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Type III radio bursts observed by Ulysses pole to pole, and simultaneously by wind

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Abstract. We consider 555 type III bursts observed by Ulysses and/or Wind while Ulysses traversed a large range of longitude and latitude. We find:

1) The percentage of bursts seen by both spacecraft was 59.5%. It was higher, about 80%, when Ulysses was to the south and east of the Sun as seen from Wind. It decreased to about 50% when Ulysses was near the ecliptic behind the Sun, and it remained near 50% as Ulysses moved to the north and west.

2) The distribution of low frequency cutoffs f_{lo} of type III radiation is very similar for bursts seen by Ulysses and those seen by Wind, whereas the distribution of the in-situ plasma frequency f_p at the two spacecraft is very different. Many bursts descend to close to $f_p \sim 30$ kHz at Wind but few descend to the lower $f_p \sim 10$ kHz at Ulysses. We confirm earlier findings that f_{lo} is rarely lower than about 20 kHz.

3) Statistically, the low frequency limit depends strongly on the burst intensity, being about four times lower for strong bursts than for weak bursts.

We consider three hypotheses for the close relation between intensity and f_{lo}: proximity of the burst source to one spacecraft or the other, directivity and propagation effects, and density and speed of the fast electron stream. We conclude that, while the first two may be important for some bursts, for many others the character of the electron stream is the dominant factor in establishing both the burst intensity and the lowest frequency attained.

Key words: Sun: radio radiation – activity – corona

1. Introduction

In this paper we extend past studies of the visibility and low frequency limit of type III bursts by considering the period from November 1994 to September 1995, the pole to pole excursion of Ulysses. We use radio observations from Ulysses and simultaneous observations from Wind. During the interval considered, Ulysses traversed a wide range of heliospheric latitudes and longitudes, and a small range of heliospheric distances, while Wind remained in the ecliptic plane near Earth at 1 AU.

Type III bursts originate in solar active regions when electrons are accelerated and travel outward along open magnetic field lines, often into interplanetary space, generating high levels of Langmuir waves at the plasma frequency. Some energy is converted into radio radiation that is directive, with maximum intensity in the direction of the magnetic field (Reiner and Stone 1988).

The visibility of type III bursts observed simultaneously from two directions has been studied since the 1970's, starting with the STEREO experiment (Steinberg and Caroubalos 1970). A spacecraft and a ground-based telescope were observing the same type III radiation from two different directions, allowing Poquerusse and Bougeret (1981) and Poquerusse et al. (1988) to measure the 3-D positions of some type III bursts in the solar corona. Later, simultaneous measurements by ISEE–3 and Voyager established that some type III bursts are visible from almost any direction, even from behind the Sun, but with a reduction of intensity of ~ 100 (MacDowall 1983; Dulk et al.1985; Lecacheux et al. 1989). More recently, Hoang et al. (1995) compared simultaneous observations from Ulysses (out of the ecliptic) and ICE (in-ecliptic); they found that multiple components of some type III bursts have different visibilities as viewed from the two spacecraft, and gave evidence of significant propagation effects, especially within the ecliptic plane. Dulk et al. 1996 compared observations by Wind and Ulysses during the period from November 1994 to April 1995, finding that $\sim 68\%$ of the bursts were seen on dynamic spectra of both spacecraft. Only about half of the bursts were simultaneously detected when Ulysses was nearly directly behind the Sun and within 20° of the ecliptic, while 80% were detected when Ulysses was at high southern latitudes. Poquerusse et al. (1996) compared ground-based and Ulysses observations and derived the average radiation pattern of type III bursts.

Another parameter of interest in the theory of type III bursts is the lowest frequency attained as the electron streams travel

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outward. In an earlier study, Leblanc, Dulk and Hoang (1995) considered type III bursts observed by Ulysses where the plasma frequency f_p at the spacecraft was between 3 and 20 kHz. During the entire period of the Ulysses flight, 9 kHz was the lowest frequency at which type III electromagnetic radiation was ever seen, even though f_p was often 3–4 kHz. The distribution of cutoffs was found to be independent of ecliptic latitude, and of f_p at the spacecraft (excepting of course that $f_{lo} \geq f_p$) and to be broadly spread between 17 and 300 kHz. Here we have qualitative measurements of the intensity of the bursts, and we determine how the intensities are correlated statistically with the low frequency limit.

In this paper we present the statistics on the visibility, intensity, and low frequency limit of type III bursts by using observations by Ulysses from pole to pole and simultaneous observations by Wind in the ecliptic plane. In Sect. 2 we describe the observations and data analysis. In Sect. 3 we give the results on the reception probability, the intensity of the bursts, and then on the low frequency limit and how it is related to the burst intensity, and in Sect. 4 a discussion for the interpretation of the results.

2. Observations and method of analysis

We utilize data from the Unified Radio and Plasma Wave (URAP) experiment on Ulysses (Stone et al. 1992) and the Radio and Plasma Wave Investigation (WAVES) on Wind (Bougeret et al. 1995). Both spacecraft have long dipole antennas in the spin plane and short antennas along the spin axis, feeding into receivers covering the range from 1.25 to 940 kHz on Ulysses and 4 kHz to 13.8 MHz on Wind.

We concentrate on the common frequency range below 1 MHz and study the type III bursts that occurred from 18 November 1994 to 4 September 1995. Wind was always near Earth, in the ecliptic at 1 AU. Ulysses was moving from south to north in the hemisphere opposite Earth; Table 1 shows its location on 5 dates, the heliographic longitude being with respect to Earth.

Heliographic location of Ulysses			
Date	R (AU)	Latitude	Longitude
18 Nov 94	1.83	–65°	102° E
25 Feb 95	1.35	–6°	180°
5 Mar 95	1.34	0°	164° W
5 Aug 95	2.05	+80°	122° W
4 Sep 95	2.25	+75°	133° W

We measure the intensity, the low frequency limit (f_{lo}) of the type III and the plasma frequency at the spacecraft (f_p) for all bursts that are visible on daily plots of dynamic spectra from two sources, DESPA and Goddard Space Flight Center. The plasma frequency is revealed on these plots by the quasi-thermal plasma line. Our estimate of errors in f_{lo} is about $\pm 12\%$, a number based on multiple readings of the same dynamic spectrograms. Regarding the intensity of the bursts, we have only a qualitative measure at this time; quantitative measurements of the 555 bursts are in progress. As we examined the dynamic spectrum of each burst we noted whether it was strong, moderate, weak or barely visible. This notation is subjective, particularly in marginal cases. In addition, the dynamic range and sensitivity of the dynamic spectra vary from day to day, and although we tried to take this into account using the information encoded on the plots, there is an uncertainty from one measurement to another. Hence in this paper we concentrate on "strong bursts" and "weak or very weak bursts", for which there is little ambiguity.

We have estimated the difference in flux density between weak, moderate and strong bursts by generating quantitative measurements of a sample of 19 bursts recorded by Ulysses at 148 kHz, which is above f_{lo} for most bursts. "Weak bursts" have a typical flux density $\langle 2 \times 10^{-20}$ W m^{-2} Hz$^{-1} \rangle$. "Moderate bursts" are typically 10 times more intense, $\langle 15 \times 10^{-20}$ W m^{-2} Hz$^{-1} \rangle$. "Strong bursts" are typically 300 times more intense than weak bursts $\langle 700 \times 10^{-20}$ W m^{-2} Hz$^{-1} \rangle$, and can be a few $\times$ 1000 times more intense. The large range for strong bursts comes from saturation of the dynamic spectra above some high intensity. In the following the intensity notation is 2, 3, 5, and 7 for very weak, weak, moderate and strong bursts respectively.

3. Results

An example of the dynamic spectra of Ulysses and Wind from which our measurements were made was published by Dulk et al. (1996), showing a number of type III bursts with a variety of intensities and low frequency limits, and the quasi-thermal plasma line from which f_p is measured. That example illustrates that there is very little ambiguity as to whether a given burst is visible by both spacecraft and with what relative intensity.

Here in Fig. 1 we show a different example, where four or five type III bursts were simultaneously recorded by both spacecraft, but where four or five others, some quite strong, were recorded only by Ulysses. Examples like this are rare: during the whole period with 555 bursts, only 12 strong bursts were recorded by one spacecraft with no trace on the dynamic spectrum of the other.

3.1. Reception probabilities

Excluding times of data gaps and occurrences of type III storms, we measured the properties of 555 type III bursts: 59.5% were seen on dynamic spectra of both spacecraft, 81% by Wind, and 78% by Ulysses. Because the sensitivity of Ulysses and Wind is essentially the same, this demonstrates that the high latitude of Ulysses neither decreases nor increases the visibility of type III bursts relative to Wind at latitude near zero. The greater heliospheric distance of Ulysses is unimportant because the resultant intensity decrease is $\lesssim 5$, which is very small compared with the burst dynamic range of ≈ 1000.

Fig. 2 shows some of the measured properties of these 555 bursts, where the abscissa is burst number. In each of the two

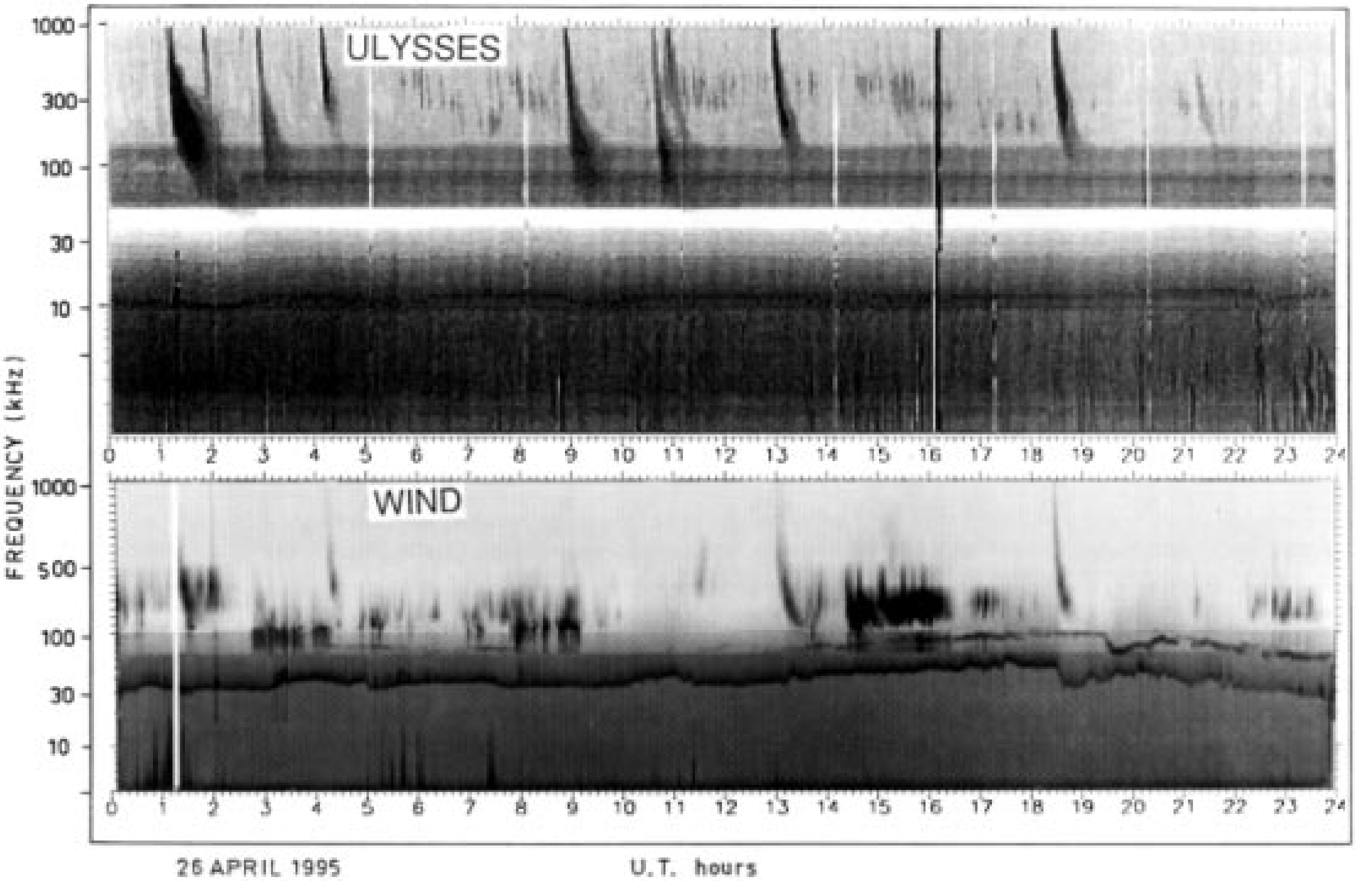

Fig. 1. Dynamic spectrum of 24 hours on 26 April 1995 with type III bursts observed simultaneously by Wind (top) and Ulysses (bottom). The intense, spiky radiation recorded by Wind at 100 to 400 kHz is Auroral Kilometric Radiation. On Wind, f_p varies between about 30 and 50 kHz as seen from the plasma line at f_p and the line due to the Earth's bowshock at $2\,f_p$, while at Ulysses it is nearly constant at 10–12 kHz. Several strong and weak bursts on Ulysses are not present on Wind, but some of the stronger bursts are present on both spacecraft with low frequency cutoffs that are generally the same despite the different plasma frequencies and the fact that Ulysses was at latitude +40° and solar longitude 129°W relative to Wind

panels, the top half is for Wind and the bottom half is for Ulysses, plotted negatively. Vertical lines are drawn every 27 days starting from 18 November 1994. From Table 1 and the heliographic latitude and longitude of Ulysses printed near the center of the top panel, we note that Ulysses was south of the solar equator until 5 March and north of it afterward. Similarly it was east of the Sun as seen from Wind until 25 February and west of the Sun afterward. It was always in the solar hemisphere opposite Wind.

At the top of the upper panel are the percentages of bursts that were recorded by both Ulysses and Wind during the 27 day intervals. For the first three 27 day intervals, when Ulysses was far south and to the east, about 80% of bursts were simultaneously recorded. As Ulysses approached the ecliptic, nearly directly behind the Sun, the percentage decreased to about 50%. It remained near 50% afterward, varying between 24% and 65%, while Ulysses was climbing to high northern latitudes and staying at westerly longitudes.

In the lower panel the square symbols indicate bursts recorded on one spacecraft and not the other. For instance, during the 27 day period labelled 19/03, 63% of the 65 bursts were seen by both spacecraft. Of the remaining 24 bursts, 22 were recorded on Wind and not Ulysses, and 2 were recorded by Ulysses and not Wind. On the other hand, during the 27 day intervals of 15/04 and 12/05, more bursts were recorded by Ulysses than by Wind.

During the interval 12/05, only 24% of the 46 bursts were recorded by both spacecraft. At this time Ulysses was at +50° latitude and 118°W longitude. In contrast, there is the interval 28/12 when Ulysses was at –47° latitude and 130°E longitude, not very different in absolute value, but 88% of the 58 bursts were recorded by both spacecraft.

In the lower panel of Fig. 2, very weak, weak, moderate and strong bursts aligned near ordinates 2, 3, 5 and 7 respectively (negative values for Ulysses). To allow the quantized readings to be better seen, random numbers between -0.5 and +0.5 have been added to the intensities. The large majority of the bursts not seen by one or the other spacecraft are weak or very weak; strong bursts seen by one spacecraft and not the other are very rare.

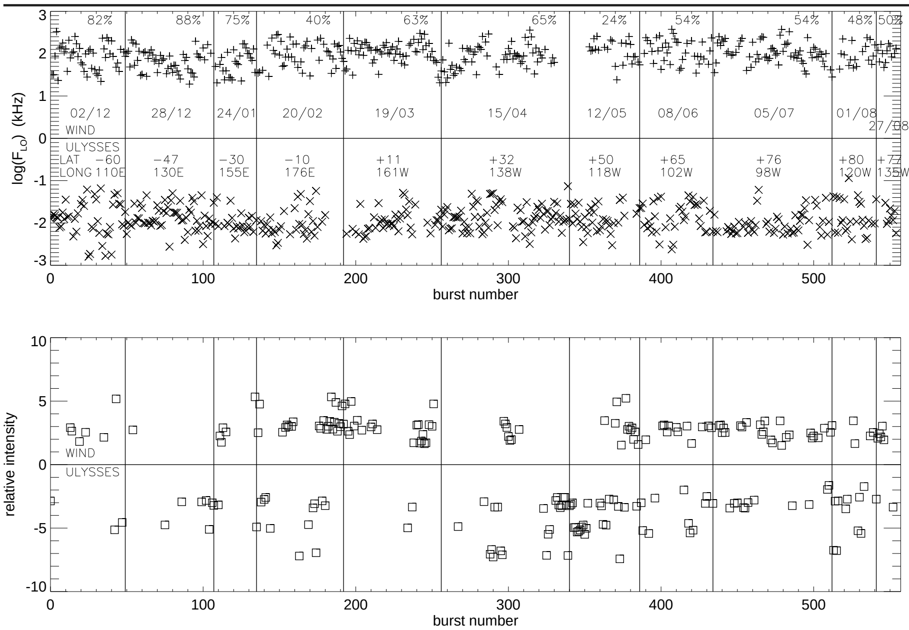

Fig. 2. Upper panel: low frequency limits of bursts seen simultaneously by Ulysses and Wind. Bottom panel: intensity of bursts seen by Ulysses and not Wind, or vice versa. Vertical lines separate 27 day intervals. Dates in 1994/1995 are printed near the center of each interval along with the heliographic latitude and the longitude of Ulysses relative to Wind. The numbers near the top give the percentages of bursts recorded simultaneously by Ulysses and Wind. Ordinate values near 2, 3, 5 and 7 represent very weak, weak, moderate and strong bursts respectively.

In searching the square symbols in the diagram for a pattern, it seems that symbols sometimes occur for one spacecraft at times of gaps for the other. However, this anticorrelation, if it exists, does not seem to be related to phase in the 27 day periods, as one might expect if it were caused by the rotation of the active region(s) generating the type III bursts.

3.2. Low-frequency limit

The upper panel of Fig. 2 shows that the log of f_{lo} is spread between about 1.3 and 2.5 (f_{lo} between about 20 and 300 kHz) for both Wind and Ulysses. Statistically, f_{lo} is very similar for the two spacecraft.

Fig. 3 shows the distributions of low frequency cutoffs at Wind and Ulysses. On these scatter plots of f_{lo} vs. f_p, the dotted line denotes the limit $f_{lo} = f_p$ below which radiation is forbidden. At Ulysses f_p was usually around 10 kHz, while on Wind, closer to the Sun, it was typically 20 to 30 kHz and never less than 15 kHz. On Ulysses f_{lo} very rarely approached f_p, whereas on Wind f_{lo} often approached (the higher values of) f_p. After taking into account the forbidden zone $f_{lo} < f_p$, the two distributions of f_{lo} are seen to be similar even though the distributions of f_p are very different.

In these scatter plots we note that 20 kHz is the threshold below which very few bursts are recorded. This result is similar to that of Leblanc, Dulk and Hoang (1995) based on 1028 bursts measured by Ulysses betweeen 1990 and 1994, during which time Ulysses traversed large heliocentric radii where f_p was as low as 3 kHz. Those authors found that 17 kHz is the threshold below which few bursts are seen, and 9 kHz was the lowest radio frequency ever recorded.

3.3. Intensity and low-frequency limit

Fig. 4 shows normalized histograms of f_p and f_{lo} for the bursts recorded by the two spacecraft. For Ulysses the histogram of f_p is concentrated at about 10 kHz, a frequency less than half that of f_p at Wind. Two histograms of f_{lo} are plotted, one for bursts noted as being weak and the other for bursts noted as being strong, where the latter have flux densities about 300 times larger. There is a striking difference in that strong bursts have cutoffs at a frequency 4 times lower than weak bursts. A few strong bursts have cutoffs as high as 100 kHz, while a few weak bursts have cutoffs as low as 20 kHz. The value of f_p at the spacecraft is of little or no importance (excepting of course that $f_{lo} > f_p$).

Fig. 5 is similar to Fig. 4 but for Ulysses only, and covering a larger span of time and plasma conditions. The Ulysses data are split into 6 periods: in the left half are three periods when Ulysses was in the ecliptic or at a latitude less than 35 degrees. In the right half are three periods when Ulysses was at higher latitudes. The three histograms in each subplot represent f_p, f_{lo} for strong bursts, and f_{lo} for weak bursts.

Comparing the subplots we see that the histograms of f_p differ greatly, but those of f_{lo} are all rather similar. In each subplot, the histogram of f_{lo} for strong bursts is displaced toward a lower frequency than that for weak bursts, with typical values of f_{lo} for strong bursts being 20 to 40 kHz while those for weak bursts being 100 to 200 kHz. With a few exceptions the histograms for periods in-ecliptic are somewhat broader than those for periods out-of-ecliptic.

4. Summary and conclusions

We have determined the visibility of type III bursts seen simultaneously by Wind and Ulysses while Ulysses traversed a large

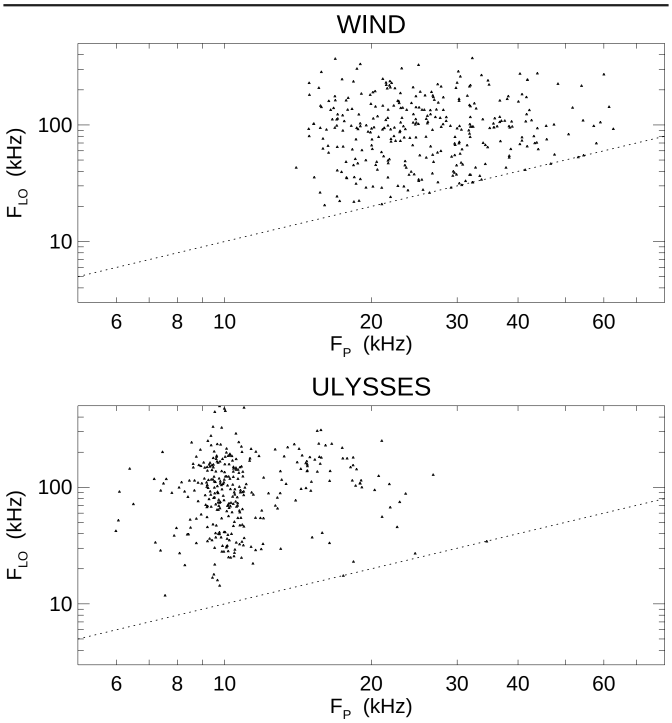

Fig. 3. Scatter plots showing f_{lo} and f_p for the 330 bursts recorded simultaneously by Ulysses and Wind. Few points lie close to the dotted line representing $f_{lo} = f_p$, particularly for Ulysses.

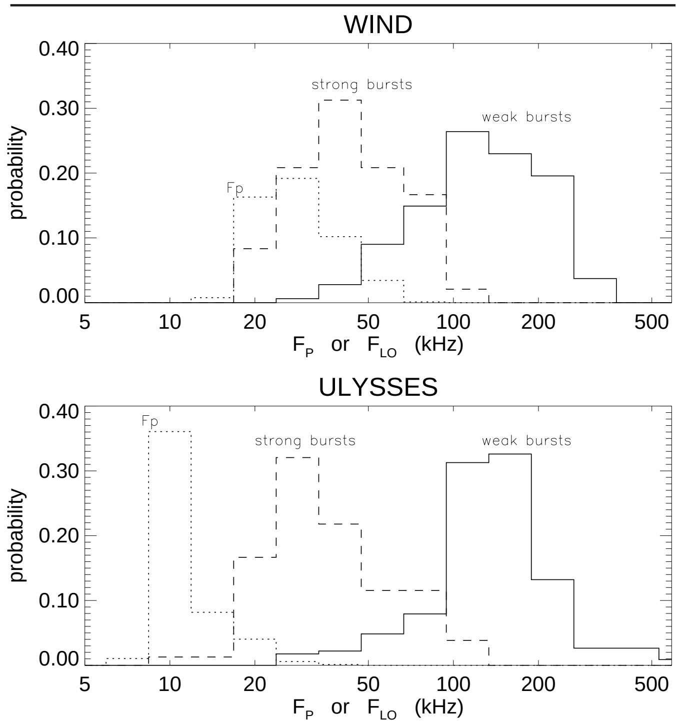

Fig. 4. Histograms of f_p and f_{lo} showing how the low frequency cutoffs are strongly affected by burst intensity but are essentially independent of the value of f_p at the spacecraft.

range of longitude and latitude. Our major new results are as follows:

1) The percentage of bursts seen by both spacecraft was 59.5%. It was high, up to 88%, when Ulysses was to the south and east of the Sun as seen from Wind. This percentage decreased to about 50% when Ulysses was near the ecliptic behind the Sun, and it remained near 50%, with variations between 24% and 65%, as Ulysses moved to the north and west of the Sun.

2) The distribution of low frequency cutoffs is very similar for the bursts seen by Ulysses and those seen by Wind, whereas the distribution of f_p at the two spacecraft is very different. Many bursts descend to close to $f_p \sim 30$ kHz at Wind but few descend to the lower $f_p \sim 10$ kHz at Ulysses. We confirm earlier findings that f_{lo} is rarely lower than about 15 to 20 kHz.

3) Statistically, the low frequency limit depends strongly on the burst intensity, being about four times lower for strong bursts than for weak bursts, at least 100 times less intense.

4.1. Interpretation

We know of no logical explanation for the result that many fewer bursts were recorded simultaneously by Ulysses and Wind when Ulysses was behind the sun to the north and west than when it was to the south and east. Perhaps the spiral direction is important, but its effect in the present situation is not obvious.

For the finding that f_{lo} is hardly ever lower than 15 to 20 kHz, this might be related to the dilution of the electron beam as it travels outward (Leblanc et al. 1995): Because of the divergence of the field lines and/or velocity dispersion, at some distance from the Sun the density of fast electrons may be insufficient to form a positive slope in competition with the background plasma.

This possibility has recently been examined in more detail by Robinson (1996), who concluded that high density, high velocity beams can maintain positive slopes to the greatest heliospheric distances and, hence, to the lowest values of f_{lo}. This arises both because such beams are denser relative to the solar wind background distribution, and because they are located farther out in the tail of the background distribution, where there are fewer background particles. Coupled with the observation that intense electron beams at 1 AU do not produce large average positive slopes (Lin et al. 1996), this implies that no beams, even the densest, can maintain positive slopes very far beyond 1 AU (Robinson, 1996). Hence, f_{lo} cannot be significantly lower than f_p at 1 AU (i.e., 10 – 40 kHz), in agreement with Leblanc et al.'s (1995) observations.

The finding that the low frequency limit depends strongly on the burst intensity might be due to one or more of three effects that we discuss separately: i) proximity effect: bursts are better observed when on the same side of the Sun as of the spacecraft, ii) directivity and propagation effects due to beaming of the radiation and impediments in propagating to a spacecraft, and iii) density and speed of the fast electron beams.

Regarding the first hypothesis, the proximity effect, those bursts with f_{lo} near f_p at the spacecraft might on the average be closer, and hence stronger than the others. Consider bursts with

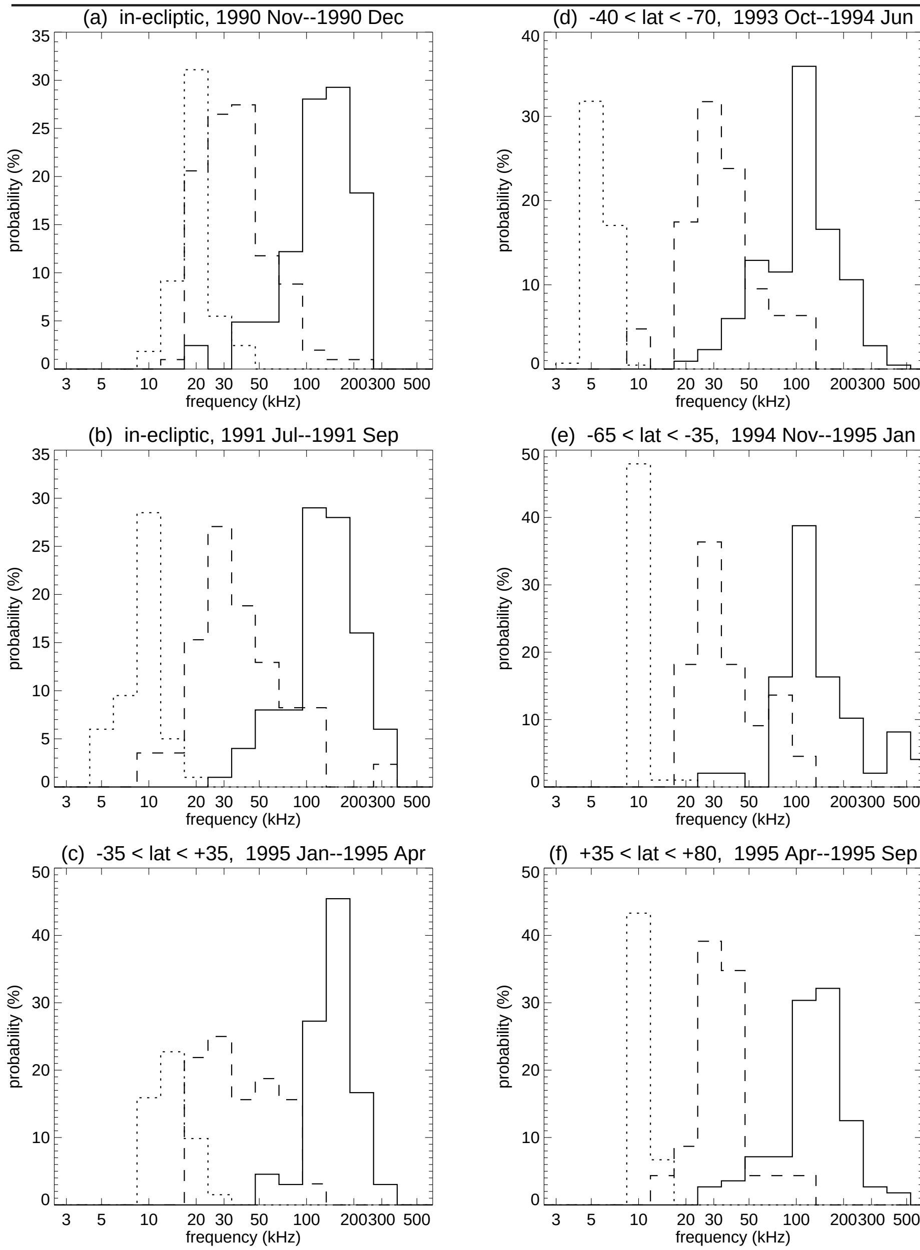

Fig. 5. Normalized histograms of f_p (dotted line), f_{lo} for strong bursts (dashed line) and weak bursts (solid line) for Ulysses observations at different periods from 1990 November to 1995 September.

a specific intrinsic intensity: the most intense observed bursts will be those closest to the spacecraft, with frequencies (assuming fundamental emission) close to f_p. Ignoring refraction and directional effects, bursts observed to be less intense will lie at some greater distance and will have f_{lo} somewhat higher, near the maximum value of plasma frequency along the ray path, which usually will be near the point of closest approach of the ray to the Sun. The correlation between distance, intensity, and f_{lo} will be weakened after merging a range of intrinsic intensities, and weaker for Ulysses at high latitudes and large distances than for Wind. But it should have the same qualitative form. Some of the distributions of Fig. 5 resemble what might be expected: the lowest f_{lo}'s of weak bursts are about 2.5 times higher than those of strong bursts. The prevalence of this proximity effect can be evaluated by considering how many bursts are strong or moderate and with $f_{lo} \lesssim 2f_p$ on one spacecraft, and are weaker and have a higher f_{lo} at the other spacecraft; we find 38 strong and moderate bursts that fit the criterion. This represents 23% of strong and moderate bursts.

Another means of evaluating the importance of the proximity effect is to consider the flux densities of bursts at different longitudes around the Sun. In their study of ISEE–3 and Voyager observations, Lecacheux et al. (1989) found that bursts directly behind the Sun are typically 100 times less intense than those in front, while those to one side or the other are about 10 times less intense. For a random distribution of burst longitudes we thus expect the proximity effect could account for a factor of 10 in intensity, which is much smaller than the flux density difference of about 300 between our "strong" and "weak" bursts.

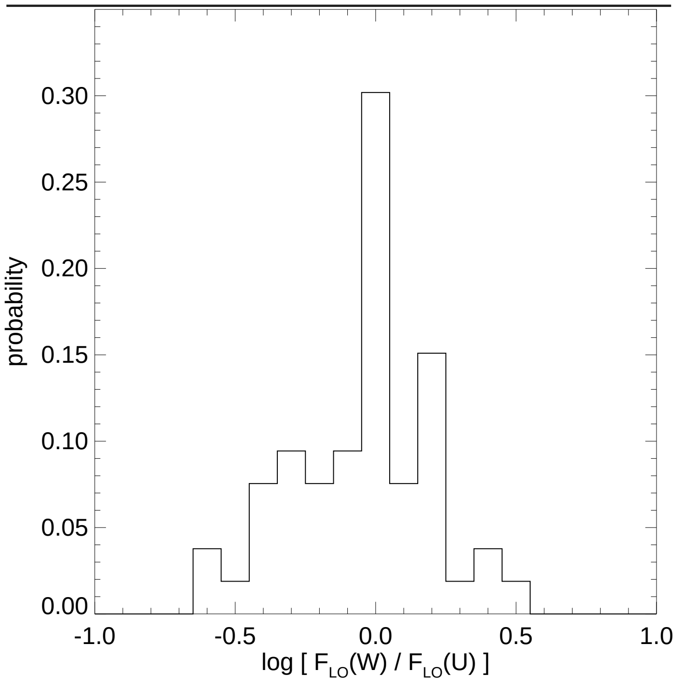

Fig. 6. Histogram of the log of $f_{lo}(W)/f_{lo}(U)$for 47 bursts that were of moderate or strong intensity on both spacecraft.

The second hypothesis, propagation effects and directivity, has been considered by Dulk et al. (1996) as an explanation for different values of f_{lo} recorded by Ulysses and Wind for a subset of the bursts in this paper. They conclude that blockage or refraction of the radiation by large scale, overdense structures between the source and observer might be the reason for a moderate fraction of the bursts with very different cutoffs.

Consider now the third hypothesis, that the low frequency limit and the burst intensity are both related to the density and speed of fast electrons in the type III streams. As discussed above, fast electron streams of high density and high speed can more easily form a positive slope in the velocity distribution. Such beams also carry a larger flux of free energy, which has been found to be proportional to the intensity of the Langmuir waves in the source, all else being equal (Robinson, 1996). In particular Robinson (1996) argued that the volume emissivity of Langmuir waves from a type III stream balances the rate of build-up of stream free energy, finding good agreement with Langmuir energy densities observed in situ by ISEE–3. Fundamental and harmonic emission are positively correlated with Langmuir-wave intensity and, hence, with large values of beam density and velocity.

The prevalence of bursts being affected by dense beams, can be evaluated by considering the intensities and values of f_{lo} for bursts recorded as strong or moderate by both spacecraft, with $f_{lo} > 1.2 f_p$, i.e., not so close to f_p to be directly affected by it. Fig. 6 shows the resulting histogram of $f_{lo}(W)/f_{lo}(U)$. The remarkable peak at zero shows that more than 30% have the same f_{lo} within a factor of 1.12, evidence that the bursts' high intensity and same f_{lo} at the two spacecraft is very likely due to the bursts being produced by dense beams.

In conclusion, from our results, which we emphasize are statistical, we consider it likely that the intensity of most bursts is increased and f_{lo} is decreased when the density of the beam is high, while for some bursts the intensity and f_{lo} are affected by proximity and/or propagation conditions between the source and one or the other spacecraft.

It may be possible to examine the prevalence of the different effects by examining a set of bursts associated with plasma waves at the spacecraft. A test to examine the effect of the beam density and speed is to measure the frequency drift rate of the bursts. This work is in progress.

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