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Solar electron beams associated with radio type III bursts: propagation channels observed by Ulysses between 1 and 4 AU

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Abstract. Solar and interplanetary type III (TIII) radio bursts are produced by solar electron beams of flare origin streaming away in the interplanetary medium. The radio emission process implies the excitation of Langmuir waves by the electron beam which are converted by non linear processes into transverse electro-magnetic waves. The study of the beam properties reveals information about their propagation regime in the interplanetary medium. The local plasma condition observed in the vicinity of the radio emission zone are important in understanding the Langmuir waves excitation process and their conversion into electromagnetic radiation as well as the propagation of the electron beams. Interplanetary TIII have therefore long been studied for either of theses aspects but only for few isolated cases could the three aspects of such events be studied together. This paper presents for the first time a complete study of the three aspects of nine interplanetary TIII events observed by the radio, particle and plasma experiments aboard the Ulysses spacecraft between 1.3 and 4.3 AU. The main result of this study is to establish that the interplanetary medium contains well beyond 1 AU 'propagation channels' previously identified around 1 AU. Those plasma structures are rooted in solar corona and seem to channel the propagation of solar electron beams. They have been identified in each of the nine events studied here; Langmuir waves and almost scatter-free propagation of the solar electrons were observed while the spacecraft was crossing these formations. Plasma properties of the 'propagation channels' have been studied: their main characteristic is a very low level of magnetic field fluctuation. This property may be at the origin of a stabilization process of the plasma inside the channels explaining why they are maintained on such large distances as well as a key element in understanding the particle propagation regime and Langmuir waves excitation observed inside. The implications on the medium distance (1–5 AU) heliosphere are also discussed.

Key words: Sun: corona – Sun: particle emission – Sun: radio radiation – interplanetary medium

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1. Introduction

Radio type III bursts are produced by solar electron beams injected during solar flares along magnetic field lines extending into the interplanetary medium. The emission is the result of a two-step process which implies in a first stage the excitation of Langmuir waves at the local plasma frequency (f_p) by electron beams of energies ranging from 2 to 20 keV and the conversion of the electrostatic waves into electro-magnetic radiation at f_p and/or 2 f_p by non-linear effects. The density decreases with heliocentric distance in the corona and interplanetary medium. Therefore, as the electron beams move away from the Sun, they excite plasma waves at lower and lower local f_p and the radio emission drifts from higher to lower frequencies.

Solar TIII bursts have long been studied either for their radio properties (frequency drift rate, Langmuir waves excitation, fundamental or harmonic emission...) or the properties of the associated particles (beam propagation, evolution of fluxes or pitch angle distribution with time, composition ...). The beams associated with TIIIs are often highly collimated along magnetic field lines due to decreasing field strength and the frequently weak pitch angle scattering as the particles move from the Sun to the observer (Beeck and Wibberenz, 1986; Earl, 1976; Earl, 1981). Statistical as well as detailed single-case studies have shown that Langmuir waves were produced at the arrival of $\sim$5-10 keV electrons (Hoang et al., 1994; Lin et al., 1981). The question of fundamental or harmonic emission is still unresolved as an accurate measurement can only be made for the local emission. Both harmonic and fundamental emissions have been observed in the interplanetary medium. Some electron beams associated with TIIIs have been shown to be channelled by plasma structures. At heliodistances of $\sim$1 AU, the local transverse dimension of the "propagation channels" is of the order of 10^6 km (Anderson and Dougherty, 1986).

In this paper, I will present a study of 9 associations of TIII, Langmuir waves and electron beams observed by Ulysses. This study will a) extend to greater heliocentric distances the results previously obtained at $\leq$1 AU; b) for the first time provide a joint analysis of the 3 aspects of such events (i.e. radio, particle and plasma). We will see in Sect. 3 why this type of joint analysis is useful and even sometimes essential for a complete description of TIII related events. This more extensive analysis provides a

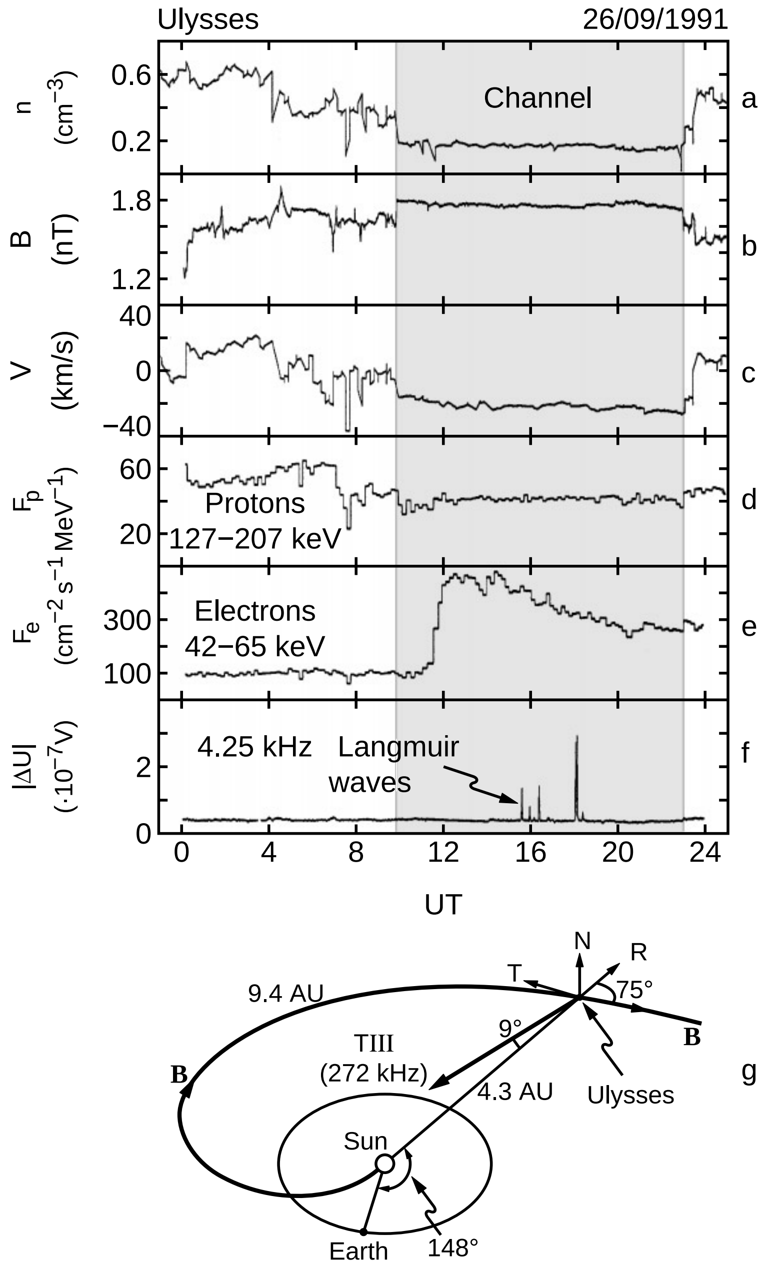

Fig. 1. Summary of the Sept. 26, 1991 observations. Plots: plasma density (a); magnetic field amplitude (b); transverse solar wind speed (c); ∼100 keV ion fluxes (d); 40-60 keV electron fluxes (e); radio noise at 4.25 kHz (f). Ulysses-Sun connection configuration (g). The zone delimited in grey corresponds to the channel crossing clearly identified on a) b) and c) panels.

deeper understanding of the radio wave process and the structure of the heliosphere.

2. Data and selection procedure

The interplanetary medium data analyzed here come from various instruments aboard the Ulysses spacecraft: magnetic field measurements by the magnetic field experiment aboard Ulysses (Balogh et al., 1992), solar wind speed by the SWOOPS instrument (Bame et al., 1992), radio and plasma emissions by the URAP experiment (Stone et al., 1992) and electron fluxes and pitch angle distributions by the HISCALE experiment (Lanzerotti et al., 1992). In addition, solar observations made from Earth or Earth-orbiting satellites were used in order to identify, when geometrically possible, the flares responsible for the radio-particle events observed by Ulysses. The events studied here are TIII bursts going down to very low frequencies (close to the local plasma frequency or its harmonic) which were: 1) unambiguously associated with Langmuir waves 2) associated with solar electron events detected above 30 keV by HISCALE. Among the quite numerous examples of TIII bursts observed during the mission, only about 20 in three years drifted to low enough (i.e. close to local f_p or its first harmonic) frequencies, about half of those were unambiguously associated with Langmuir waves[1]. Only 9 such events could then be associated with solar electron events observed by HISCALE and were the subject of this

[1] out of ecliptic events were excluded for this reason as many Langmuir waves occur there in association not with TIIIs but magnetic holes as shown by (Lin et al., 1996)

study. An example of one such case is presented on Fig. 1. The restrictions used for the selection procedure are to ensure that Ulysses is intercepting the field lines followed by the exciting beam of the burst being observed. It is then possible to make double checks of some parameters which have a key importance in determining for example the exciter energy for the Langmuir waves or the path length followed by the particles. A comparison with solar surface observations also assists location of the injection site on the solar surface and gives an accurate estimation of particle injection time. The time dispersion of the particle arrival in the different HISCALE energy channels has been used in order to determinate both the injection time and path length followed. The pitch angle distribution is then checked to confirm solar origin of the beam. This procedure firmly establishes that the detected electron beam is the higher energy part of the one responsible for the observed TIII. The presence of channels has then been investigated using plasma and magnetic field data.

The 9 selected cases are presented in Table 1. Although most of these events were previously published (see Table 1 for the references), these publications analyzed only one or occasionally two of the three radio, plasma and particle aspects of the events. In this paper, all the three aspects of each individual event have been taken into account and a statistical study of their properties was made. Table 2 is a summary of the different results obtained during the study on propagation channel transverse size, magnetic field variance and Langmuir waves exciter speed. The following sections will describe the results obtained for the electron beams propagation, the radio events and the channels observed in the 9 selected events. I will then discuss the implications of these results on the understanding of TIII emissions as well as on heliosphere structure.

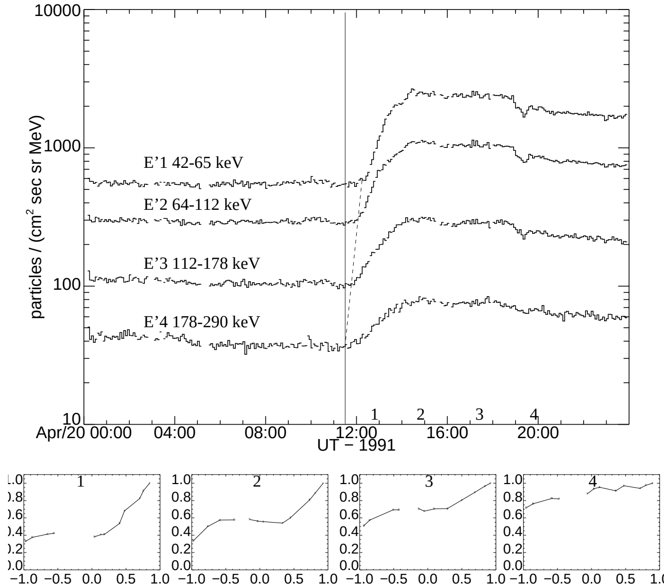

Fig. 2. HISCALE observations on Apr. 20, 1991. Top: electron fluxes versus time in the four energy channels of the instrument. The time dispersion of the event is visible on this plot as the higher energy channel fluxes increase prior to those of lower energy channels (see the dashed lines). Bottom: four pitch angle distribution (flux in each direction, normalized to the maximal flux, versus cosine of pitch angle); the numbers indicate at which instant the pitch angle distribution are observed. The event is anisotropic at onset, and gradually returns to isotropy as time passes.

3. The results

3.1. The electron beams

The electron beams observed during this study were detected at distances ranging between 1.3 and 4.3 AU. Even for the most distant observations, anisotropy in the electron beams is clearly discernible in the beginning of the events. This is especially remarkable considering that some of the electron beams had propagated along spiral paths of $\sim$10 AU (i.e. April and September 1991 cases). Fig. 2 is a presentation of a typical electron event. The conservation of beam collimation along such long distances shows that adiabatic focusing is very efficient or that pitch angle diffusion is weak along all the path. All the electron beams were observed inside propagation channels suggesting that those channels may have special properties to allow weak-scatter propagation of such particles. In Sect. 3.3, we show that the magnetic field inside these channels is very quiet with a level of fluctuation of $\leq$10 % in energy. This property of the magnetic field is consistent with the very weak pitch angle scattering in these channels.

The time dispersion curve of event onset at different energies gives an estimate of both the path length and injection time of the particles at the Sun. The path length estimated from those measurements agreed within 30% with the Parker spiral length in 8 of the 9 cases studied. The local magnetic field direction also agreed with Parker spiral field. This shows that guiding magnetic field lines of those beams have the shape of Parker spirals up to large distances from the Sun (i.e. at least 4 AU). The case of December 10, 1990 in which there is a strong disagreement between the electron path estimation and Parker spiral length, occurred when the interplanetary medium structure was perturbed by the presence of a Coronal Mass Ejection (CME). This perturbation results in a deformation of the Parker spiral which increases one's path length from the Sun to Ulysses as suggested by Reiner et al. (1995). The otherwise good observed agreement between electron path estimation and Parker spiral length shows that apart from some unusual situations, the structure of the magnetic field in the heliosphere is well described by the Parker model out to distances of at least 4 AU.

Particle observations also reveal small-scale structures of the plasma. Occasionally, some very large variations of the particle fluxes (both electrons and protons) were observed to occur simultaneously in all energy channels. Those variations were identified as the S/C entry and exit in plasma substructures. These substructures were identified a posteriori on the plasma and magnetic field data but their signature were much less striking as on particle data from which they were first pointed out. An example of such a detection is given in Fig. 3.

Table 1. Summary of the selected cases characteristics. Onset times indicated here are those of the high frequency burst observed at Ulysses by URAP. Note that they are neither of the injection time of the exciting particles at the Sun (t_{onset}) or the onset time of Langmuir waves at Ulysses (t_{LW}). f_p^{ul} and f_{ul} are respectively the local plasma frequency and local emission of the TIII frequency. α determines if the local emission was on the fundamental (α=1) or harmonic (α=2) modes. Letters refer to the different publications concerning those cases: [A] Anderson et al. (1992); [B] Anderson et al. (1995); [C] Buttighoffer et al. (1995); [D] Chaizy et al. (1995); [E] Hoang et al. (1994); [F] Pick et al. (1995); [G] Reiner et al. (1995); [H] Reiner et al. (1992)

Date $^{[publication]}$	onset	$v_\odot$ km.s^{-1}	r_{ul} AU	lat. °	f_p^{ul} kHz	f_{ul} kHz	α –
04 Dec. 90 $^{[E]}$	08H25	380	1.30	1.3	19.00	19.00	1
10 Dec. 90 $^{[E-G]}$	07H15	375	1.35	1.0	20.00	20.00	1
11 Dec. 90 $^{[A-D-H]}$	11H35	375	1.35	1.0	13.80	13.80	1
22 Dec. 90 $^{[D-H]}$	23H30	350	1.5	0.0	10.00	10.00	1
22 Feb. 91 $^{[B-D-H]}$	04H00	320	2.2	-3.0	11.00	11.00	1
20 Apr. 91	10H25	445	2.78	-4.30	6.50	13.00	2
26 Sept. 91 $^{[C]}$	06H00	480	4.29	-5.63	4.25	8.50	2
13 March 95 $^{[F]}$	06H48	345	1.34	+7	20.00	20.00	1
14 March 95 $^{[F]}$	05H20	345	1.34	+7	22.00	22.00	1

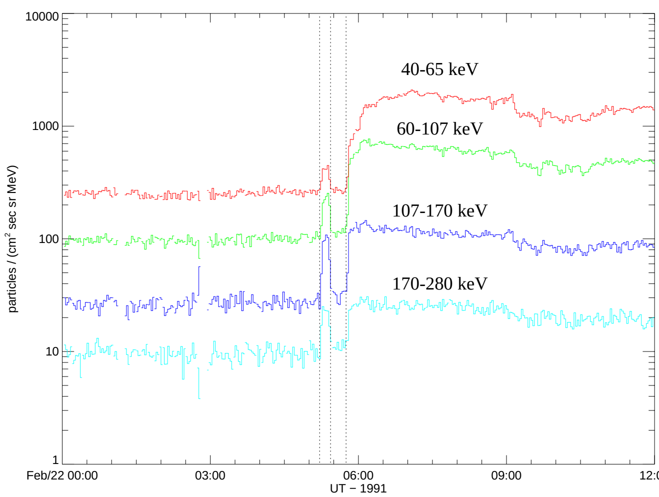

Fig. 3. Fluxes variations of the 4 HISCALE electron channels as observed on Feb. 22, 1991. Notice the brutal flux increase and decrease around 05:00 UT. This is the signature of Ulysses entry and exit inside a 11min duration plasma structure. The corresponding structure is identified with more difficulty on the plasma and magnetic field data (not shown here). (Figure adapted from Anderson et al., 1995)

3.2. The radio events: TIII bursts and Langmuir waves

The TIII bursts analyzed here were typically traced from 1 MHz down to a few kHz close to the local plasma frequency or its harmonic. The local emission was observed to occur on the fundamental mode except for events observed at greatest distances when it was observed at the harmonic frequency. Some bursts were occulted at high frequencies indicating that Ulysses was shielded from the emission site by high density layers in the corona. Those cases occurred on days when the geometric configuration was such that the flare site was on the invisible side of the solar disk as seen from Ulysses. For each event, the timing (onset time at 1 MHz or higher observable frequency is compared with flare onsets as published in Solar Geophysical Data (SGD) and electron onset time estimation) and geometrical configuration (position of Parker spiral footpoint is compared to flare site) have been checked (see Fig. 1). We were thus able to track the exciter beam from its origin on the Sun to the position of Ulysses. An important issue in the study of these radio events is the determination of the exciter speed for Langmuir waves. On Ulysses, the only available method is to estimate the exciter speed from the radio measurements. The exciter energies range from 2 to 20 keV. This range is not covered by any particle instrument aboard the S/C. But it is possible to estimate the exciter speed by the following method which has long been used in many previous statistical studies of TIII and more recently on Ulysses by Hoang et al. (1994). The injection time of the exciting particles at the Sun t_{onset} is given by the flare onset as observed on Earth (corrected from light propagation time). The onset time of the Langmuir waves observed at Ulysses t_{LW} is accurately measured by URAP. The path length d followed by the beam is estimated by the Parker spiral length computed from the SWOOPS solar wind speed measurements. The exciter speed is then simply: $v_{ex} = d/(t_{LW} - t_{onset})$. The main sources of errors in such an estimation are: the error on d and the Langmuir waves onset time. The error on d can be reduced using the electron path length estimation. The possibility of an error on t_{LW} has been pointed out by our study. Indeed, all the Langmuir waves bursts observed were observed inside the channels which seem to suggest that they do not occur outside and means that the channel properties must be investigated in order to determine which characteristic of them is necessary for Langmuir waves production. But as far as exciter speed determination is concerned, this raises another issue: when Langmuir waves are observed to begin in coincidence with a channel entry does this onset time correspond to the actual onset time of the waves or has the emission already begun when Ulysses can observe it entering the channel? Such an example is given in

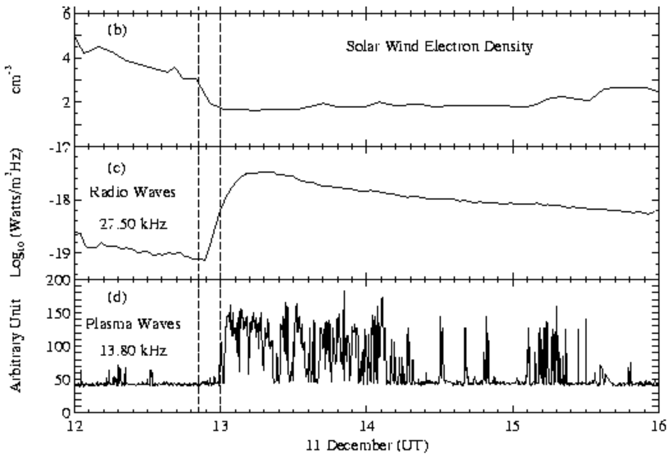

Fig. 4. Observations made by Ulysses on Dec. 11, 1990 event. Top panel: plasma density measured by SWOOPS. Second and third panels: radio noise as measured by URAP at 27.5 harmonic and 13.8 kHz fundamental of the plasma frequency (frequency at which Langmuir waves are produced). Note that the harmonic emission onsets a few minutes prior to the Langmuir waves emission which is only detected by URAP as Ulysses enters a plasma channel (characterized by a lower density). (Figure adapted from Chaizy et al., 1995)

Fig. 4. It corresponds to the case of December 11, 1990 studied by Anderson et al. (1991), Chaizy et al. (1995) and Reiner et al. (1992) when an harmonic emission is detected outside a channel and the onset time of Langmuir waves occurs a few minutes after in coincidence with channel entry. We could not find any means to answer the above question and therefore caution must be used in such cases as the speed determined is only a lower limit to the actual exciter speed. This bias could have affected statistical studies and partly explain the dispersion observed at low energies.

3.3. The propagation channels

In all nine cases studied propagation channels were identified in the plasma data. Ulysses's entry (or exit) inside a channel is marked by changes in amplitude and/or direction of the magnetic field accompanied by simultaneous changes in solar wind plasma parameters. The distinction between the crossing of channel frontier and usual variations due to the presence in the interplanetary medium of various plasma waves (i.e. Alfvèn . . .) is made because of the larger magnitude, simultaneity and quasi-instantness of those variations showing that the feature encountered is more likely spatial than temporal. Another key element is to look for simultaneous discontinuities in the temporal evolution of non-thermal particles, ions and electrons, such as those measured by HISCALE. Such simultaneous variations are the trace of a change in the nature of the plasma surrounding Ulysses. In some occasions channel frontiers are much easier to detect this way than on plasma parameters as discussed in the last paragraph of Sect. 3.1. As discussed above, propagation channels are preferred sites for weak-scatter propagation as well as Langmuir wave excitation. The different properties of the channels (size, magnetic field variance, pressure equilibrium...) were studied for the 9 channels in order to find their common characteristics. The first parameter analyzed was the transverse size of the channels. A determination of their local size at Ulysses is made from the equation $d_{UL} = v_{sw}.\sin < Bv_{sw} >.\Delta t$ (Anderson and Dougherty, 1986). d_{UL} is the local transverse size of the channel; $< Bv_{sw} >$ the average angle between magnetic field and solar wind speed vectors; Δt is the channel crossing time. Since those channels originate in the solar corona and since they are detected at distances ranging from 1 to 4 AU, a direct comparison of their local size is not possible. A simple model of radial expansion has been used to deduce from the local Ulysses size the size on solar surface. $d_\odot = R_\odot / L_{Parker}.d_{UL}$. $d_\odot$ is the channel transverse size on solar surface; $R_\odot$ solar radius; L_{Parker} Parker spiral length. The results are shown in Table 2 and show that the channels are of quite comparable size ∼10" (i.e. 7000 km) on solar surface. When geometrically possible the presence of active regions in the vicinity of Ulysses's footpoint (always found within reasonable vicinity of the flare site related to the studied TIII burst) has been investigated. It has been found that footpoints were in the vicinity of active regions. This result must of course be used with caution because of the various sources of uncertainties due to the use of the back mapping technique on quite long distances and the relatively little number of cases.

The most striking characteristic of the channels is the remarkable constancy of the magnetic field inside of them. This feature may be seen on plots of amplitude or direction (Fig. 5). In order to quantify this property, a minimum variance analysis was performed on the magnetic field data for each of the 9 cases. The properties studied were:

– the portion of magnetic field energy implied in the fluctuations: $\Sigma\epsilon_i / < B^2_{tot} >$ (sum of the co-variance matrix eigenvalues $\epsilon_{min}\epsilon_{med}\epsilon_{max}$ normalized to the total magnetic field.
– the unidimensionality of the fluctuations: $\epsilon_{min}/\Sigma\epsilon_i$
– the anisotropy in maximal variance plane: $\epsilon_{med}/\epsilon_{max}$
– the angle between B and minimal variance direction.

This variance analysis has been performed on all channels with a magnetic field resolution of 24 s and analysis running windows ranging from 100 min down to 5 min (166 to 3333 μHz) the average duration of the channels being about 5 hours. At those frequencies, the fluctuations outside the channels represent in average ∼20% of the magnetic field energy there is no characteristic polarization of them and ϵ_{min} ∼20% of $\Sigma\epsilon_i$. Inside the channels, the fluctuations never represent more than 10% of the total energy and average at ∼5%. The unidimensionality is important (i.e. $\epsilon_{min}/\Sigma\epsilon_i$ of a few percent). The minimum variance direction is aligned with B to within 30° .

Most of the channels contain a number of sub-channels having different orientations of B but remain approximatively parallel to $\boldsymbol{B_{Parker}}$. Unexpectedly, those sub-channels are more frequently detected at smallest distances from the Sun [2]. Indeed,

[2] This effect does not appear in Table 2 as only the presence and averaged duration of the sub-channels is reported and not their number

Table 2. Summary of the results obtained for the 9 cases studied. Days marked with ⋆ are those during which sub-channels were detected (see text). The averaged values of duration or field variance are then indicated in the table. The estimated channel widths on solar surface are given in km and arc seconds ("). Variance percentages are the ones of magnetic fluctuations to total magnetic field in energy (when the sub-structures were of too short duration they have been evaluated "by eye" as large, average or low). The path lengths (l_{spir}) are those computed from local solar wind speed measurements with a Parker spiral model; those after the "/" are electron path length estimations (see text) when a significant disagreement was observed. Langmuir waves exciter speeds were derived from those measurements and are given in percentage of light speed (%c). The cases where only a lower limit to the speed is indicated correspond to those when the measurement could be biased as Langmuir waves onset in coincidence with Ulysses channel entrance (see text).

Date	Distance at	Duration	Size Ulysses (AU)	Size Sun (km ")	Variance $\Sigma\epsilon_i/<B^2>$	l_{spir}(AU)	v_{exci} (%c)
04 Dec. 90	1.3	04H00	0.03	13000 - 18	5%	1.7	$\geq$7.4
10 Dec. 90	1.4	08H30	0.076	18000 - 24	~5%	1.8/3.0	8.3/14
11 Dec. 90	1.4	CME 46H	0.30		~2%	1.8	$\geq$17
22 Dec. 90⋆	1.5	~40 min	0.006	2000 - 3	average	2.1	$\geq$30
22 Feb. 91	2.2	02H00	0.016	3200 - 4	5%	4.0/3.3	21/17
⋆		~15 min	0.001	200 - 0.27	very low		
20 Apr. 91	2.8	09H10	0.069	5800 - 8	3%	4.8/7.6	17/27
⋆		02H00	0.015	1300 - 2	2%		
26 Sept. 91	4.3	13H00	0.15	6000 - 9	2%	9.6/14	16/21
13 March 95	1.3	05H00	0.041	16300 - 22	8%	1.8	$\geq$12.5
14 March 95	1.3	05H00	0.041	16300 - 22	15%	1.8	$\geq$16.7
⋆		02H00	0.016	6500 - 9	2%		

as the structures expand in the solar wind, their size increases with distance and sub-channels are then wider at large distances and should therefore be more easily detected at large distances away from the Sun. This higher occurrence of sub-channels at small distances may be due to a statistical effect as almost all the channels were detected around 1.3 AU and only two of them at larger distances. However, if the effect is not only statistical, this suggests that some process acts during expansion to merge the different sub-channels into a single wide channel.

4. Discussion and conclusions

This study has consisted in the joint analysis of radio, particle and plasma aspects of TIII related events. We have shown that certain plasma structures (the propagation channels) are rooted in the Sun and channel solar particle propagation through the heliosphere to distances of 4 AU and possibly greater. The joint analysis procedure used here allowed cross-checking of most parameters and warned about possibly biased measurements of Langmuir waves exciter speed.

The results obtained for electron propagation as well as radio and Langmuir waves emission are similar to those obtained close to 1 AU. Near scatter-free propagation of the particles is still observed out to 4 AU away from the Sun. Fundamental emission are more often observed than harmonic emission in the local bursts observed here[3]. We have shown that a bias could be introduced in the exciter speed evaluation procedure used on Ulysses (see Sect. 3.2). When possibly biased measures were excluded from the panel, the average exciter speed we have measured was ~15%c[4] (i.e. ~6 keV electrons). This value is in agreement with those measured around 1 AU showing that there is probably no significant change in velocity of the exciter as heliorange increases. We have also shown that near scatter-free propagation of electron beams and Langmuir waves excitation occured only inside the channels.

The main result in this work was to establish that propagation channels previously discovered at ~1 AU persisted as far as 4 AU showing that the heliosphere has embedded filamentary structures rooted in the Sun, reaching up to 4 AU away and channeling solar particle propagation. Their global as well as local properties have been investigated and are the following ones.

The local properties of the channel are:

L1 very quiet plasma and magnetic field parameters.
L2 extremely low level of magnetic field fluctuations (i.e. less than 10% in energy)
L3 the structures appear to be in pressure equilibrium with the surrounding plasma

The main local characteristic of the channels is their signature in the magnetic field (L2). The very low level of magnetic field fluctuations (i.e. never more than 10% in energy), and the confinement of these fluctuations inside the plane perpendicular to the averaged magnetic field might very well explain why near scatter-free propagation is possible inside the channels along distances beyond 10 AU or why Langmuir wave excitation is also favored. Further work is needed to be done to clarify which property or properties lead to these processes. In particular extension of the spectral magnetic field analysis should reveal

[3] This might be an effect of the selection procedure used in the first place for TIII bursts as low frequency TIII were searched for

[4] 15 precent of light speed

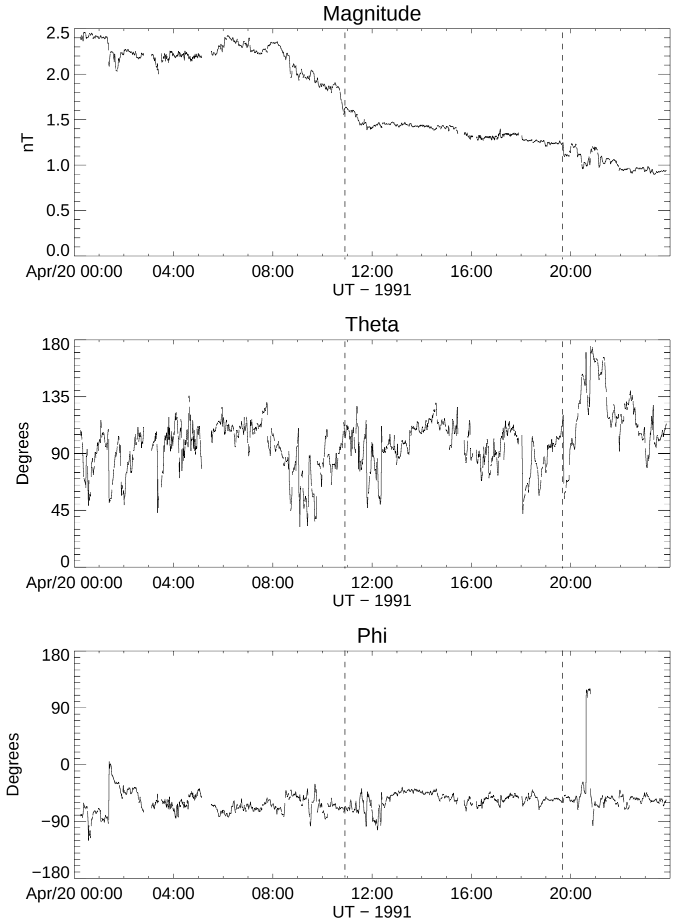

Fig. 5. Magnetic field measurements made by Ulysses on April 20-21, 1991. From top to bottom: magnetic field magnitude in nT; θ polar angle and φ azimuthal angle in the local heliocentric coordinate system both in degrees. The propagation channel is noticeable on magnitude and direction plots and is delimited by the dotted lines on each plot. (See also Fig. 4 in Buttighoffer et al., 1995).

more about the fundamental physical processes involved. A preliminary spectral study suggests that the magnetic field spectrum is indeed different inside and outside the channels Buttighoffer et al. (in preparation).

The global properties of the channels are:

G1 their topology is generally governed by a Parker spiral geometry.
G2 the channels detected here probably originate close to active regions on the Sun.
G3 their transverse size on solar surface (as estimated by a simple radial expansion model) was typically of ∼10” or 7000 km.
G4 particle measurements showed that some channels extended well beyond 4 AU where the S/C detected them.

All the channels detected here were observed inside the ecliptic plane. It is not very likely that this result is only an effect of selection as Dulk et al. (1985) showed that TIII bursts trajectories were forced from low or mid-latitudes zones down to the ecliptic plane, probably by the fast solar wind, at distances on the order of 0.5 AU. Since our observations were made beyond 1 AU it is then quite normal to find all channels inside the ecliptic. Sub-channels were observed inside some propagation channels. Those sub-channels seemed to disappear at large distances. If this effect is not purely due to statistics, it means that some process must act inside the channels to homogenize the internal plasma and merge the different sub-channels as expansion occurs.

One of the events studied here is found inside an interplanetary CME. This case is not the only one during which solar particles were reported inside CME (see for ex. Armstrong et al., 1994). This result is understandable for the two following reasons. CME are known to be zones of extremely quiet magnetic field which is the main characteristic of the channels. The topology of CME is quite complex: non-thermal particles have revealed that some parts of the CME had closed magnetic field line configuration (where bi-directional distributions are observed); while at other times uni-directional particle streaming showed that magnetic field lines were opened up to large distances (Bothmer et al., 1996; Gosling et al., 1995; Hammond et al., 1996). Such field lines could even be rooted to solar surface and therefore explain the presence of solar particles inside some CMEs. Further work needs to be done to precise whether these rooted zones are comparable to propagation channels or are particularities of some CMEs.

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