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Observations of plasma waves in magnetic holes

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Abstract. We report the first observations of Langmuir waves excited within magnetic holes, which are characterized by a depression of magnetic field strength. This phenomenon is very common in the solar wind. In addition to Langmuir waves, waves at a few kHz, which are typical of Doppler-shifted ion acoustic frequencies in the solar wind, and low frequency electromagnetic waves (below the electron cyclotron frequency) are sometimes observed simultaneously within the holes. In the holes with directional discontinuities at the boundary, the above plasma waves may occur at the edges of the holes. Possible physical mechanisms of the wave excitation are discussed.

Introduction

Small scale structures of magnetic field in the solar wind, characterized by local depressions in the field magnitude, have been observed previously and been named "magnetic holes" [*Turner et al.*, 1977; *Fitzenreiter and Burlaga*, 1978]. Magnetic field depressions associated with discontinuities in the solar wind, which resemble the magnetic hole, have been reported earlier [for example, *Burlaga*, 1968]. During the mission of Ulysses, which covers a wide range of distance from the Sun (1 AU to 5 AU) and of heliographic latitude (+80° to ~ −80°), a large number of magnetic holes have been observed [*Winterhalter et al.*, 1994], and the number of holes appears to increase with increasing heliographic latitude. The formation of these holes has been attributed to the diamagnetic effect due to localized plasma inhomogeneities or magnetic merging [*Turner et al.*, 1977] or to remnants of mirror mode structures [*Tsurutani et al.*, 1992].

We report here new observations made by the Ulysses Unified Radio and Plasma Wave (URAP) experiment of plasma waves excited within magnetic holes in the solar wind. It has been reported previously that whistler mode waves may occur in magnetic holes [*Neubauer et al.*, 1977]. We discovered that short bursts of Langmuir waves are frequently observed in magnetic holes. In many cases the Langmuir waves are accompanied by ion acoustic waves and whistler mode waves. In this study, we identify a "hole" as a short duration magnetic field depression (from a few tens of seconds to about half an hour). They includes "linear holes" which have little directional change across the holes, and magnetic holes bounded by directional discontinuities.

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Instrumentation and Observations

The plasma wave data used here were obtained by two instruments of the URAP experiment: The data for signals between 570 Hz and 35 kHz are the peak values of the electric wave power measured in the spacecraft spin plane by the plasma frequency receiver (PFR) at a rate of 16 sec/frequency sweep. Data for signals between 0.2 and 448 Hz are obtained by the waveform analyzer (WFA), which analyzes both electric and magnetic components, and are 64 sec averages of spin plane measurements [*Stone et al.*, 1992]. The magnetic field data used are 32 or 64 sec averages of measurements made by the Ulysses magnetometer experiment [*Balogh et al.*, 1992].

Waves in Linear Holes

Figure 1 shows an example of Langmuir waves occurring in an isolated magnetic hole on Oct 29, 1991, when Ulysses was near the ecliptic plane at about 4.56 AU from the Sun. The hole was seen at ~ 0742 UT for less than 2 minutes (marked by an arrow). As seen in high resolution data [*Winterhalter et al.*, 1994], the field magnitude drops from ~ 0.8 nT outside of the magnetic hole to ~ 0.1 nT within the hole. There is little directional change in magnetic field across the hole (< 5°). The lower two panels show electric wave power. At the time of the magnetic hole occurrence, a strong wave burst is observed in channels between 3 kHz and 7 kHz. The peak power of the waves is at about 4.3 kHz. The electron density near the hole is ~ 0.2/cc as measured by the SWOOPS experiment [*Bame et al.*, 1992], while the density inside the hole is 1.29 times higher than the ambient density. This gives the plasma frequency within the hole as ~ 4.57 kHz, which suggests that the wave burst in the magnetic hole is Langmuir waves oscillating near the electron plasma frequency.

Ulysses HISCALE data [*Lanzerotti et al.*, 1992] indicates that this hole-wave event occurred in the middle of a few days of a large enhancement of electron fluxes at 42-290 keV (not shown), and the pitch angle distribution of the electrons suggest a field-aligned streaming from the sun. Since Langmuir waves suggest electron

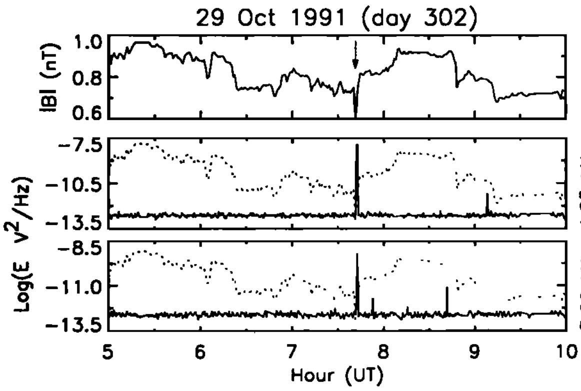

Figure 1. Five hour interval of data on Oct 29, 1991, showing the magnetic field magnitude (top panel), and the spin plane electric field data in two channels ($\sim$ 4 kHz) of the PFR. The magnetic field magnitude is also overplotted as dotted lines in each panel of URAP data. The arrow in the top panel points to the magnetic hole.

streaming, one might speculate that the electron beam which excited the Langmuir waves in the hole consists of the electrons streaming from the Sun. But the fact that the wave bursts occurred only within the hole, whereas the field and plasma conditions were about the same for many hours before and after the hole, indicates that the electron streaming is not the likely cause of the Langmuir waves. MacDowall et al. [1995] suggested that adiabatic focusing of thermal electrons in magnetic holes may lead to counterstreaming electron beams and Langmuir waves. Due to the conservation of magnetic moment, as the electrons propagate through the holes, the electron distribution is converted into beams propagating along the magnetic field. These electron beams are unstable and will lead to the rapid amplification of Langmuir waves.

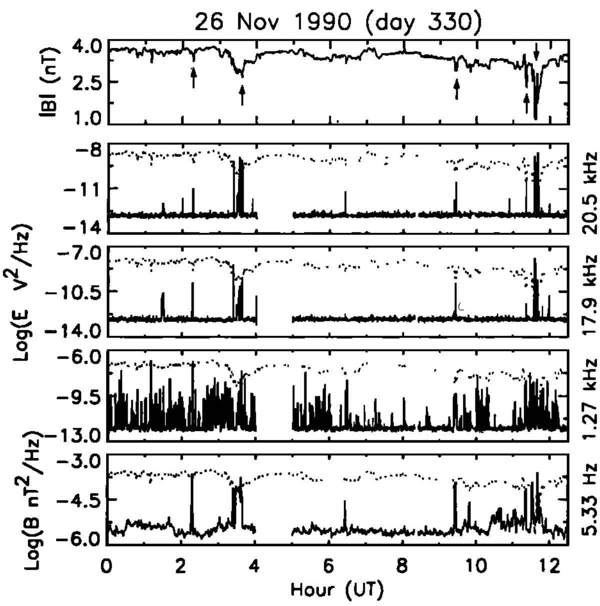

Figure 2a. Similar to Figure 1 but for interval 0000 to 1200 UT, Nov 26, 1990. Panels 2 to 4 are PFR data, and the bottom panel is WFA data showing magnetic wave power at 5.3 Hz.

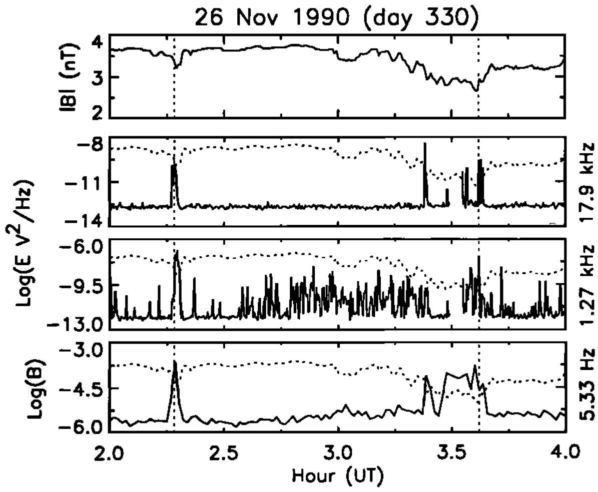

Figure 2b. A subinterval of Figure 2a showing simultaneous occurrences of plasma waves (marked by vertical lines) in three frequency ranges.

Langmuir Waves Accompanied by Lower Frequency Waves

In many cases, Langmuir waves occurring in magnetic holes are accompanied by waves at lower frequencies. Figure 2a gives such an example. The spacecraft was at 1.2 AU near the ecliptic plane. Wave bursts are seen at the times of the magnetic holes (marked by arrows). They occurred in three distinct frequency ranges as seen in the URAP data: 10–20 kHz, a few kHz, and below $\sim$ 10 Hz. The plasma density near the holes is $\sim$ 2.5 – 3.0/cc, which gives a plasma frequency 14–16 kHz. The wave frequencies at the highest range are similar to the Langmuir wave frequency for a density somewhat higher than that of the ambient plasma. The a-few-kHz waves are apparently Doppler shifted ion acoustic waves. Although this kind of waves also occurred outside the holes, it is clear that strong wave bursts occurred in every hole. A subinterval from Figure 2a is plotted in Figure 2b to show simultaneous occurrences of the waves at 17.9 kHz, 1.27 kHz and at 5.33 Hz. The low frequency waves below $\sim$ 10 Hz are electromagnetic and are likely to be whistler mode waves. Their frequencies are below the electron gyrofrequency within the holes (25 - 80 Hz).

Simultaneous observations of Langmuir waves, ion acoustic waves and whistler mode waves have been

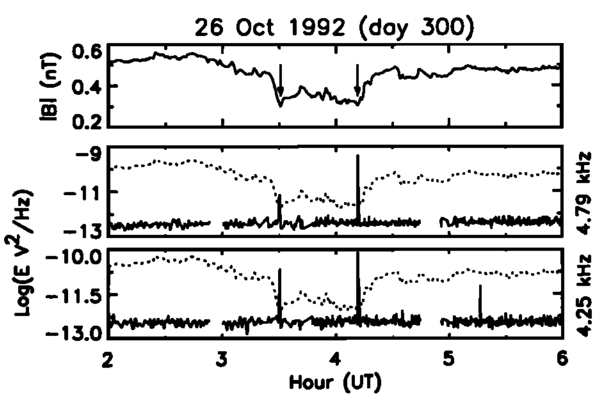

Figure 3a. The same format as Figure 1, for the interval 0200–0600 UT, Oct 26, 1992. Two channels of PFR data are shown.

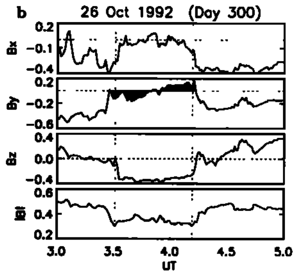

Figure 3b. Three components of magnetic field B_x, B_y and B_z in the despun spacecraft coordinate system, and the field magnitude for the event in Figure 3a. Dark area marks the bipolar signature in B_y.

reported previously [*Lin et al.*, 1986; *Kellogg et al.*, 1992]. The waves were associated with type III solar bursts and are believed to be caused by non-linear wave-wave interactions in which a Langmuir wave decays into an ion acoustic wave or another Langmuir wave and an electromagnetic whistler mode wave. Although the events in Figure 2a occurred after a strong type III burst, starting at about 1930 UT on the previous day, the fact that the Langmuir waves in this period occurred only within the holes suggests that they are not associated with the type III burst. Further work using high resolution data is needed to examine if the three kinds of waves are generated by different mechanisms or are generated through Langmuir wave decay processes mentioned above.

Waves at Discontinuities

Magnetic depressions are often associated with discontinuities. We found that in such magnetic holes, plasma waves are often excited at the edges of the holes, i.e., at the discontinuities. The top panel of Figure 3a shows a "shallow" magnetic hole between 0328 and 0415 UT, Oct 26, 1992, when Ulysses was at $-19°$ latitudes and $\sim$ 5.2 AU from the Sun. The field magnitude decreases from $\sim$ 0.5 nT outside the hole to $\sim$ 0.3 nT inside. The URAP data show that wave bursts occur at the two edges of the structure at frequencies $\sim$ 3–5 kHz, which are approximately the plasma frequency near the structure.

The two edges of the hole structure are actually rotational discontinuities. Figure 3b show the variation of three magnetic field components B_x, B_y, and B_z in the despun spacecraft coordinates. The times when the wave bursts occurred are marked with dashed lines. In this case, $-z$ essentially coincides with the direction radially outward from the Sun. Outside the structure, the magnetic field is basically in the $x-y$ plane while

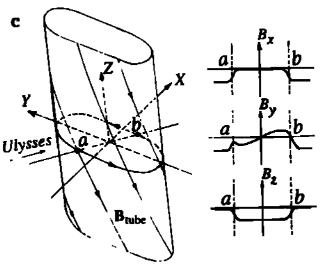

Figure 3c. Schematic diagram illustrating the model variation of magnetic field in Figure 3b.

the radial component B_z is almost zero. Within the structure, the magnetic field becomes mainly in the $-z$ direction. While B_x becomes essentially zero within the hole, B_y exhibits a bipolar signature, from negative gradually becoming positive. A possible explanation of these changes is illustrated schematically in Figure 3c: a slightly twisted flux tube with magnetic field basically in the $-z$ direction convects past the spacecraft. The cross section of the flux tube on the $x-y$ plane is elongated in the y direction. Outside the tube the field is in the $x-y$ plane. When the spacecraft entered the flux tube at point a, the spacecraft then observed the magnetic field mainly in the $-B_z$ direction, while the projection of the flux tube field onto the $x-y$ plane was observed as $B_x \sim 0$ and bipolar B_y. The variation of three components in this model, shown in the right side of the figure, is consistent with the data. Since the structure is convecting in the x direction with a velocity of $\sim$ 15 km/s (SWOOPS data), its spatial scale can be estimated as $\sim 4 \times 10^4$ km wide, which is comparable to those reported previously [*Turner et al.*, 1977]. The Langmuir waves are excited at the boundary of the flux tube at points a and b. The electron beams exciting the waves may have been produced through physical processes at the discontinuities. A separate study is being conducted to investigate these processes and the occurrence rate of Langmuir waves at discontinuities.

Waves in the High Latitude Holes

In the approach to the southern solar polar region, Ulysses observed no interplanetary shocks southward of $\sim -60°$ and significantly fewer type III solar bursts, but the URAP instrument observed more frequent bursts of Langmuir waves as the number of magnetic holes increased with the latitude [*Balogh et al.*, 1995]. Figure 4 show observations of plasma waves in an interval during Sep 14, 1994, the day when the highest latitudes were reached by Ulysses ($-80.2°$ latitude, 2.29 AU from the Sun). In a several day interval, the URAP instrument observed no other major wave activity except for the waves in magnetic holes, similar to those in Figure 4.

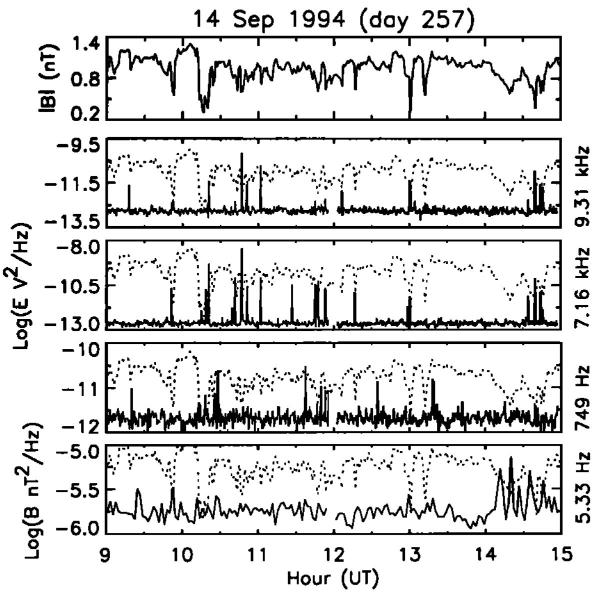

Figure 4. The same format as Figure 2, for the interval 0900–1500 UT, Sep 14, 1994.

The top panel in Figure 4 show frequent fluctuations in magnetic field magnitude forming various hole-like structures. The next three panels of PFR data show wave bursts in 3 channels, representative of two frequency ranges: 6-10 kHz, which is near the ambient plasma frequency indicating the bursts are Langmuir waves; and about 1 kHz, typical for Doppler shifted ion acoustic waves in the solar wind. Note that almost all the wave bursts occurred at magnetic field depressions, i.e., at the holes. At a longer duration hole, occurring near 1015 UT, the bursts appeared at the edge of the structure, as in the case of Figure 3a. There are signatures that low frequency waves (below ten Hertz) are also excited in some holes, as shown in the last two panels of Figure 4. In some holes, (for example, at ~ 1145 and 1440 UT) simultaneous occurrence of Langmuir waves, ion acoustic waves, and low frequency e-m waves is observed, as in the case of Figure 2.

Summary

It is found that Langmuir waves are often excited within magnetic holes, which are characterized by the depression of magnetic field strength. The waves occur in various types of holes: with or without directional change in the magnetic field across the holes and with deep or shallow depressions in the field magnitude. They are observed throughout the interplanetary medium, from the ecliptic plane to the solar polar region, in low and high speed solar wind streams.

The hole structure seems to favor the excitation of Langmuir waves. This is more clearly seen in the high latitude region, as we often see enhanced wave activity in magnetic holes against otherwise very quiet background. Waves at a few kHz which are typical of a Doppler-shifted ion acoustic frequency in the solar wind and low frequency e-m waves (below the electron cyclotron frequency) are also observed within the holes. These lower frequency waves are more rarely observed in magnetic holes than Langmuir waves. In some cases the three kind of waves are observed simultaneously within the time resolutions of the instruments (16 sec for PFR and 64 sec for WFA). In the holes with directional discontinuities at the boundary, waves often occur at the edges of the holes. It is very likely that electron beams which excite the Langmuir waves are generated by local processes.

Although the observed hole-wave events look similar, they may involve several physical mechanisms of wave excitation. Many questions are still open: for example, the formation of electron beams within the hole, the excitation of and the relation among the waves at three frequency ranges, and the role of hole structure in the wave excitation. Future work will require higher time resolution data from various instruments for the detailed collaborative study of hole-wave phenomena.

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References

Balogh, A. et al., The magnetic field investigation on the Ulysses mission, *Astron. Astrophys. Suppl. Ser.*, *92*, 221, 1992.

Balogh, A., et al., *Science, 268*, 1016, 1995.

Bame, S. J. et al., The Ulysses solar wind plasma experiment, *Astron. Astrophys. Suppl. Ser.*, *92*, 237, 1992.

Burlaga, L. F., Micro-scale structures in the interplanetary medium, *Solar Phys.*, *4*, 67, 1968.

Fitzenreiter, R. J., and L. F. Burlaga, Structure of current sheets in magnetic holes at 1 AU, *J. Geophys. Res.*, *83*, 5579, 1978.

Kellogg, P. J., K. Goetz, N. Lin, S. J. Monson, A. Balogh, R. J. Forsyth, and R. G. Stone, Low frequency magnetic signals associated with Langmuir waves, *Geophys. Res. Lett.*, *19*, 1299, 1992.

Lanzerotti, L. J., et al., Heliosphere instrument for spectra, composition, and anisotropy at low energies, *Astron. Astrophys. Suppl. Ser.*, *92*, 207, 1992.

Lin, R. P., W. K. Levedahl, W. Lotko, D. A. Gurnett, and F. L. Scarf, Evidence for nonlinear wave-wave interactions in solar type III radio bursts, *Astrophys. J.*, *308*, 954, 1986.

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, submitted to *Proceedings, Solar Wind 8*, 1995.

Neubauer, F. M., H. J. Beinroth, H. Barnstorf, and G. Dehmel, Initial results from the Helios-1 Search-Coil magnetometer experiment, *J. Geophys.*, *42*, 599, 1977.

Stone, R. G., et al., The unified radio and plasma wave investigation, *Astron. Astrophys. Suppl. Ser.*, *92*, 291, 1992.

Tsurutani, B. T., D. J. Southwood, E. J. Smith, and A. Balogh, Nonlinear magnetosonic waves and mirror mode structures in the March 1991 Ulysses interplanetary event, *Geophys. Res. Lett.*, *19*, 1267, 1992.

Turner, J. M., L. F. Burlaga, N. F. Ness, and J. F. Lemaire, Magnetic holes in the solar wind, *J. Geophys. Res.*, *82*, 1921, 1977.

Winterhalter, D., M. Neugebauer, B. E. Goldstein, E. J. Smith, S. J. Bame, and A. Balogh, Ulysses field and plasma observations of magnetic holes in the solar wind and their relation to mirror-mode structures, *J. Geophys. Res.*, *99*, 23371, 1994.

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