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Langmuir waves associated with discontinuities in the solar wind: a statistical study

Naiguo Lin[1], **P.J. Kellogg**[1], **R.J. MacDowall**[2], **B.T. Tsurutani**[3], **and C.M. Ho**[3]

[1] School of Physics and Astronomy, University of Minnesota, Minneapolis, MN 55455, USA
[2] NASA/Goddard Space Flight Center, Greenbelt, MD 20771, USA
[3] Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109, USA

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Abstract. We have reported previously that short bursts of Langmuir waves are frequently observed in the solar wind in isolated local depressions in the magnetic field magnitude, which are called "magnetic holes". The magnetic depression regions are often bounded by directional discontinuities (DDs). To study the relation between the waves and the discontinuities, we have examined 402 magnetic field discontinuities in 11 days of Ulysses data which cover a range of radial distances from the Sun (1.8 to 5.2 AU) and of heliographic latitudes ($-1.9°$ to $-80°$). It is found that Langmuir waves occur at only $\sim$ 9% of the discontinuities identified. About 75% of the DDs which have waves are associated with magnetic depressions. The waves have a higher occurrence rate at tangential discontinuities with magnetic depressions than at rotational discontinuities with little change in the field magnitude. The results suggest that the reduction in the magnetic field strength (a hole-like structure) is important for the excitation of the observed Langmuir waves. The adiabatic focusing of suprathermal electrons passing through the magnetic holes may be a source of free energy for this process.

Key words: solar wind – plasmas – waves

1. Introduction

It has been found (Lin et al. 1995; MacDowall et al. 1996) that Langmuir waves are frequently excited within magnetic holes, which are characterized by a small scale magnetic field depression. The phenomena are observed throughout the interplanetary medium, from the ecliptic plane to the solar polar region, in low and high speed solar wind streams. As shown in Lin et al. (1995), the appearance of holes where plasma waves are excited is varied. They can be isolated short duration (a few tens of seconds) magnetic field depressions in a quiet background, or much longer (a few hundreds of seconds) field depressions, which may consist of a train of magnetic holes. In these cases, the short duration of observation results from the small size of the holes, which are convected past the spacecraft by the solar wind. Based on modeling the adiabatic motion of thermal electrons propagating through the holes, MacDowall et al. (1996) proposed that the formation of electron beams due to the conservation of magnetic moment as the electrons move into a reduced field structure is responsible for the excitation of the short burst Langmuir waves.

The edges of a magnetic hole can be considered as magnetic field discontinuities, with a large or small directional change. Earlier observations (for example, Burlaga 1968; Turner et al. 1977; Fitzenreiter & Burlaga 1978; Klein & Burlaga 1980) showed that short duration magnetic depressions in the solar wind could often be associated with directional discontinuities (DDs). The structure called "D-sheet" (cf. Burlaga 1968), which is characterized by a dip in the magnetic magnitude at a discontinuity, is a good example of discontinuity associated magnetic holes. Recently Ho et al. (1995) showed that a magnetic depression in mirror structures was often bounded by a pair of tangential discontinuities. It has been found (Lin et al. 1995) that short bursts of Langmuir waves are observed at magnetic discontinuities, frequently at those where a magnetic field depression is formed. The purpose of this study is to investigate the dependence of the excitation of the Langmuir waves on properties of the discontinuity.

2. Wave and discontinuity identification

The plasma wave data used here were obtained by the plasma frequency receiver (PFR) of the Unified Radio and Plasma Wave (URAP) instrument (Stone et al. 1992) onboard the Ulysses spacecraft. Peak values of the electric wave power in 32 channels between 570 Hz and 35 kHz, which are measured in the spacecraft spin plane at a rate of 16 sec per frequency sweep, are used. Directional discontinuities are identified by applying the Tsurutani & Smith (1979) criteria to one minute average magnetic field data (Tsurutani et al. 1994; Ho et al. 1995). These criteria are $|\Delta \mathbf{B}|/B_{\mathrm{L}} \geq 0.5$ and $|\Delta \mathbf{B}| \geq 2\delta$, where $|\Delta \mathbf{B}|$ is the

Send offprint requests to: N. Lin

change in one minute average vectors separated by 3 minutes, δ is the field variance on either side of the discontinuity, and B_L is the larger field magnitude on either side of the discontinuity. The detailed description and discussion of the criteria has been presented in the papers cited above. To further identify the discontinuity type, we adopt the following criteria used in recent studies (Ho et al. 1995; Tsurutani et al. 1996): (1) a DD with $\Delta|\mathbf{B}|/B_L \leq 0.2$ and $B_N/B_L \geq 0.4$ is classified as a rotational discontinuity (RD), where $\Delta|\mathbf{B}|$ is the change of the field magnitude across the discontinuity, and B_N is the normal component to the discontinuity determined by a minimum variance analysis; (2) a DD with $\Delta|\mathbf{B}|/B_L \geq 0.2$ and $B_N/B_L < 0.2$ is classified as a tangential discontinuity (TD). There are two intermediate groups with properties of both TDs and RDs: (3) DDs with $\Delta|\mathbf{B}|/B_L \leq 0.2$ and $B_N/B_L < 0.4$, which have a small change in the field magnitude across the discontinuity and have a small normal component; and (4) DDs with $\Delta|\mathbf{B}|/B_L \geq 0.2$ and $B_N/B_L \geq 0.2$, which have a large change in the field magnitude and a large normal component. Shocks may fall into this category.

A wave event is selected as occurring at a discontinuity if it is detected within ± 1.5 min of the nominal DD time in more than one channel. Since we are investigating Langmuir waves, the selected wave bursts must be detected near and including the local electron plasma frequency, which is estimated by using density measurements from the Ulysses SWOOPS instrument. The peak value of the wave bursts must be one half decade higher than the instrument noise level.

3. Observations and statistics

For this study we have selected data on 11 days when Ulysses was at heliographic latitudes ranging from $-1.8°$ to $-80.0°$ and at distances between 1.8 AU and 5.2 AU from the Sun. The location of Ulysses on those 11 days is plotted in Fig. 1 in terms of the heliographic latitude and the radial distance from the Sun. Not all data on those 11 days are used. We selected only the intervals when the PFR was in the fast scan mode, when the detector scans through its frequency range 32 times in 16 seconds providing peak and average values at each frequency. With this restriction, we have a total of 183.23 hours with 402 DDs identified using the criteria in the previous section.

3.1. Observation examples

Fig. 2 shows an example of observations, made on Jan 21, 1991, 0800 - 1100 UT, when Ulysses was near the ecliptic plane at about 1.8 AU from the Sun. The first four panels display three magnetic field components, B_r, B_t, and B_n, in solar heliospheric coordinates followed by the field magnitude (cf. Tsurutani et al. 1994). Below are four plots of the electric wave power (expressed in V^2/Hz) measured in four PFR channels whose central frequencies were near the local electron plasma frequency, f_{pe}, which was about 8 kHz during this interval.

There are 8 DDs detected (marked by letters a to h in the $|\mathbf{B}|$ panel). Among them, one discontinuity (f) is identified as a

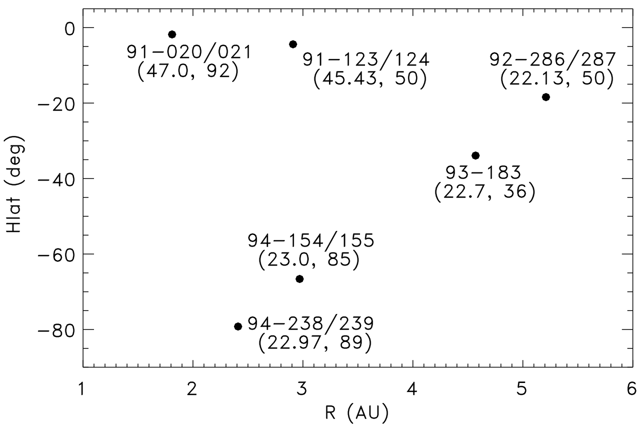

Fig. 1. Ulysses locations (solid circles) plotted with respect to heliographic latitude and radial distance from the Sun for the days selected in this study. The year and the days of the year are marked near the circles. The numbers within the brackets are the number of hours followed by the number of DDs identified during the days

TD (category (2) in the previous section), one (e) as a clear RD, and the rest falls in category (3), which has a small change in the magnetic field magnitude across the discontinuity and also a small normal component. Langmuir wave bursts are observed at 5 of the DDs (b, c, e, f, g). At two of the DDs (f and b), which are accompanied by a dip in $|\mathbf{B}|$, the wave bursts are strong. Discontinuity b falls in category 3, but the change in the field magnitude across the discontinuity $\Delta|\mathbf{B}|/B_L (\sim 0.12)$ is much larger than that of other DDs in the same category (0.01 - 0.05) in this interval. Waves at DDs c, e, and g, where no magnetic depression is seen, are much weaker than those at DDs with magnetic depressions. We notice that, in our study, such waves, which occurred at DDs without magnetic depressions, were observed at low latitude (within 0° to $-35°$) only. A small wave burst in 8.22 kHz channel at discontinuity e is not included in our statistics because it is seen only in a single channel, although its peak power is more than half decade higher than the background noise. There is also a strong wave burst near 0915, which occurred when the field strength was reduced from $\sim$ 2.5 nT to $\sim$ 1.0 nT forming a hole-like structure. No DD is identified around that time because the changes in magnetic field direction and magnitude (see the first four panels) are not rapid and dramatic enough to meet the criteria used. There are some wave bursts associated with neither DD nor magnetic depression. The strong wave burst near 1037 UT (between DDs g and h) is such an example.

Fig. 3 show another example of observations, made on Aug 26, 1994, 0030-0230 UT, when Ulysses was at $\sim -79.2°$ latitude and $\sim$ 2.41 AU from the Sun. There are 12 DDs identified and labeled with letters a to l in the figure. DDs a, g, h are classified as RDs; e, j are TDs; b, c, i fall into category (4), which has a large change in the field strength across the discontinuity but also has a large normal component; and d, f, k,l are in category (3). During this period, the local f_{pe} was about 6-7 kHz. Langmuir waves are excited at 3 DDs, each of which is associ-

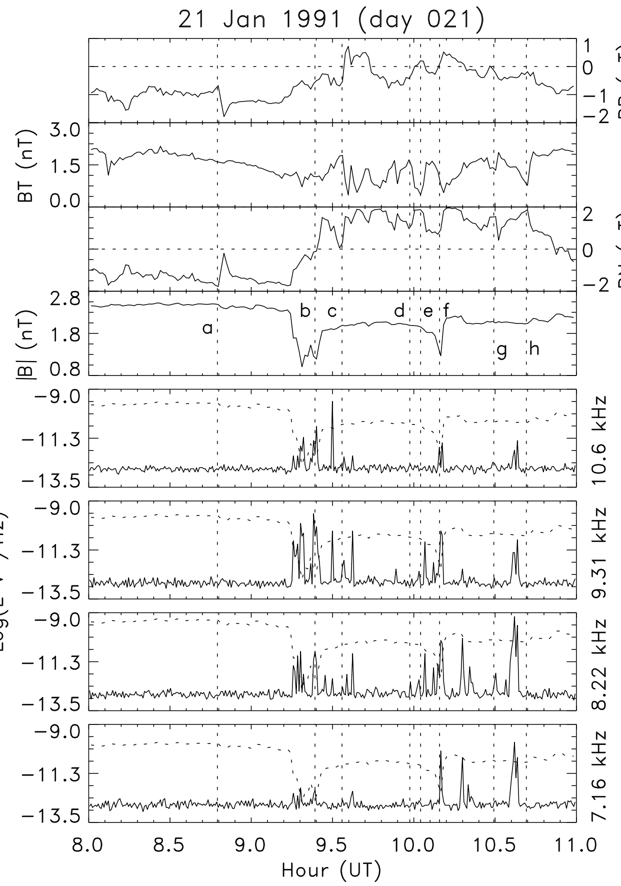

Fig. 2. Observations of magnetic field and Langmuir waves for the interval on Jan 21, 1991, 0800-1100 UT. The first four panels are magnetic field components, B_r, B_t, and B_n, and the field magnitude in solar heliospheric coordinates. The other plots are the spin plane electric wave power (expressed in V^2/Hz) measured in four PFR channels. The central frequencies of the channels are marked on the right side. The magnetic field magnitude is overplotted in each wave panel for comparison. The vertical dashed lines marked the times of directional discontinuities, which are labeled with letters a to h in the $|\mathbf{B}|$ panel

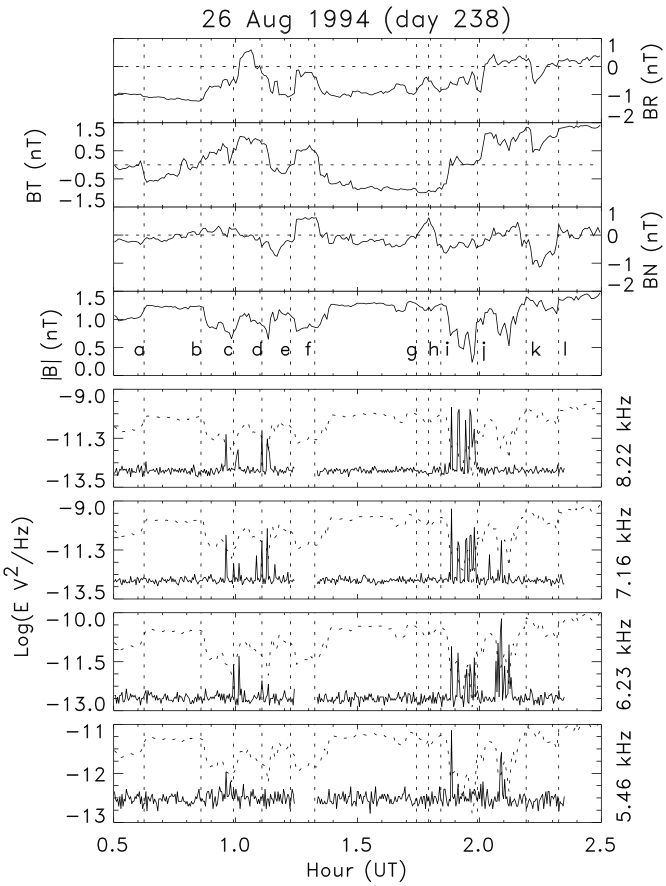

Fig. 3. Similar to Fig. 2 but for interval 0030 to 0230 UT, Aug 26, 1994. Twelve DDs are identified and marked with letters a to l

ated with a magnetic hole: c and j, which have large $\Delta|\mathbf{B}|/B_L$ and form magnetic depressions; and discontinuity d, which is detected during a magnetic field reduction. The reduction leads to the formation of a magnetic hole in which a Langmuir wave burst is seen. Between DDs i and j, there is about 9 min of a magnetic depression which apparently consists of a train of 3 magnetic holes. We note that Langmuir wave bursts are seen in each of the holes. There is also another similar magnetic depression between DDs j and k where strong wave bursts are observed, which have peak power at 6.23 kHz.

3.2. Statistical results

Among the 402 DDs examined, most of them ($\sim$ 89.3%) are RD (56.7%) and intermediate discontinuities in category 3 (32.6%), which has little change in the field magnitude across the discontinuity. Only 10.7% fall into category 2 (TD, 6.2%) and 4 (4.5%), which have a large magnitude change across the discontinuity. The number distribution of the observed DDs is shown in Fig. 4a. The DDs are grouped into 4 groups, G1 to G4, corresponding to the four categories in the previous section, respectively.

As shown in the examples, Langmuir waves can be excited at some DDs. In 402 DDs we examined, there are 36 DDs ($\sim$ 9%) at which Langmuir wave bursts are observed. The occurrence rate of the waves at various DDs are also examined, and the results are plotted in Fig. 4b. It is found that the wave occurrence rate, which is the number of DDs with waves divided by the total number of DDs in each group, is much higher in TDs (32.0%) and in the intermediate group 4 (44.4%) than in RD (4.8%) and the intermediate group 3 (6.9%).

We have seen that some of the Langmuir waves at DDs actually occurred in magnetic holes associated with the discontinuities, for example, the waves at DDs b and f in Fig. 2, and the waves at DDs c, d, j in Fig. 3. Our statistics show that 75% of DDs (27 out of 36) which have waves are associated with short duration magnetic field depressions, and the waves are seen at the edges of the 'holes' where there is a large magnetic field gradient or at the field minima. This result with the fact that the wave occurrence rate is higher in group 2 and 4 than in group 1 and 3 implies that the change in the field magnitude which

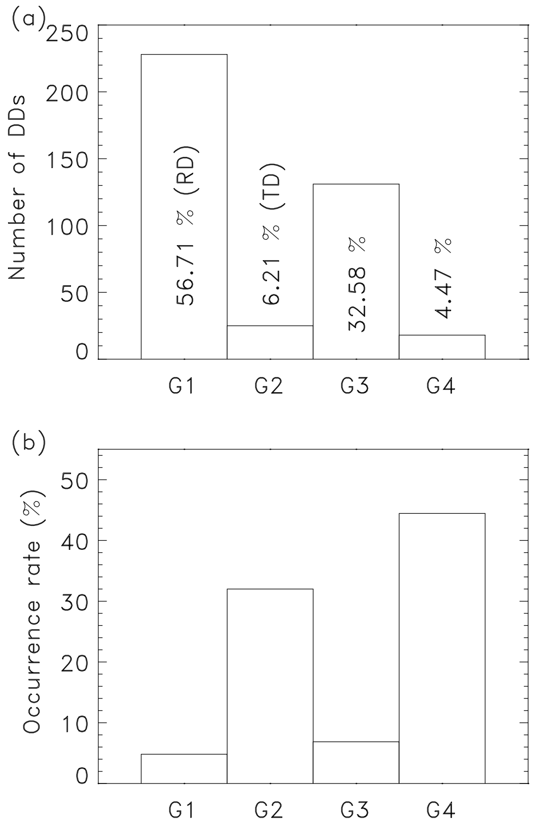

Fig. 4. a The number of occurrences of directional discontinuities (DDs) in each group: 'G1' for RDs, 'G2' for TDs, 'G3' and 'G4' for intermediate DDs with small and large $\Delta|\mathbf{B}|/B_{\mathrm{L}}$, respectively. The occurrence rate of each group expressed by a percentage is also marked. **b** The occurrence rate of Langmuir waves at each group of DDs

forms a magnetic depression is favorable to the excitation of Langmuir waves. The reduction of the field strength in these holes ranges from $\sim 8\%$ to $\sim 85\%$ of the ambient field as seen in one min average magnetic field data. We note that in this study, all DDs with waves but with no magnetic depressions are found near the ecliptic plane (within $\sim -35°$ heliographic latitude), and all DDs with waves at higher latitudes are associated with magnetic holes.

In a recent study, Ho et al. (1995) observed two types of tangential discontinuities: (1) TDs with small directional changes ($< 40°$), found at the edges of mirror mode structures, which are generated locally by ion anisotropies, and (2) TDs with large directional changes ($> 60°$), found at the boundary between two streams. The second type of TDs usually have larger current intensity than those of the mirror mode associated TDs. The TDs in this study apparently include these two types of TDs and those between the two types, based on the directional change only. The directional change of the TDs in our study ranges from $\sim 10°$ to $\sim 100°$. In Fig. 5 we plotted the directional change vs $\Delta|\mathbf{B}|/B_{\mathrm{L}}$ of all DDs which have waves. The figure shows RDs and the intermediate group 3 (solid circles) have directional changes $> 30°$, while those of TDs and of the intermediate group 4 (open circles) spread between $10°$ and $100°$. Since a

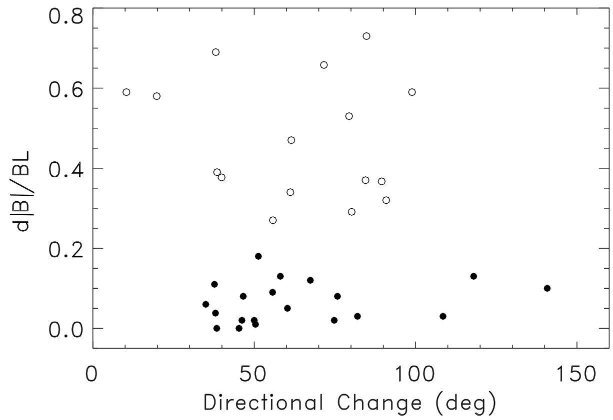

Fig. 5. The directional change (in degrees) of discontinuities at which Langmuir waves are observed, plotted versus $\Delta|\mathbf{B}|/B_{\mathrm{L}}$. Data for RDs and intermediate group 3 are plotted with solid circles, while the open circles are for TDs and intermediate group 4

large directional change across a DD usually corresponds to a large current intensity (Ho et al. 1995), our statistical results imply that currents generated at magnetic field discontinuities play little role in the excitation of the Langmuir waves. The values of $\Delta|\mathbf{B}|/B_{\mathrm{L}}$ cover a large range, implying that the reduction in the magnetic field strength needed to have Langmuir waves excited can be a small fraction of the ambient field.

4. Summary and discussion

Excitation of short bursts of Langmuir waves in magnetic holes in the solar wind is a common phenomenon as observed by Ulysses. Short duration magnetic depressions are often formed in association with magnetic field directional discontinuities. This statistical study is conducted to investigate what properties of DDs are important to the excitation of the waves. Among the 402 DDs on 11 days we examined, only $\sim 9\%$ of DDs (36/402) are observed to have Langmuir waves. Among the 36 DDs at which Langmuir wave bursts are seen, 27 (75%) have associated magnetic holes, and the waves occur within or at the edges of the holes. At high latitudes, all waves observed at DDs occurred in DD-associated magnetic holes. Although the identification of DDs depends on the criteria and the time resolution of the data used, and thus the statistical numbers may change with different criteria and data resolution, the following results are believed generally to be true: only a small fraction of DDs have associated Langmuir wave activity, and most of those Langmuir waves occur in the magnetic depressions formed at the DDs. These results seem to imply that the hole structure (the small scale reduction in the magnetic field strength) is important to the excitation of the isolated Langmuir wave bursts, especially at high latitudes. We note that the holes need not be very 'deep' to excite Langmuir waves. We have observed Langmuir waves excited in a reduction as small as $\sim 10\%$ of the ambient field.

The occurrence rates of the waves for the four groups of DDs support the above conclusions. Most (89.3%) of the DDs identified are RDs or intermediate group 3 which have small magnitude changes and thus are less likely to form a magnetic field depression. The occurrence rate of the waves at these DDs is much lower (5.6%) than that (37.2%) at TDs or the intermediate group 4, which have large changes in magnitude and are more likely to form a depression. The change in directional angles across the DDs that have waves covers a large range of degree. This result implies that the change in the field direction at a DD, and thus the intensity of the current generated at the DD is not as important for the excitation of the Langmuir waves as the reduction of the field magnitude.

The physical process of how a magnetic hole structure generates Langmuir waves has been discussed by MacDowall et al. (1996). It was suggested that thermal electrons propagating through the holes form counterstreaming electron beams due to the conservation of magnetic moment, changing the electron distribution. These electron beams are responsible for the excitation of the observed short duration Langmuir wave bursts. The electron distribution functions inside the holes consist of both electrons trapped in the holes and electrons propagating through the holes. The detailed form of the distribution function depends on the initial conditions due to the mechanism(s) by which the hole forms and the consequences of wave-particle interactions.

The formation of magnetic depressions or magnetic holes at DDs may be caused by different mechanisms. Winterhalter et al. (1994) attributed some of the magnetic holes they observed to remnants of mirror mode structures (Tsurutani et al. 1992). Ho et al. (1995) observed that at edges of mirror mode structures, a pair of TDs may form an isolated short duration magnetic depression. In an earlier study, Burlaga (1968) discussed a physical process operating at the discontinuity. The process may annihilate antiparallel components of magnetic field lines and thus reduce the field intensity and form a 'D-sheet' structure. Additional magnetic field lines may drift toward the discontinuity carrying some matter with them. A jet of matter may be squeezed out by the incoming flux tubes. It is possible in this kind of process that electrons are carried in and form the beams responsible for the Langmuir wave excitation. More work needs to be done to study the excitation mechanism of these waves in discontinuity associated magnetic holes.

Although most Langmuir waves seen at DDs occur in associated magnetic holes, there are some waves excited at DDs without magnetic depression, as seen in Fig. 2. These cases make up only a small part (25%) of DD-related Langmuir waves. We notice that the Langmuir waves in these cases are usually weaker than those in the magnetic holes, and they are observed only in low latitudes. These results seem to suggest that there is a physical process other than the hole-related mechanism generating Langmuir waves at the discontinuity, which has not been explored. This mechanism may operate in the solar wind with more inhomogeneity and turbulence at low latitudes. The wave bursts so generated may be transient and may have much shorter durations than those of hole-related waves, and thus are much less frequently observed.

As reported in Lin et al. (1995), there are other kinds of plasma waves excited in magnetic holes. In magnetic holes associated with discontinuities we have also observed plasma waves at frequencies typical for the Doppler shifted ion acoustic waves in the solar wind and at frequencies below the local electron gyrofrequency. We notice that, at the DDs without magnetic depression, the above waves are often observed. The occurrence and generation mechanisms of these lower frequency waves at the discontinuities have not been studied in detail and represent other tasks for the future work.

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