

# Plasma waves above the ion cyclotron frequency in the solar wind: a review on observations

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**Abstract.** Since the very beginning of the space venture, discrepancies between hydrodynamic models and observations have raised the attention to the kinetic effects taking place in the interplanetary medium. After discussing some of these constraints, a review on the state of the art knowledge on the waves in the range  $f_{ci} < f < f_{pe}$  ( $f_{ci}$  – about  $10^{-1}$  Hz – is the ion cyclotron frequency, and  $f_{pe}$  – a few 10 kHz – the electron plasma frequency) observed in the free solar wind, i.e., not magnetically connected to the Earth’s bow shock, is addressed.

## 1 Introduction

The solar wind is a supersonic, super Alfvénic flow of tenuously magnetized ( $f_{pe} \gg f_{ce}$ , where  $f_{pe}$  stands for the electron plasma frequency and  $f_{ce}$  for the electron cyclotron frequency), highly ionized and almost collisionless plasma. A first predictive, theoretical model of solar wind was given by Parker (1958) from an hydrodynamic approach (steady state expansion of a thermally driven electron-proton flow out of the hot solar corona). However, this model and the many derived from it were unable to explain the high speed solar wind observed at 1 AU without ad-hoc deposition of momentum and/or energy in the corona. Exospheric/kinetic models have provided better descriptions (Lemaire and Scherer, 1971; Maksimovic et al., 1997; Zouganelis et al., 2004). Moreover, detailed in situ measurements of the shape of the particles distribution function also support kinetic approach. Since the collision length is much larger than the typical interaction length between the waves and particles, the distribution functions are expected to deviate from a Maxwellian shape. Observations indeed reveal that the electron distri-

bution functions consist of a core (typically below 50 eV) almost Maxwellian, but also of a halo (representing electrons of higher energy) which strongly departs from a thermal distribution function. In some specific environments (high speed solar wind, far from magnetic sector boundaries), a third component appears: called a “strahl”, it represents an enhancement of particles with energies between 100 eV and 1 keV propagating away from the Sun (Pilipp et al., 1987a,b). Moreover, whereas the core of the distributions is rather isotropic, the halo part is highly anisotropic. The high energy particles of the halo present a broad pitch angle while the particles of the strahl are more focused along the magnetic field lines. However, this schematic picture varies considerably according to the solar wind conditions. The proton distribution functions also deviates from a thermal distribution. They show noticeable anisotropies between the temperatures parallel and perpendicular to the magnetic field (Montgomery et al., 1968; Marsch et al., 1981, 1982, and Fig. 1) and present a pronounced field-aligned heat flux or deformations like a bump at high energy.

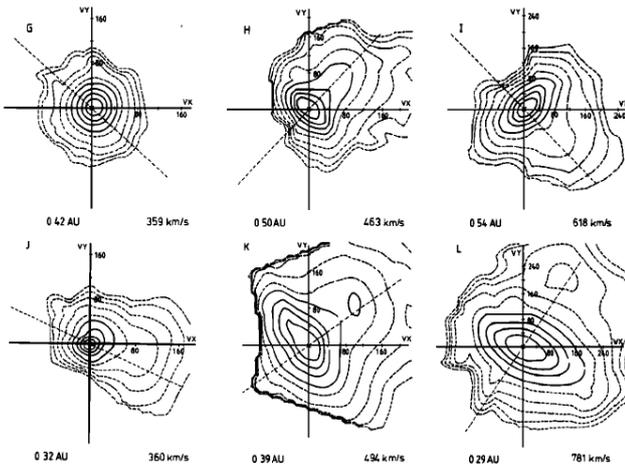
In situ measurements revealed that the total temperature<sup>1</sup> anisotropies increase with decreasing heliocentric distances and sometimes exhibit a second proton component that moves along the magnetic field direction with high differential velocities (Marsch et al., 1981, 1982; Marsch, 1991a, and Fig. 1).

The observed deformations of the distribution functions are, however, not as strong as one would expect from the free propagation of the particles. Likely, numerous instabilities develop that limit the scope of the deformations. This means that the plasma somehow reacts to restore stability to the system. Two kinds of back reaction may occur: a

<sup>1</sup>It must be stressed that the use of the total temperature (i.e. third moment of the distribution function, integrated over all energy) may contradict the detailed anisotropies when an extended tail exists in one of the parallel or perpendicular component.



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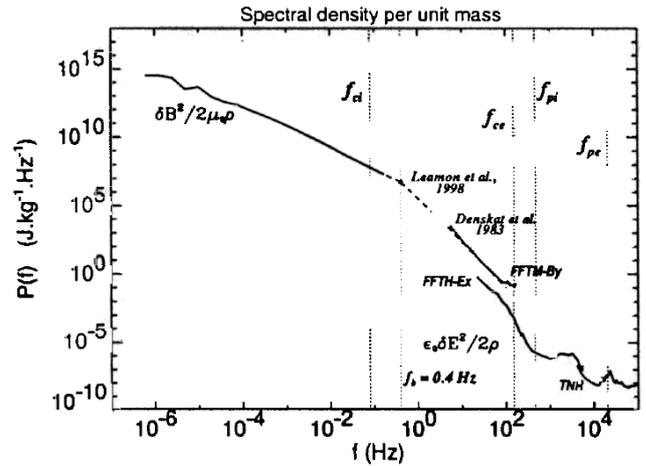


**Fig. 1.** Helios 2 proton distribution function as measured for low, intermediate and fast solar wind speed (from left to right) and various radial heliocentric distances. Dashed (non contour) line indicates the direction of the magnetic field. From Marsch et al. (1982).

quasilinear relaxation leading to waves with random phases (turbulence) or more complex nonlinear effects which induce coherent structures.

The solar wind energy spectrum shows that the energy is distributed over a broad range of frequencies (Fig. 2). Three zones are usually distinguished following the exponent  $\alpha$  of the power law that characterizes each of them: the very low energy regime with  $\alpha \approx -1$ , the inertial region (roughly  $10^{-4} \text{ Hz} < f < f_{ci}$ ) where  $\alpha \approx 5/3$  and the high frequency domain ( $f > f_{ci}$ ) which is thought to be where the energy is finally converted into heat. The evolution of the first part of the diagram (low frequencies) is compatible with the WKB propagation of fluctuations in a spherically expanding solar wind. As the frequency gets closer to about  $\approx 10^{-4} \text{ Hz}$  nonlinear coupling between MHD (Alfvén) waves start to be important and allow the cascade of energy through a broader range of frequencies. Finally, above the ion cyclotron frequency, the fluid description of the plasma becomes unsuitable since the phase velocity of the waves is close to the thermal velocity of the particles, thus allowing nonlinear instabilities to develop and energy to transfer between waves and particles. Linking the two regimes (fluid and kinetic) is thus fundamental to follow the energy cascade and to understand the role of the microphysics in the macrostructure of the solar wind (for extended reviews on turbulence in the solar wind, see Marsch, 1991b; Bruno and Carbone, 2005).

The magnetic power spectrum is, however, reliable only up to the ion-cyclotron frequency: above this frequency, the sensitivity of the magnetic field instruments is reduced (as compared to electric field measurements). The high frequency range of the spectrum (corresponding to the dissipative range) is thus better explored through electric field measurements. Intermittent fluctuations of the electric field



**Fig. 2.** Magnetic power spectrum observed in the solar wind. From Mangeney et al. (2001).

well above the thermal noise level are indeed observed in the range  $f_{ci} \ll f$ . Part of these fluctuations are the counterparts of the coherent electrostatic structures observed with waveform analyzers (Lacombe et al., 2002). Linking magnetic and electric power spectrum is far from being a trivial task, since, for example, the contribution of electrostatic waves is not seen in the magnetic spectrum but may represent a large contribution in the higher frequency range.

This paper aims to review the present knowledge on several of the waves in the range  $f_{ci} < f < f_{pe}$  from the observational point of view in the free (i.e., not magnetically connected to the Earth bow shock) solar wind. The information obtained from such observations set the fundamental constraints on the most basic physical processes leading to the permanent and large scale structure of the solar wind. This range of frequencies is dominated by electrostatic waves in the higher part (like ion acoustic and Langmuir waves), and includes also electromagnetic waves in the lower part (like whistler-modes and lower hybrid waves). Numerous papers describe these waves in the Earth magnetospheric environment and auroral region but much less exist in the free solar wind (Gurnett and Murdin, 2000).

The paper is organized as follows: after a rapid overview on the different space instruments that have been providing data of the solar wind since the 60's (Sect. 2), a review on the present knowledge on different coherent waves is given. It concerns in particular the Langmuir waves (Sect. 3.1), the ion acoustic waves (Sect. 3.2), the lower hybrid and whistler-mode waves (Sect. 3.3) and finally the multipolar isolated electrostatic structures (Sect. 3.4).

**Table 1.** List of the space missions that have been providing data on plasma waves in the solar wind. The horizontal line in the table splits up missions with spectrum analyzer (first part) from missions with waveform measurements on board. The peripasis and apoapsis of the orbit of the mission (fifth and sixth column) are given in astronomical units. (\*): in December 1983, ISEE-3 was renamed ICE and its main scientific objectives were redefined. (\*\*): missions which have provided waveform measurements during their journey in the solar wind while reaching their final destination (Galileo and Cassini) or during excursions outside the Earth magnetosphere (Cluster II).

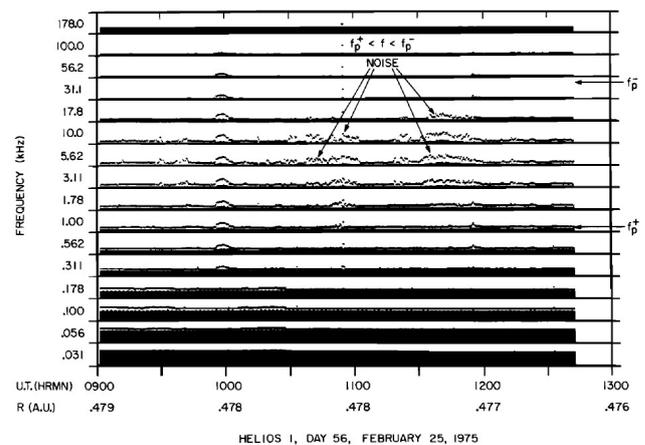
Mission Name	Launch year	End Year	Orbit	Periapsis (AU)	Apoapsis (AU)
PIONEER 8	1967	1996	Heliocentric near ecliptic plane	0.992	1.088
PIONEER 9	1968	1983	Heliocentric near ecliptic plane	0.754	0.99
HELIOS 1	1974	1981	heliocentric near ecliptic plane	0.309	0.985
HELIOS 2	1976	1986	heliocentric near ecliptic plane	0.29	0.983
ISEE 1-2	1977	1987	Highly elliptical geocentric	1.	1.
ISEE 3	1978	1983(*)	Highly elliptical geocentric	1.	1.
VOYAGER 1/2	1977	2007	Interstellar mission	1	–
GALILEO(**)	1989	2003	Jupiter Orbiter	1	5
ULYSSES	1990	2008	Solar Polar	2.3	5.4
WIND	1994	–	Ecliptic plane		
CASSINI(**)	1997	–	Saturn Orbiter	1	10
CLUSTER II (**)	2000	–	Elliptical geocentric	1	1
STEREO	2006	–	Ecliptic plane	0.9 (sat A)	1 (sat B)

## 2 Space instrumentation

Immediately after the beginning of the space venture during the International Geophysical Year (1957), the exploration of the interplanetary medium started (see Table 1). The PIONEER missions provided the very first in situ measurements of the interplanetary environment albeit still in the Earth vicinity. HELIOS 1 and 2 explored regions down to a distance of 0.3 AU to the Sun (Gurnett and Anderson, 1977) while VOYAGER provided information from the heliosphere well beyond 1AU. This two dimensions view of the interplanetary space was afterwards completed with ULYSSES which probed the unknown regions perpendicular to the ecliptic plane (Wenzel et al., 1992; Marsden et al., 1996).

Low frequency (below the ion gyrofrequency) hydromagnetic instabilities were first studied. The higher frequency domain ( $f \sim f_{pe}$ ) attracted more attention when spectrum analyzers and waveform receivers were implemented on board interplanetary missions. Spectrum analyzers give the intensity of the electric field in several frequency channels with narrow bandwidth. The intensity is usually averaged from a fraction of a second (typically 0.5 s) to a few seconds (36 s in case of HELIOS for example). Peak intensities are also measured. Such measurements provide continuous measurements over long time intervals(Fig. 3).

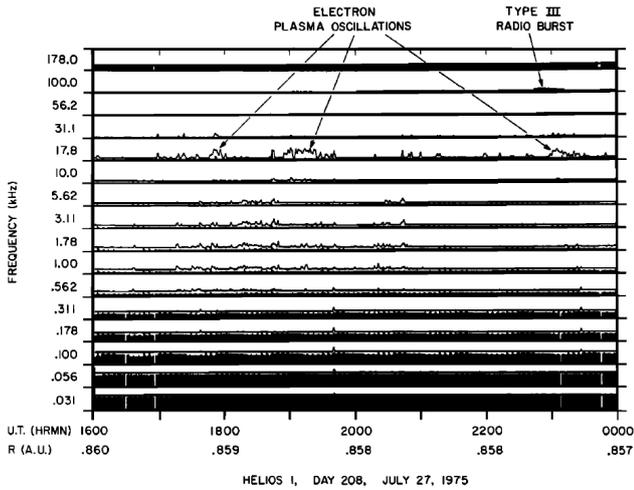
However, spectral analyzers lose an important information: the phase of the signal. Waveform analyzers have been implemented since the 90's<sup>2</sup>. Contrary to



**Fig. 3.** Example of data obtain by the spectral analyzer on board of HELIOS 1. Black area shows the time average (over 50 ms) field strength while the upper curve gives the maximum intensity peak for the same time interval. From Gurnett and Anderson (1977).

the spectrum analyzers, the records of waveforms at high frequency rate are often much shorter. WIND/WAVES (Bougeret et al., 1995), for example, provides waveforms of 15 msec or 230 msec each (see for example Fig. 7) and STEREO/WAVES (Bougeret et al., 2008) provides events 131 msec long. Due to telemetry constraints, one to two hundreds events can be recorded each day. An extremely small fraction of the day (a few seconds at most) is thus covered by the observations. Longer time coverage can, however, be achieved at the expense of the frequency rate (CASSINI/RPWS or CLUSTER/WBD).

<sup>2</sup>Note that Voyager had a waveform analyzer but the data were mainly used to generate high spectral resolution dynamical spectrum.



**Fig. 4.** HELIOS first measurements revealing the presence of Langmuir waves in the solar wind. From Gurnett and Anderson (1977).

### 3 In situ measurement of waves in the free solar wind

#### 3.1 Langmuir waves

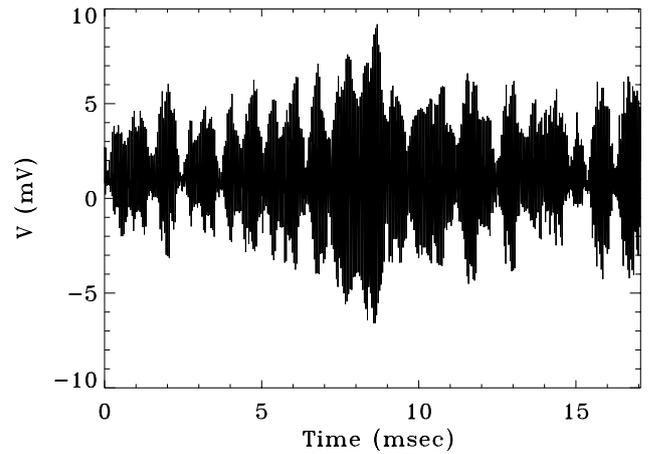
Langmuir waves are commonly observed in the Earth environment (for example in the vicinity of the bow shock or the foreshock), and they are also a common feature of the solar wind spectrum (Fig. 4). They are observed associated with electron beams generated by flares, beam induced by shocks, or in the presence of magnetic depressions (also called magnetic holes). Langmuir waves are usually thought to result from bump-on-tail instabilities induced by beams propagating in the solar wind. Their dispersion relation is given by:

$$\omega^2 = \omega_p^2(1 + 3k^2\lambda_D^2) \quad (1)$$

$$\omega_p \propto n_e^{1/2} \quad (2)$$

where  $\lambda_D$  stands for the Debye length and  $n_e$  the electron density of the medium.

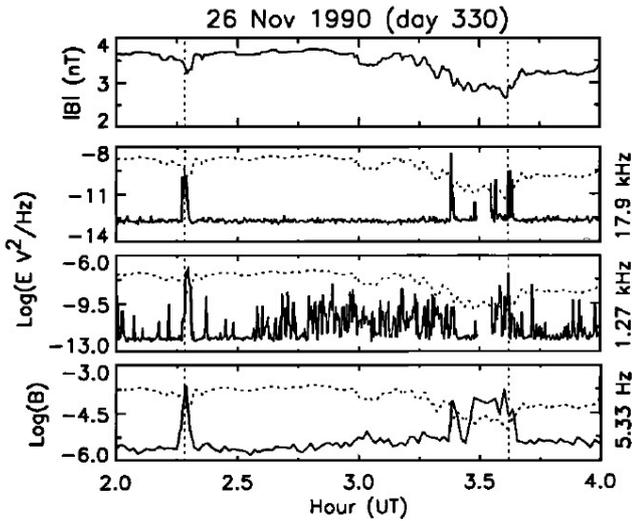
Since the pioneer work of Ginzburg and Zheleznyakov (1958), Langmuir waves have been intensively studied in relation with Type III radio emission. Indeed, these electromagnetic radio emissions at the plasma frequency, or twice of this frequency, are thought to result from wave coupling implying ion acoustic waves and Langmuir waves. From the observational point of view, numerous works have been devoted to test the validity of this model (Lin et al., 1981, 1986; Gurnett et al., 1993; Thejappa et al., 1993; Cairns, 1995; Thejappa et al., 2003). New evidence of such wave coupling processes have been recently provided from the analysis of waveform data from the STEREO/WAVES experiment (Henri et al., 2009). Since the phase of the waves are available from such measurements, it is possible to test the energy and momentum conservation laws induced by such coupling.



**Fig. 5.** Langmuir waveform as observed by WIND in the quiet solar wind (15/09/2007).

As can be expected from the  $1/r^2$  variation of the electron density with heliocentric distance  $r$ , the Langmuir wave peak, observed in the context of Type III bursts, moves towards lower frequencies as the heliocentric distance increases (Fig. 15 of Gurnett and Anderson, 1977). Their amplitude is of a few mV/m. The development of waveform analyzers has provided more information about these waves. The analysis of waveforms from the WIND/TDS instrument first revealed their coherent nature (Fig. 5), and show that they often appear as highly modulated wavepackets (Kellogg et al., 1999; Mangeney et al., 1999). Recently, Malaspina et al. (2008) proposed a model based on waves trapping in density homogeneities to explain the envelop of Langmuir waves.

Langmuir waves also develop within magnetic holes (Lin et al., 1995; MacDowall et al., 1996). These structures consist of magnetic depressions lasting for a few tens of second up to half an hour. Figure 6 displays such an event as observed by Ulysses. At higher latitudes, the occurrence of Langmuir waves increases in close correlation with the increase of the number of magnetic holes (Fig. 3 of Winterhalter et al., 1994). The amplitude of the electric field decreases with the heliocentric distance to the sun, as in the case of Type III related Langmuir waves (MacDowall et al., 2003). As noted by Lin et al. (1996), the depression of the magnetic field where Langmuir waves occur does not need to be deep (10% of the ambient magnetic field is enough). More recently, MacDowall et al. (2003) pointed out that Langmuir waves, when not related to particles beams, are mostly encountered in magnetic holes throughout the heliosphere and preferentially in the fast solar wind. The mechanism at the origin of the Langmuir waves within magnetic depression is still unclear. The only model (waves generated by electron beams of thermal energies, formed by adiabatic focusing of the electrons) is indeed unable to also explain the presence of



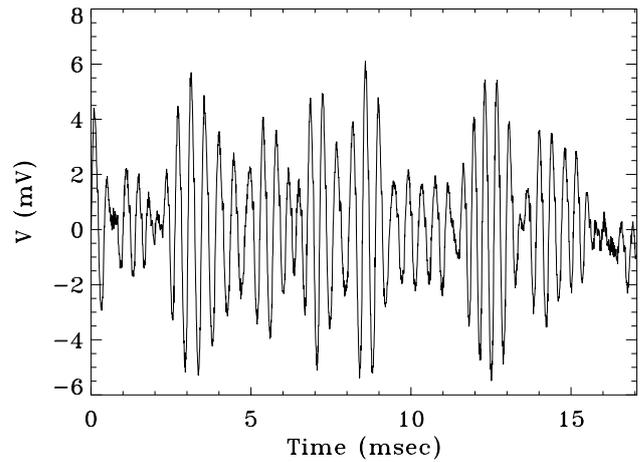
**Fig. 6.** Time series of magnetic and electric field measurements from Ulysses. The plasma wave (17.9 kHz) occur in depression in magnetic field (upper panel). The 1.27 kHz electric signal is identified as whistler mode. Note the correlation in time between the occurrence of the two electric signals; From Lin et al. (1995).

other waves often observed simultaneously with the Langmuir waves (and other observational aspects not discussed here).

Finally, Thejappa et al. (2003) have reported Langmuir wave activity not related to either the presence of magnetic holes nor to interplanetary shocks or Type III beams. Such observations encourage statistical studies on Langmuir waves outside obvious periods of electron beam propagation or presence of magnetic holes to complete our knowledge about the formation of Langmuir waves in the solar wind.

### 3.2 Ion acoustic waves

The very first measurements obtained by spectrum analyzers revealed the presence of low frequency turbulence in the quiet solar wind. These emissions, called “ $f_p^+ < f < f_p^-$  noise” by Gurnett and Anderson (1977, where  $f^+$  and  $f^-$  stands for the local ion and electron plasma frequency respectively), appear as sporadic bursts with a duration from a few minutes to a few days. Figure 3 shows such emissions detected by HELIOS 1 at a distance of 0.47 AU in the quiet solar wind. The “ $f_p^+ < f < f_p^-$  noise” is clearly visible between 1.78 and 17.8 kHz. The absence of magnetic field signature and the alignment with the interplanetary magnetic field reveal their electrostatic nature. From comparisons with events produced upstream of the Earth bow shock, which show similar characteristics, the waves were finally identified as Ion Acoustic Waves (thereafter IAW), Doppler shifted by advection in the solar wind (Gurnett and Anderson, 1977; Gurnett and Frank, 1978; Kurth et al., 1979).



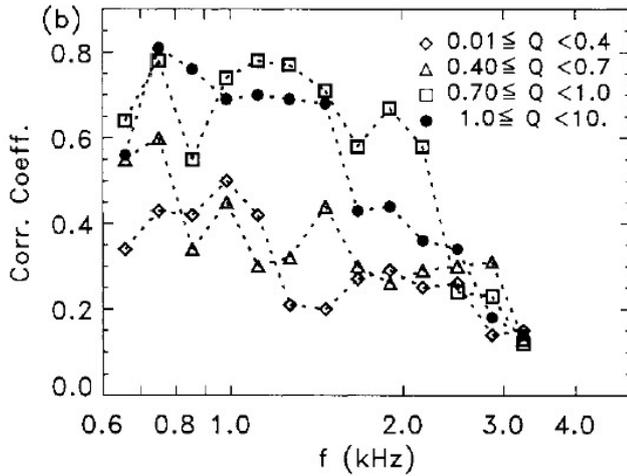
**Fig. 7.** Example of ion acoustic waveform as observed by the waveform analyzer (TDS) on board of WIND.

The intensity of the waves varies between 1 to 10  $\mu\text{V/m}$  in quiet period of solar activity but may reach a few tens of mV/m during more active periods. Combined observations from HELIOS I and VOYAGER showed that the intensity of the waves decreases and the frequency peak drifts towards lower frequencies with increasing heliocentric distance (see Fig. 1 of Gurnett et al., 1979). The measurements from ULYSSES also revealed that the IAW activity level depends on the latitude: at low latitude (mostly slow solar wind), the waves present a strong intensity and occur very often, while at higher latitudes (intermediate and fast solar wind) their occurrence and intensity decrease (Lin et al., 2001).

More recently, Mangeney et al. (1999), using the waveform analyzers on board of the WIND spacecraft, gave more details on the characteristics of the IAW. The coherent nature of these waves are obvious from their data (Fig. 7).

A polarization analysis and simultaneous magnetic field measurements confirmed the electrostatic nature of the waves. They estimated the wavelength from the Doppler shift and found  $10 \leq \frac{\lambda}{\lambda_D} \leq 50$  (where  $\lambda_D$  stands for the Debye length). They also showed that the wave vector is always directed towards the Earth, independently of the sign of the radial component of the magnetic field. A more surprising result concerns the relationship between the occurrence of these emissions and the proton temperature.

Theoretical arguments, corroborated by numerous simulations, have shown that the ratio of the electron to proton temperature,  $T_e/T_p$ , is a fundamental parameter for the stability of the IAW. If  $T_e/T_p \approx 1$ , the phase velocity of the waves  $\sqrt{\kappa(T_e + 3T_p)/m_p}$  is very close to the thermal speed of the protons and they are strongly damped by Landau effect. Thus, a necessary condition for the ion acoustic wave to exist is that  $T_e/T_p \gg 1$ . Gurnett et al. (1979, their Figs. 7 and 8) indicated that the average peak intensity of the IAW increases with the temperature ratio  $T_e/T_p$ . However, according to



**Fig. 8.** Correlation of the electric field energy (normalized to temperature energy) in IAW and the ratio  $T_p/T_e$  vs. frequencies for several values of (normalized) electron heat flux. From Lin et al. (2001).

Mangeny et al. (1999) from WIND observations, (i) IAW are measured even when  $T_e/T_p \leq 1$  and (ii) the presence of IA wave packets depends more strongly on  $T_p$  than on  $T_e/T_p$ , with a low value of  $T_p$  ( $\leq 10eV$ ) favoring the waves. In fact, this apparent contradiction between observations results from the fact that in the solar wind, the temperature ratio variations are mainly controlled by the proton temperature, since electrons keep an almost constant temperature of  $1-2 \times 10^5$  K.

Lin et al. (2001) analyzed the correlation between ion acoustic waves energy, electron heat flux and electron to proton temperature ratio from ULYSSES data. They concluded that heat flux and temperature ratio are not completely independent parameters (Fig. 8). The correlation with temperature ratio is higher when the electron heat flux is large (when normalized to the energy of the core electron velocity).

Ion Acoustic Waves are also often (but not always) reported in connection to interplanetary shocks (Kurth et al., 1979; Hess et al., 1998; Wilson et al., 2007). The IAW activity is strongly increased at the shock time passage but is also noticeable several hours upstream and downstream of a shock. However, the presence of a shock is not a sufficient condition to generate ion acoustic waves: in several cases, no increase of IAW activity has been noted in spite of the presence of a shock. The occurrence probability of IAW related to interplanetary shocks increases with decreasing latitude but no specific variation with heliocentric distance has been reported. As in the case of the quiet solar wind, temperature of the particles and shape of the distribution functions are the most critical parameters related to the increase of the IAW activity.

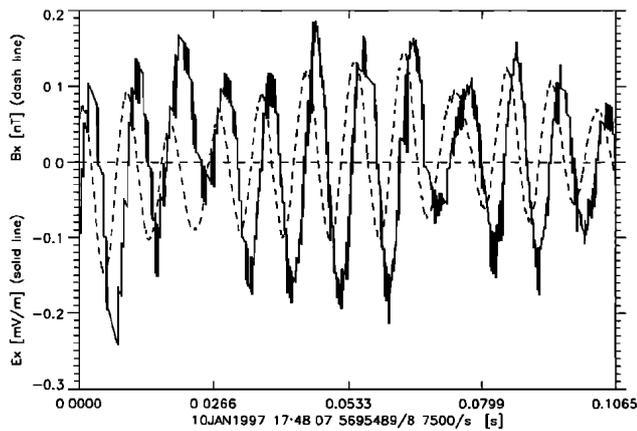
Two sources of free energy have been proposed to explain the generation of ion acoustic waves: (i) an electron heat flux

(Forslund, 1970), (ii) an electrostatic double-ion beams instability (Gary, 1978). However, up to now, observations have not been able to disentangle between the two sources. Ion acoustic waves have been observed in regions where the ratio  $T_e/T_p$  would predict strong Landau damping and particle distribution function measurements lack of energy and time resolution to check the stability criterions. The identification of the mechanism(s) at the origin of the ion acoustic waves from direct hydrodynamical conditions of the solar wind is thus still an open question.

### 3.3 Lower hybrid and whistler-mode waves

Lower hybrid waves (also called lower “hybrid” whistlers) and whistler-mode waves are electromagnetic waves propagating parallel to the background magnetic field. At large angle from the magnetic field, the electromagnetic lower hybrid becomes electrostatic. The electromagnetic modes are typical modes found within the electron MHD (where the frequencies are sufficiently high for protons to be considered as fixed). Electromagnetic and electrostatic modes should be distinguished from each other by means of simultaneous measurements of magnetic and electric fields. However, such measurements at low frequencies are hardly available since the sensitivity of the instruments are not always compatible.

Low frequency ( $f_{ci} < f < f_{ce}$ ) magnetic signals are a permanent feature of the solar wind, at least close enough to the sun - below 3 AU (Lengyel-Frey et al., 1996). This magnetic activity is enhanced in case of disturbances of the solar wind like near interplanetary shocks (Lin et al., 2003), high-speed streams (Coroniti et al., 1982; Lin et al., 1997; Lengyel-Frey et al., 1996) or magnetic clouds (Moullard et al., 2001). It does not exhibit any specific dependence with latitude (Lengyel-Frey et al., 1996). The spectral density shows a  $f^\alpha$  power law, with a spectral index  $\alpha = -0.65$  in quiet solar wind condition (Beinroth and Neubauer, 1981). From one day average values, Beinroth and Neubauer (1981) showed that the spectral density of the magnetic fluctuations correlate with the proton density and magnetic field strength. Since the correlations disappear in shorter time averages, the spectral density variations reflect the large scale behaviors of these parameters. Lin et al. (1997, 1998) also showed that the occurrence of these waves was associated with enhanced heat flux conditions. Moullard et al. (2001) observed whistler-mode waves in magnetic clouds. The electric and magnetic waveforms measurements analysis (Fig. 9) reveals that the waves are planar, (right-handed) circularly polarized. Contrary to the results of Coroniti et al. (1982) who found waves propagating at large angle to the magnetic field background, the observations of Moullard et al. (2001) seem to show a propagation aligned with the interplanetary magnetic field. This discrepancy can be explained by an incorrect identification of the waves in the former case. Marsch and Chang (1983) indeed suggested that the waves observed by Coroniti et al. (1982) are more likely lower hybrid waves.



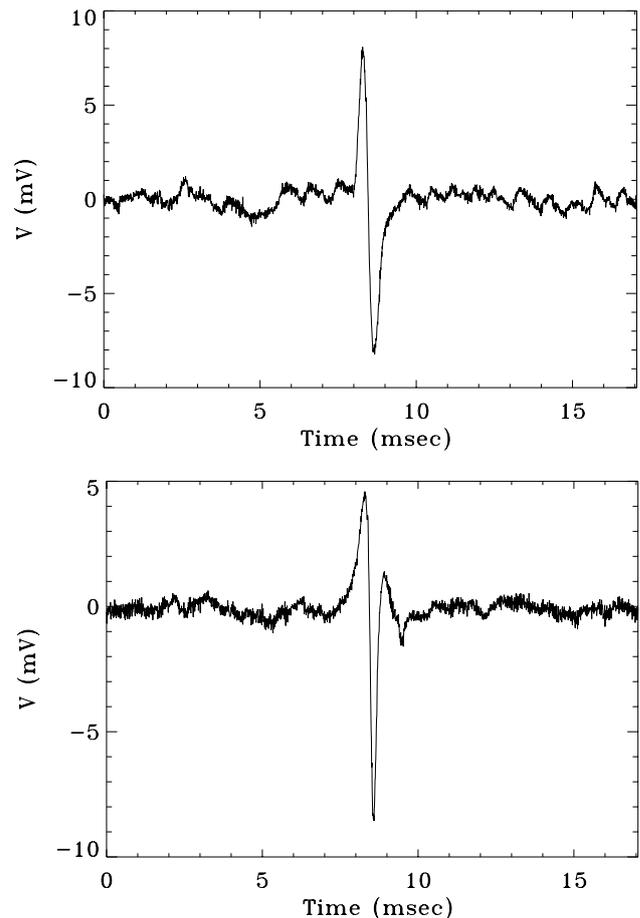
**Fig. 9.** Example of whistler waveform: Electric field component (solid line) magnetic field component (dashed line). Observed inside a magnetic cloud by the WIND/WAVES(TDS) instrument. From Moullard et al. (2001).

The long-lived background of whistler-mode (or lower hybrid) waves rises the question of the presence of a permanent source of free energy. Loss cone in the electron distribution function, heat flux and electron beams with  $T_{\perp} \gg T_{\parallel}$  (and combination of these conditions) are thought to be some possible sources of such free energy. Lengyel-Frey et al. (1996) also suggested that a nonlinear cascade of low-frequency Alfvén waves merging to give higher frequency waves could be at the origin of the background whistler-mode activity. The analysis of the electron distribution function at the time of increased activity of whistler-modes show the presence of loss cone oriented either sunward or anti-sunward (Fig. 7 of Moullard et al., 2001). These observations favor the idea of a local generation of the waves; still a lot of observations and theoretical developments are required to explain the mechanisms leading to the formation of these very low frequency waves.

### 3.4 Multipolar electrostatic structures

We cannot close this review on plasma waves in the solar wind without saying a few words about the bipolar (sometimes tripolar) electrostatic structures (Fig. 10). From the observational point of view they are also referred to as electron, ion or electrostatic solitary waves. In the following, we will prefer the term “isolated bipolar electrostatic structures” (rather than solitary waves) since the mechanism at the origin of these structures is likely to be quite different from the one of solitons. When a net potential drop exists across the structure, they are called double layers.

The first detection of bipolar electrostatic structures and weak double layers was obtained in the auroral region (Temerin et al., 1982). Since then, they are commonly observed in auroral regions (Ergun et al., 1998; Cattell et al.,



**Fig. 10.** Examples of isolated electrostatic structures as observed by WIND (15/09/2007): bipolar structures (top panel) and tripolar structures (bottom panel).

2001; Pickett et al., 2004) but also in several Earth magnetic environments (Matsumoto et al., 1994; Franz et al., 1998; Cattell et al., 2003; Pickett et al., 2003) and in the Earth bow shock (Bale et al., 1998; Behlke et al., 2004). Evidence for the presence of isolated bipolar electrostatic structures in the solar wind is more recent: Mangeney et al. (1999) first reported the observation of such structures in the free solar wind and Williams et al. (2006) showed some examples associated to an interplanetary shock. Finally, they were also observed in the vicinity of the magnetosphere of Europa (Kurth et al., 2001) and Saturn (Williams et al., 2006).

From observations with the WIND/WAVES waveform analyzer, Mangeney et al. (1999) deduced that the typical spatial width is about  $25\lambda_D$ . They also showed that the structures propagate along the magnetic field line at a velocity smaller than the solar wind velocity. Moreover, 29% of the observed isolated electrostatic structures consists in weak double layers, with a potential jump of a few mV<sup>3</sup>. The

<sup>3</sup>An error of calibration seems to be at the origin of the published tripolar shape. A new calibration of the data was performed and

low potential side is directed towards the Earth and a rough estimate of the total potential difference generated by the succession of such weak double layers from the solar corona to the Earth is consistent with exospheric models (Lacombe et al., 2002). Pickett et al. (2004) performed an extensive statistical analysis of the bipolar and tripolar electrostatic structures observed all along the Cluster II trajectory, which includes auroral zone, polar cusp, polar cap, magnetosheath, plasma sheet and solar wind. They first showed that the electric field amplitude (peak-to-peak) of such structures seem to slightly depend on the magnetic field strength. This could explain why the amplitude of the pulses observed in the solar wind are smaller compared to other magnetospheric environments. They also concluded that the duration of such structures is almost independent of the surrounding, except for the magnetosheath where they are much smaller.

Many questions are still unsolved that require more observations. For examples: what is the origin of these waves (ion/electron phase space holes or electron acoustic solitary waves)? what is the 3-D shape of these structures? 1-D simulations have shown that small structures are easily destroyed to form larger structures, but 2-D simulations demonstrate that, in a weakly magnetized plasma, fast and small amplitude structures are stable while large amplitude waves are unstable (Mottez et al., 1997; Muschietti et al., 1999; Mottez, 2001).

#### 4 Conclusions

The waves above the ion cyclotron frequency play a critical role in the microphysics of space plasma. A better understanding of the generation, evolution and decay is required to understand not only the behavior of the plasma at small scale but also to explain the permanent or intermittent behavior of the large scale structures of the solar wind. These waves also play a fundamental role in many physical processes that fall out of the scope of this review (like magnetic reconnection, particles acceleration, Type III radio emissions, etc.). In situ measurements in the region 1–30 solar radii, where basic physical processes are expected to take place are necessary to solve the question of the solar wind heating and acceleration.

As already mentioned, the identification of the waves is often a difficult task for two main reasons. Firstly, contemporaneous measurements of magnetic and electric field are often missing. Secondly, the absence of phase information on the waves limits the studies on the polarization and coupling processes. Waveform analyzers for both electric and magnetic field are thus a requisite to progress any further. In particular, long time coverage events are necessary to study the low frequency range and try to follow the energy cascade from the MHD regime to the kinetic regime. In addition, high energy and temporal resolution of particles distribution

the presence weak double layers was confirmed (Salem, personal communication).

functions are necessary to validate possible theories. As can be seen from Table 1 very few instruments will be available in the coming years. Efforts to maintain and develop new instrumentation are necessary to succeed in explaining the solar wind behavior and also Sun–Earth relation.

If more observations are required to impose new constraints on the theories or to validate (or invalidate) some of the already proposed ones, numerical simulations and laboratory experiments are required to understand the, often nonlinear, physics of the medium. The simulations with particles-in-cell, Vlasov-Poisson or hybrid codes have been intensively developed owing to the new capabilities of the computers. In particular, multi-dimensional codes allow now to simulate more realistic situations.

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