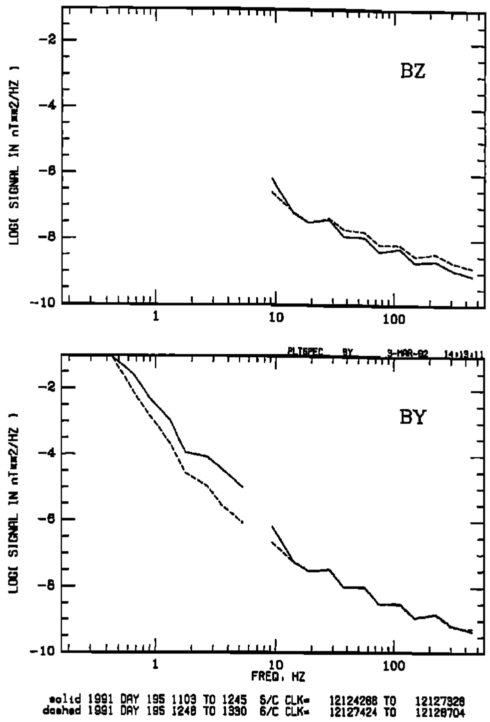

Fig. 3. The spectrum of magnetic signals averaged for the period 1100-1245 (solid line), together with the noise level from a slightly later time (dashed line).

but the fact that B is nearly along the axis of the spacecraft allows easy measurement and comparison of just the transverse components. The only question here is as to whether the observed frequencies of 0 to 10 Hz correspond to the frequencies which would be observed in the rest system of the plasma or whether they are strongly Doppler shifted by a solar wind speed. The velocity of 1.4×10^6 m/s, three to four times the solar wind speed, indicates that the observed frequencies are not strongly Doppler shifted.

Our picture [Kellogg, 1986; Melrose et al., 1986] for the Langmuir waves is that they are trapped in the normally occurring density fluctuations in the solar wind, because the frequency which would be generated by a 6 keV electron beam is closer to the local plasma frequency than typical variations of the plasma frequency, even at quiet times. (For an opposing view, see Melrose and Goldman, 1987.) However, the whistler mode signals are free to propagate freely. Hence, we should expect only limited correlation between the Langmuir mode signals and the whistler mode signals. In fact, the correlation looks rather unimpressive on a typical point by point correlogram. Nevertheless, we consider that these data show a remarkable time correlation between the Langmuir mode signals and the whistler mode signals in their overall time coincidence.

In considering what is the cause of the whistler mode signals then, we consider two categories of possibilities: first, that the whistler mode signals are generated in parallel with the Langmuir mode signals by a whistler mode instability due to the electron beam and second, that the whistler mode signals result from a nonlinear process involving the Langmuir waves. In the first category it is generally accepted that the Langmuir mode signals are driven by the bump-on-tail instability resulting from a temporal time-of-flight separation of energetic electrons from lower energy electrons in the outburst. The close time correlation shows that the whistler mode instability would have to be driven by the same bump-on-tail distribution, which therefore would require that the whistler mode signals fulfill a resonance condition

$$\omega - k v_b \cos\theta = N \Omega_e \qquad (2)$$

where we would expect $N = \pm 1$ or 0 to be the only important resonances. For the parameters here plasma frequency equal to 8.2 kHz, electron cylotron frequency 25 Hz, the speed of whistlers is too slow to have a resonance at $N = 0$. The two resonances at $N = \pm 1$ can occur only for frequencies which are very low compared to the electron cyclotron frequency. Using the whistler mode dispersion relation of eq. (1), we find that the two resonant frequencies for $N = j$ (Doppler-shifted cyclotron resonance and anomalous Doppler-shifted cylotron resonance) would occur at a very low frequency:

$$\omega = \frac{c^2}{v_b^2}\frac{\Omega_e^2}{\omega_p^2}\frac{\Omega_e}{\cos\theta} \sim \frac{2\pi(.01)}{\cos\theta}\ \text{Hz} \qquad (3a)$$

and a wave number which gives a Doppler shift:

$$kv_{sw}\cos\theta = \pm\frac{v_{sw}\,\Omega_e}{v_b\cos\theta} \sim \frac{2\pi(.2)}{\cos\theta}\ \text{Hz} \qquad (3b)$$

This is so low that ion motion cannot be neglected, and the dispersion relation becomes:

$$\omega = k V_a F \qquad (4)$$

where F is a factor of order unity, and V_a is the Alfven speed. This still gives a very low frequency. As it falls below our observed upper limit of about $.4\ \Omega_e$, we feel that this process is ruled out.

Therefore, we are lead to consider nonlinear processes involving the Langmuir waves. There is an extensive literature on nonlinear processes involving Langmuir waves, including their decay to an electromagnetic wave at 2 fp, or to an ion acoustic wave. Most discussions deal with decay to ion acoustic waves, and this process, in addition to extensive laboratory observation, has been observed in type III bursts by Lin et al. [1986]. Conversion to whistlers has received very little attention, but was first observed in space by Anderson et al. [1981]. In the processes involving ion acoustic waves, the role of the ion acoustic wave is to take up the excess wave vector of the original Langmuir wave or waves,

$$k_L = k_w \pm k_2 \qquad (5a)$$

without contributing much to the frequency matching relation:

$$\omega_L = \omega_w \pm \omega_2 \qquad (5b)$$

In the solar wind, the magnetic field is weak, $\Omega_e \ll \omega_p$, and so whistler mode waves, electromagnetic ion cyclotron waves and MHD waves all have very low frequencies, and so also can play the role which ion acoustic waves play above. One would expect two differences, first that these latter waves have little or no longitudinal electric field, so that they would only be coupled to Langmuir waves for oblique propagation, and second, they are less strongly damped than ion acoustic waves are, so that the threshold for some processes would be lower. We consider four processes: 1) decay of a Langmuir wave to a whistler mode wave and electromagnetic wave, 2) to a whistler mode wave and another Langmuir wave, 3) coalescence of two oppositely directed Langmuir waves to give a whistler, and 4) a modified oscillating two-stream instability in which a long wavelength Langmuir wave gives rise to two short wavelength Langmuir waves and a whistler (the normal oscillating two-stream instabilities replaces the whistler with an ion acoustic wave). Each of these nonlinear processes must obey the resonance conditions, eq. (5).

Since the whistler has a small or nonexistent longitudinal component of electric field, we expect that there will be coupling between these waves only for values of the k_w vector which are oblique to the magnetic field. For process 1 the electromagnetic wave will have approximately the frequency of the Langmuir wave and therefore a much smaller wave number. The whistler wave number must therefore be approximately equal in magnitude to that of the Langmuir wave.

$$k_L = \omega_p/v_b \qquad (6)$$

Using this in eq. (1), the frequency is:

$$\omega = \Omega_e \cos\theta/(1 + v_b^2/c^2) \qquad (7)$$

These whistlers are near the resonance cone therefore, which is not well described by eq. (1), but which gives an order of magnitude. However, the Doppler shift for such a whistler wave would be:

$$k_w\, v_{sw}\cos\theta \sim \omega_p \frac{v_{sw}}{v_b} \cos\theta \sim 2\pi(65\ \text{Hz}) \qquad (8)$$

This process would therefore occupy a bandwidth which is too large to be consistent with our observations.

The second process, decay of the Langmuir wave to another Langmuir wave plus whistler mode signal, is also a possible one on these grounds, since the whistler mode signal in that case could have essentially any wavelength and any small frequency. The third and fourth processes also give rise to whistler mode signals of almost any wavelength and frequency and therefore cannot be ruled out on these simple grounds but will require comparison with a presently nonexistent theory to see which process proceeds most rapidly.

In addition to the possibility of a modified oscillating two stream instability above, we also consider the normal oscillating two stream instability [Nishikawa, 1968]. As shown by Papadopoulos et al. [1974], either of these instabilities would give rise to secondary Langmuir waves of shorter wavelength and lower phase velocity, which can then interact with electrons to give "tails", electrons with lower energy than the beam but higher than ambient. These, in turn, can be slow enough to resonate with whistlers through, for example, the N = 0 mode discussed and rejected above. Thus the whistlers could result from a direct instability, but involving the non-linearly created tails. If this process is taking place, it should show in the electron velocity distributions. This is under investigation in collaboration with the plasma instrument investigators (S. J. Bame and J. L. Phillips).

Late note: A paper (R.P. Sharma, Y.K. Tripathi, A.H.Al Janabi and R.W. Boswell, "Parametric Excitation of Electrostatic Whistler Waves by Electron Plasma Waves," J. Geophys. Res. 97, 4275, 1992), just published in JGR, seems to provide further theoretical understanding of the process observed here.

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K. Goetz, P. J. Kellogg, N. Lin and S. J. Monson, School of Physics and Astronomy, University of Minnesota, 116 Church St. S.E., Minneapolis, MN 55455.

A. Balogh and R. J. Forsyth, The Blackett Laboratory, Imperial College of Science and Technology, London SW7 2BZ, United Kingdom.

R. G. Stone, Code 690.1, NASA/Goddard Space Flight Center, Greenbelt, MD 20771.

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