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# Langmuir waves across the heliosphere

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All the bodies of the solar system are embedded in the supersonic flux of energetic particles emitted by the Sun. Since the advent of the space age, the models to describe the interaction of this plasma flow with the planets, asteroids, comets etc. have drastically progressed. The possibilities of *in situ* measurements of the particle distributions and electromagnetic fields have enabled the plasma theories to be tested under astrophysical conditions. Energy transfer from the Sun to the outermost regions of the heliosphere as well as the processes leading to the dissipation of this energy are central questions for heliophysicists. Understanding the dynamics of the particles is thus critical. It is a particularly complicated subject since the medium is (almost) non-collisional. Thus, next to the description of the particles, the development of waves must be considered. Indeed, they participate to the exchange of energy between different species that would not interact otherwise. In other words, waves may play the role of collisions. This paper concentrates on Langmuir waves for their strong links with the electron dynamics. The basic processes of growth and saturation of the Langmuir waves are reviewed to stress their diagnostic capabilities. Then, the characteristics of the waves are described in the several heliophysical contexts: the planetary environments (in particular the ionosphere, the magnetotail and the foreshock) and in the interplanetary medium (in quiescent conditions of the solar wind or during transient events). A particular emphasis is given to results obtained in the last 15 years.

## 1. Introduction

The heliosphere is the region spanning from the Sun to the outermost solar system (up to 100 AU), filled with the plasma and the magnetic field emanating from the hot solar surface. A supersonic, super-Alfvénic flow of low density plasma, called the solar wind, indeed permanently escapes from the Sun, carrying with it the magnetic field that emerges at the surface of the star. The interactions of the solar wind with the different objects of the solar system generates peculiar features depending on the nature and physical properties of the impacted bodies. For example, bow shocks are often observed in front of the planets and the comets. As will be detailed later, such regions are the sites of intense waves activity which strongly contribute to the energy exchange and the equilibrium of the system. Another example concerned the interaction of the solar wind with a comet. Lacking any protection, the comets undergo a strong alteration of their surface. This so-called 'space weathering' effect may be of importance to accurately date the body and to study their formation and evolution (Vernazza et al. 2009). The second effect related to the comet is the solar

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wind mass-loading effect: the solar wind flow slows down with the injection of mass coming from the cometary ions and inject back the energy into the cometary particles through plasma waves (Coates 2004). Finally, the interaction of the solar wind with the upper atmosphere of planets lacking of a magnetosphere (like Venus, Mars) also induces losses of the atmosphere, modification of the ionosphere behavior and the formation of an induced magnetosphere (Luhmann et al. 2004). The activity of the Sun disturbs this quiet picture of the solar wind-interplanetary bodies interactions. Indeed, the increase of solar activity generates transient phenomena that propagate throughout the interplanetary medium, leading to the acceleration of particles to very high energy (up to 100 MeV) in particular at interplanetary shocks ahead of coronal mass ejection sites (Reames 1999; Lin 2011). The first witnesses of the propagation of such electron beams propagations are the radio emissions, in particular the so-called Type III emissions related to the flare activity and the Type II related to the interplanetary shocks. Auroral emissions also reflect the penetration of such energetic electrons of the interplanetary medium inside the magnetosphere of the planets. On Earth, such intrusion can also damage industrial infrastructures and affects human health in certain circumstances. Such dramatic consequences of the Sun activity have stimulated the development of a new branch of studies known as space weather.

With the advent of the space age in the late 50s, we are able to measure *in situ* all the thermodynamical and kinetical parameters necessary to understand the physical processes taking place throughout the heliosphere. In particular, the measurements of the particle velocity distribution functions, of the AC and DC electromagnetic fields as well as the details of the composition of the plasma, have provided to the heliophysicists, a unique opportunity to test their astrophysical models but also more generally to test plasma physics theories.

At first glance, the bulk of the solar wind particle velocity distribution function (and of several other space environments) is not too far from a Maxwellian distribution, which is surprising in a collisionless medium. Waves are usually invoked to play the role of collisions, allowing the energy transfer between species that cannot naturally interact due to their different inertia (like ions and electrons). However, a more careful inspection of the solar wind characteristics reveals the presence of numerous features that cannot be explained by global MHD approach: the presence of proton and electron beams (Marsch et al. 1982; Pilipp et al. 1987a,b), the high velocity reached by the fast solar wind (Zouganelis et al. 2005), the departure of the electron distribution function from a Maxwellian distribution for supra-thermal electrons (Maksimovic et al. 1997) etc. All these features and many more require a kinetic treatment to be correctly modeled. These kinetic models allow the development of high-frequency waves, in close relation with the particles dynamics. Among all the plasma waves, the Langmuir waves are of special interest since they are directly related to the dynamics of the electrons in a plasma.

These waves were identified by Langmuir at the beginning of the 20th century (Langmuir 1928). The interest for Langmuir waves in the heliophysicist community was raised for at least four reasons. First, the waves provide a tool to diagnose the electron density and its fluctuations but also to determine some characteristics of the electron beams which contribute to their growth. Second, the very intense, non-thermal interplanetary radio emissions discussed above are explained by plasma processes involving Langmuir waves. Third, they could play a crucial role in the dissipation of the energy at the end of the turbulent cascade, mimicking collisions in collisionless environments. Finally, they reflect the electron energization in particular at magnetic reconnection sites and shocks. The possibility to measure *in situ* electric and magnetic

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fields as well as density fluctuations and plasma composition has provided new constraints on the models and the opportunity to test the theoretical predictions. Langmuir wave measurements thus provide a tool to diagnose the dynamics of the electrons, complementary of the measurements provided by instruments dedicated to particles.

As will be detailed in the Secs 3 and 4, Langmuir waves have been widely observed *in situ* in almost all environments visited by space probes: in the planetary environments (in particular, the foreshock but also in the ionosphere and the magnetotail), in the quiescent solar wind, and in the interplanetary medium during transient solar wind phenomena associated with solar activity (like solar flares or interplanetary shocks). To better appreciate the role of these waves and their diagnostic capabilities, the Sec. 2 summarizes the mechanisms of Langmuir wave generation, saturation and decay.

## 2. Theory

In the following, only non-relativistic plasmas are considered, which are justified for most of the cases encountered in the heliosphere. Langmuir waves are longitudinal, electrostatic waves. In an unmagnetized plasma, their dispersion relation is as follows:

$$\omega_L^2 = \omega_{pe}^2 + 3k^2 V_{the}^2 \tag{2.1}$$

with $\omega_{pe}/2\pi$ the electron plasma frequency ($f_{pe} = \omega_{pe}/2\pi = \sqrt{\frac{N_e e^2}{m_e \epsilon_0}}$, with $N_e$ et $m_e$ the electron density and mass, $e$ the electric charge and $\epsilon_0$ dielectric constant in vacuum), $k$ the wavenumber and $V_{the}$ the thermal velocity of the electrons. The second term is the thermal correction for a warm plasma. The above equation shows that the frequency of Langmuir wave provides a good estimate of the local plasma density, in particular for a cold unmagnetized medium.

In the presence of a magnetic field, several new plasma modes may grow with frequencies close to the plasma frequency. As far as electron dynamics is concerned, the electron gyro-frequency, $\omega_{ce} = 2\pi eB/m_e$, becomes an important parameter. First because the dispersion relation (2.1) must be completed with a term $\omega_{ce}^2 sin^2(\theta)$, with $\theta$ the angle between the wave vector and the ambient magnetic field vector (Melrose 1976; Willes and Cairns 2000). Then if $\omega_{pe} > \omega_{ce}$, Langmuir mode dominates for large $k$, while the magneto-ionic Z-mode dominates for small $k$. The wave electric field is then almost perpendicular to the magnetic field. The Z-mode has a high resonance near the upper hybrid frequency $\omega_{uh} = \sqrt{\omega_{pe}^2 + \omega_{ce}^2}$. Upper hybrid waves are particularly important in the magnetosphere of the planets. They can be distinguished from the longitudinal Langmuir waves since their polarization is elliptical. It is also interesting to note that when $\omega_{pe} < \omega_{ce}$, the upper bound of the whistler mode is the frequency of the Langmuir frequency (providing $k_\parallel \gg k_\perp$).

The main mechanism invoked to explain the growth of Langmuir waves from a background of turbulent electric field is the bump-on-tail instability. The free energy for the waves to grow is provided by a beam of supra-thermal electrons. Such beams can be generated during solar flares, or ahead of planetary or interplanetary shocks or even through time-of-flight effects when the bulk of the distribution function is submitted to time variation of its temperature (Briand et al. 2007). Bump-on-tail instability is a resonant instability: electrons and waves exchange energy when the particles have a velocity close to the phase velocity $v_\varphi$ of the wave. If the slope of the electron distribution function next to $v_\varphi$ is positive, the waves gain energy from the electrons while the waves transfer their energy to the particles if the slope is

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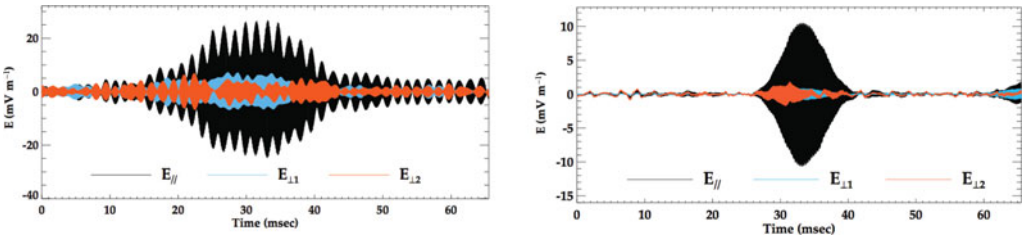



FIGURE 1. Two examples of electric waveform of Langmuir waves as observed in the solar wind. The different colors indicate the components along and perpendicular to the ambient solar wind magnetic field, as indicated in the legend (the data come from the Time Domain Sampler of the STEREO/WAVES instruments, described in Bougeret et al. 2008).

negative. The resonant character of the instability leads to an interesting property of the spectrum: a cold beam will produce a narrow band spectrum while the electrons of a hotter beam will undergo a more pronounced diffusion in velocity space, leading to a broader spectrum (Shapiro and Sagdeev 1997)†.

When the growth rate of the instability $\gamma$ is not too strong – i.e. $\gamma \ll \omega_r$ where $\omega_r$ stands for the real part of the frequency – and the wavelength is small compared the Debye length – i.e. $k\lambda_d \ll 1$ – the 'gentle bump' approximation holds. Then, the growth rate of the bump-on-tail instability is proportional to the slope of the distribution function of the electrons, estimated at the phase velocity. When the electron bulk and the beam are both described by Maxwellian distributions, this growth rate can be expressed analytically (see for example Krall and Trivelpiece 1973). It shows that the wave growth increases with the beam velocity and density, and decreases with the beam temperature.

Now, the linear growth of the waves must be stopped at some point. Several mechanisms have been proposed to explain the quenching of the wave growth: (i) spatial collapse for strong amplitude waves (strong turbulence) (ii) nonlinear evolution of wave-particles interaction (quasi-linear flattening or electron trapping), (iii) nonlinear wave–wave interaction (weak turbulence).

When the energy of Langmuir waves are high enough compared to the thermal energy of the background electrons (i.e. $\epsilon_0 E^2/n_0 \mathrm{k_B T_e} \approx 10^{-2}$, with $E$ the amplitude of the electric field, $n_0$ the density and $T_e$ the electron temperature, and $\mathrm{k_B}$ the Boltzmann constant), ponderomotrice force locally expels the plasma, and nonlinear self-focusing of the wave packet intensifies the electric field in these low density regions. Such process can overcome the linear dispersion of the wave and leads to the formation of a Langmuir soliton (Robinson 1997a). This process was first proposed to explain the observations of isolated Langmuir soliton (ILS). However, this explanation has been ruled out, at least in the context of type III (see Graham et al. 2012b, for a recent work on the subject and references therein), the intensity of the wave being too low for the ponderomotrice force to efficiently act. It must be noted that the presence of Langmuir caviton can also emerge from weak turbulence evolution and saturate at much lower energy than predicted by strong turbulence theory. From

† Bump-on-tail instability is also called *resistive* since the imaginary part of the dielectric is non-zero and it largely contributes to the growth of the waves, conversely to the reactive instability – like the two stream instability (Papadopoulos 2009). Then, the waves grow due to the bunching of electrons in space which produces an enhancement of the electric field. Such instability generates a narrow-band spectrum, since waves with different frequencies and wave numbers compete to grow from the same source of energy.

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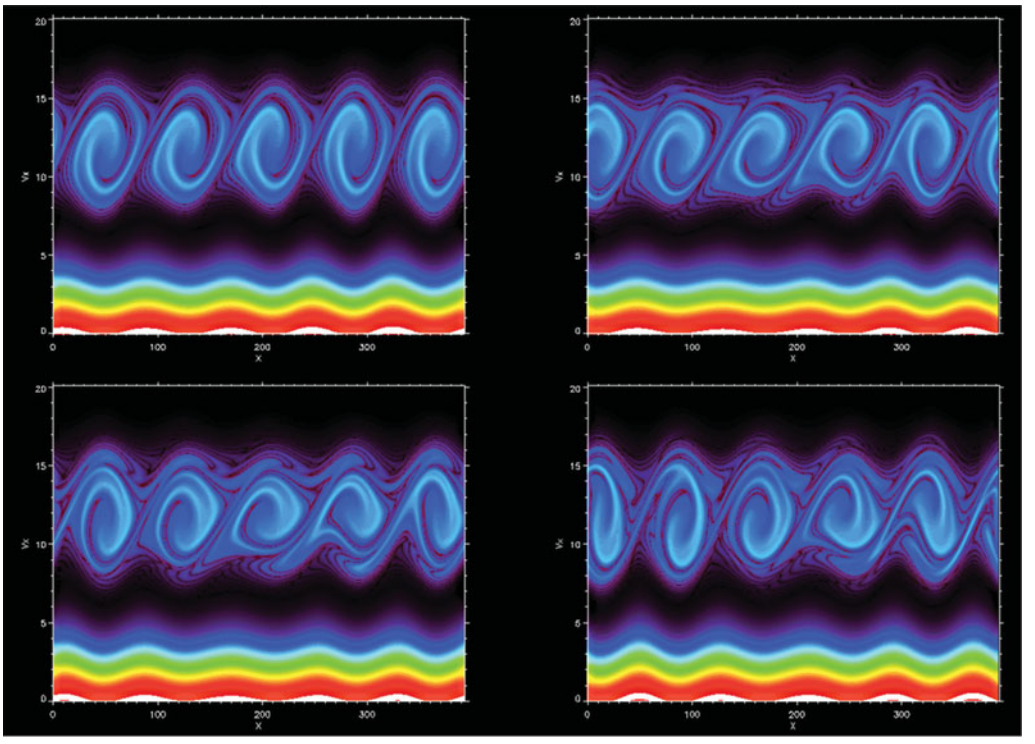


FIGURE 2. Phase space electron distribution function at several time during the nonlinear phase of the evolution of the bump-on-tail instability. The formation of vortices witness the trapping process of electrons in the potential well of the waves. The growth of the waves is stopped as the space integrated velocity distribution function formed a plateau around the waves phase velocity.

1D Vlasov–Poisson simulations, Henri et al. (2011a) indeed showed that large and shallow coherent structures result from inverse cascade and could be present in space environment. This scenario is correct at least in 1D. In 2D and 3D, the picture can change since the dispersion is unable to compensate for the collapse (Antipov et al. 1977).

The maximum level of density fluctuations induced by ponderomotrice force saturates for

$$(\delta n/n)_{sat} = \epsilon_0 E^2/n_0 k_b T_e. \tag{2.2}$$

If we are able to measure the Langmuir electric field from monopole antenna, this provides an elegant diagnostic of the density fluctuation at high frequency (Henri et al. 2011b).

When the amplitude of the waves remains small (i.e. $\epsilon_0 E^2/n_0 \mathrm{k_b T_e} \ll 10^{-2}$) the evolution is described in the frame of the weak turbulence. Wave-particles and wave–wave interactions may stop the linear growth of the waves.

As previously seen, the waves grow at the expense of the energy of an electron beam. At the same time, the particles feel an increasing electric field which may finally trap them if their velocity is too low with respect to the phase velocity of the wave. The trapping leads to the formation of Bernsteing–Greene–Kruskal (BGK) vortices in phase space (see Fig. 2 for an example of such vortices). The beam energy loss results in (i) a flattening of the distribution function around the wave phase velocity,

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(ii) the generation of waves of larger $k$ (since the resonant phase velocity $v_\varphi = \omega/k$ decreases) and finally (iii) the stop of the waves growth when the plateau (in phase space) is formed. From numerical 1D Vlasov–Poisson simulations, Shoucri (2011) studied the evolution of the bump-on-tail instability for beams of quite large density (about 10% of the total density). They showed how the electrons are trapped into vortices, and the vortices merge to form larger structures (inverse cascade, i.e. towards larger $k$). Finally, the system evolves to form a single vortex where trapped electrons are accelerated to high velocity. However, the merging of the vortices is a complex subject: BGK states may be stable and subharmonic may not developed (Balmforth 2012). Finally, as recently shown, the evolution of the bump-on-tail instability can be strongly different to the usual picture in compressible plasma. In particular, the final state will depend on the compression history (Schmit et al. 2011). If this process is clearly a fundamental aspect for laboratory plasmas, this may also concern some astrophysical contexts where compression is not negligible.

The transfer of energy from the particle to the waves is rather efficient. Sturrock (1964) pointed out that the electrons emitted during flares would lose all their energy after traveling only a few hundred kilometers, contradicting the observations. Thus, other mechanisms must be invoked to remove the electrons out of resonance with the beam. One process is the wave–wave interaction that allows a shift of the wave phase. Several types of wave–wave mechanisms exist: decay instability, oscillating two-stream instability, or modulational instability. These two last processes have proven to be inefficient in the heliophysical context (see Graham et al. 2012a, and reference therein for former works). Thus in the following, only the decay mechanisms are described.

When the Langmuir wave energy exceeds a given threshold, the wave decays into a daughter Langmuir wave of shorter $k$ and a low frequency signal $S$ (electrostatic decay (2.3)) or into an electromagnetic wave at the plasma frequency and a low frequency signal (electromagnetic decay (2.4))

$$L \rightarrow L' + S, \tag{2.3}$$

$$L \rightarrow T_{f_{pe}} \pm S. \tag{2.4}$$

In (2.4) the '—' sign refers to the coalescence process, where a Langmuir and a low frequency wave couple to generate an electromagnetic wave at the plasma frequency. Another coalescence process is also possible between two electrostatic waves $L$ and $L'$. In that case, the resulting electromagnetic signal is observed at the harmonic $2f_{pe}$ (2.5)

$$L + L' \rightarrow T_{2f_{pe}}. \tag{2.5}$$

The low frequency signal can be either ion acoustic waves (mostly invoked in solar wind conditions) or whistlers and lower hybrid waves (in the planetary contexts). All these processes have been widely studied through numerical simulations. We can in particular highlight some results obtained in the last years. Vlasov simulations performed in open boundary conditions show the development of broad spectrum around the plasma and ion acoustic frequencies (Umeda and Ito 2008). From Vlasov–Poisson simulations, Henri et al. (2010b) provided a new semi-analytical expression of the electrostatic decay threshold (for a decay with an ion acoustic waves), in the realistic case of non-monochromatic waves, and electron to proton temperature ratios typical of the solar wind conditions. This threshold is smaller compared to former works (Lin et al. 1986), easing the decay of Langmuir waves. Also, in a weakly magnetized plasma (like the solar wind), the electrostatic decay is allowed for very

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small wavenumbers and large perpendicular electric field component, which may have strong implications in the frame of interplanetary emissions and magnetospheric plasmas (Layden et al. 2013). When the decay implies ion acoustic waves, it is natural to test the validity of the weak turbulence theory for different ion to electron temperature ratios, since ion acoustic waves are strongly damped for high ion temperature. As a matter of fact, Ratcliffe et al. (2014) recently showed, from particle-in-cell (PIC) simulation, that the weak turbulence starts to fail with the increase of the ion temperature. In particular, the secondary Langmuir peak formed by the three waves process is broader, and lower than expected, and located at larger wavenumber. In 2008, Ziebell et al. studied the nonlinear mode coupling from 2D analytical developments and simulations. Their work showed the formation of a ring-like structure in the spectra of Langmuir waves, accompanied by a heating of the electrons in the perpendicular direction. Ziebell et al. (2014) performed numerical 2D electromagnetic PIC simulations allowing for all nonlinear processes to occur. They concluded that fundamental and harmonic signals can both occur, the fundamental emission dominating, and that harmonic signal increases with for large electron velocity beams. Note that concerning the harmonic electromagnetic signal, Graham et al. (2014) also proposed that sheath rectification on the antenna of a radio receiver could be at the origin of this signal that would then be of instrumental origin.

The simultaneous presence of Langmuir and low frequency waves is a necessary but not sufficient condition for decay/coalescence to occur. It may just indicate that the waves are sharing a common source of free energy. For the waves to be coupled, they must first satisfy the momentum and energy conservation equations

$$\vec{\kappa}_L = \vec{\kappa}_{L'} + \vec{\kappa}_S, \tag{2.6}$$

$$\omega_L = \omega_{L'} + \omega_S, \tag{2.7}$$

but equally important is the relation between the phase of the waves since decay/coalescence are fundamentally coherent processes

$$\phi_L = \phi_{L'} + \phi_S. \tag{2.8}$$

Only waveform measurements provide the possibility to test all these conditions mostly because they keep the information on the phase of the waves (see Sec. 4.2.1 for some examples of direct tests of these conditions on real data). Note that on data coming from space instruments, (2.6) and (2.7) are checked simultaneously since the observed frequencies are Doppler-shifted (by an amount proportional to the product of the wave vector and the solar wind velocity $\vec{k}.\vec{v}_{sw}$).

Finally, when electrostatic decay proceeds, the electron beam speed $V_b$ can be evaluated. In the solar wind conditions, it reads (Cairns and Robinson 1992; Hospodarsky and Gurnett 1995):

$$V_b = \left[\frac{C_s}{3V_{the}^2} + \frac{f_S}{2f_{pe}|C_s - V_{SW}|cos(\phi)||}\right]^{-1}, \tag{2.9}$$

with $C_s$ and $f_s$ the ion acoustic wave velocity and frequency respectively, $V_{the}$ the thermal electron velocity, $V_{SW}$ the solar wind velocity and $\phi$ the angle between the solar wind and the local magnetic field direction. This expression can be slightly simplified since the first term is much smaller than the second and $C_s \ll V_{SW}|cos(\phi)|$

$$V_b = \frac{2f_{pe}V_{SW}cos(\theta)}{f_S}. \tag{2.10}$$

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The weak turbulence is also invoked to explain the asymmetry and the non-Maxwellian character of the electron velocity distribution function observed in the solar wind (see Yoon et al. 2012, and reference therein).

As we have seen, the saturation of the waves growth can result in the emission of electromagnetic waves through three-waves processes. Now, another mechanism can also explain the formation of electromagnetic radiation: the linear mode conversion (Willes and Cairns 2003). When a Langmuir wave encounters a density gradient it may then be partly reflected and partly converted into electromagnetic waves at $f_{pe}$, providing that the incident wavevector is slightly oblique to the density gradient. Such mode conversion leads to a narrow-band signal of $O$ and $X$ electromagnetic waves. If this saturation process has long been neglected for space investigation, Kim et al. (2008) showed through numerical simulations that the conversion efficiency was not as low as previously though. Thus, linear mode conversion could indeed play a role in several environments (see Schleyer et al. 2013, for a recent work on the subject).

Most of the former theories have been developed for an homogeneous bulk plasma described by a Maxwellian distribution function. However, space environments substantially differs from this ideal situation.

In several environments, and the interplanetary medium in particular (Pierrard and Lazar 2010), the electron bulk distribution is better described with a Kappa (generalized Lorentzian) function, or even better bi-kappa distribution (Lazar et al. 2012), i.e. with enhanced supra-thermal tails compared to a Maxwellian velocity distribution. New formulation of the dielectric tensor and dispersion relations have been proposed by Summers et al. (1994) and Yoon (2014). Numerical simulations have shown that the increase of energetic electrons leads to an increase of the damping of the Langmuir waves (Zaheer et al. 2004; Qureshi et al. 2005; Mushtaq and Shah 2006; Khalilpour and Foroutan 2012). Note that not only Langmuir waves are affected by the presence of enhanced tails: the growth rate of the ion acoustic waves also decreases (Zaheer et al. 2004; Arshad et al. 2014), with the possible consequences on the decay of the Langmuir waves when coupling with on acoustic waves is considered.

Regarding the homogeneity of the space plasma, the situation is also far from ideal. The presence of density fluctuations is indeed ubiquitous in heliophysical plasmas. Since the mid 70's, several spectrum of the electron density have been provided in the interplanetary medium from *in situ* measurements (see Celnikier et al. 1983; Manoharan et al. 1994, and references therein). Recently, Malaspina et al. (2010) extended the curve to higher frequencies. The fluctuations cover several decades, present a break in the power law around 0.1 Hz and can exceed 1% of the background density. Such fluctuation value is huge with respect to the development and decay of high frequency, electron-type waves. In the frame of electron beam-plasma interaction, the presence of density fluctuations has several consequences in the growth, saturation and decay of the Langmuir waves, since they imply variations of the plasma frequency as well as refraction, reflection and scattering of the waves.

The large-scale density fluctuations are very effective in shifting the waves out of resonance with the beam, stopping thus the growth of the waves (Muschietti et al. 1985). The presence of density gradients also strongly influence the development of the turbulence: a steady state of weak turbulence is reached faster than in case of homogeneous medium (Kontar and Pécseli 2002).

Then, following the original work of Smith and Sime (1979), Robinson (1992) developed the stochastic growth theory (SGT) to explain the clumpy aspect of the electric waveforms observed in the interplanetary medium (see also Fig. 1 left): as an electron beam propagates in the plasma it encounters a medium with varying

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density thus stochastically fluctuating growth rate. This theory also predicts that the probability distribution of the electric field must be lognormal (see also Robinson 1997b).

Finally, eigenmode trapping of Langmuir waves in density depletions has been proposed to explain the soliton-like shape of some Langmuir waveform envelopes (Fig. 1 right) (McAdams et al. 2000; Yoon and Labelle 2005; Ergun et al. 2008). Recently, Krafft et al. (2014) explored the conditions for such a wave trapping and conclude that it requires density fluctuations larger than $5.10^{-2} n_o$, $n_o$ being the electron background density. They also showed that the modulation of the waveform appears even in absence of nonlinear instabilities and is due to the reflection and scattering of the waves.

All these properties of Langmuir waves have been intensively used to diagnose several space environments as we will now detail in the following sections.

## 3. Langmuir waves in planetary environment

Many electrostatic and electromagnetic plasma waves are observed in the environment of planets (see Zarka 2004, for a review on the waves observed in the outer magnetized planets). The characteristics of the plasma encountered around the planets are far from being uniform across the solar system. The presence or lack of a magnetic field, the strength of the magnetic field, the presence of active natural satellite (like Io for Jupiter or Enceladus for Saturn), the inclination of the magnetic compared to the rotation axis of the planet (with the most spectacular case of Uranus) are conditions that determine specific dynamics of the plasma around the planets.

Where an intense magnetic field is present, the plasma frequency may become comparable and even smaller than the electron cyclotron frequency $f_{ce}$. Then, rather than purely parallel-propagating Langmuir waves, upper hybrid modes as well as Z-mode arise. Also, electron solitary waves are known to play an important role in the auroral region in participating to the electrons acceleration. Coupling with the magnetic field leads to electromagnetic waves like in particular whistlers. Thus, among the waves somehow linked to the electron dynamics, Langmuir waves do not always play the dominant role in the magnetospheric regions compared to other waves, except in the outer and lower borders, i.e. the foreshock region and the ionosphere and to some extent in the plasma sheet boundary layer of the magnetotail. To help in identifying the different regions, the Figs. 3 and 4 provide a sketch of the solar wind-planet interaction in the case of a magnetized and unmagnetized planet, respectively.

Among the outstanding questions regarding the planetary environments, we can mention the following questions where (Langmuir) waves play a role: how the Earth's plasma sheet is formed? How a planet interacts with the solar wind? What are the details of the magnetic reconnection at the nose of the magnetosphere and in the magnetotail?

### 3.1. *Ionosphere and polar cap regions*

The ionosphere is an upper atmospheric layer of a planet consisting essentially of plasma. It results of the ionization of the neutral atoms under the influence of X and UV solar radiations but also of the solar wind and solar energetic particles as well as galactic cosmic rays. Due to their huge energy, these particles participate to the ionization of very deep layers of the planet's atmosphere. The ionosphere couples to the magnetosphere through strong field-aligned currents, playing thus an important

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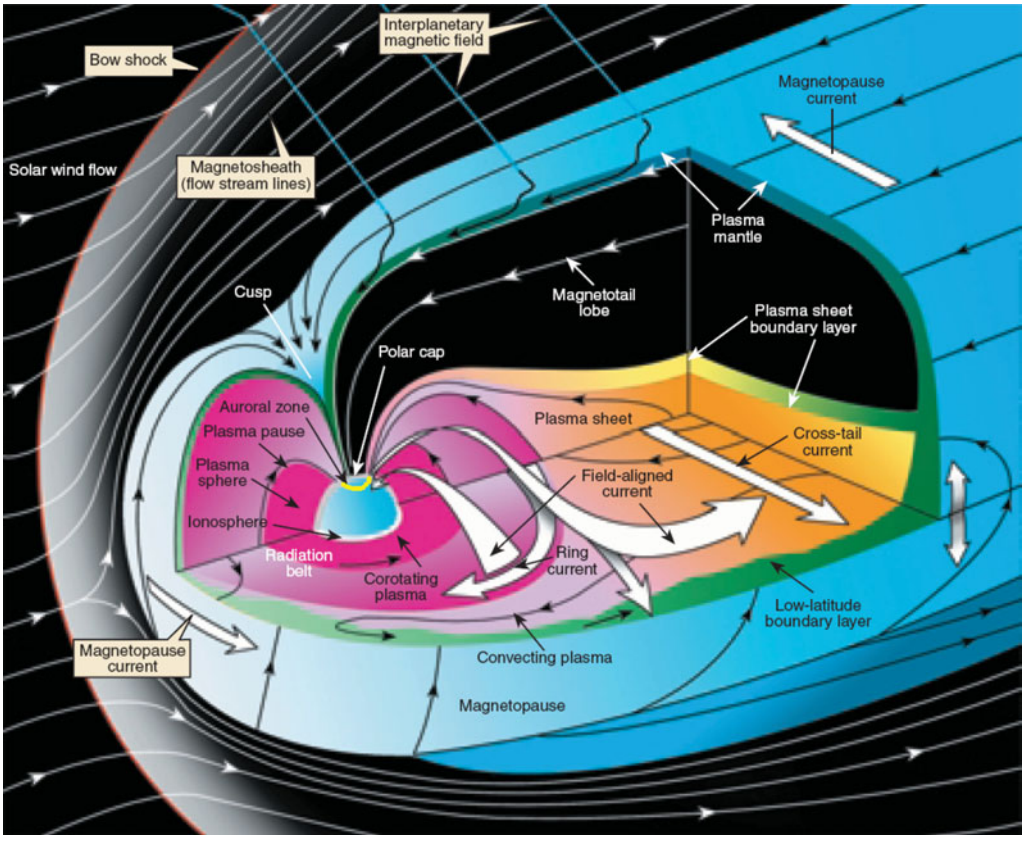



FIGURE 3. Illustration of the different planetary space regions around a magnetized planet (Earth case 'ENA measurements of the ring current' report, also accessible from http://eng.sepc.ac.cn/Introduction.php).

role in the closure of the electric currents present in the magnetosphere. Of particular interest is the polar cap auroral region where these currents carry downward (and upward) electrons to (from) the ionosphere. The energy of the electrons is sufficient to provide a source of free energy for the development of Langmuir waves. But the ionosphere also directly interacts with the solar wind when the planet has no magnetosphere. The rate of atmospheric escape is then an important parameter in the planet climate evolution.

The vertical profile and the local variations of the electron density are key parameters to describe the ionosphere and understand the physical processes taking place. It can be determined from several technics, from ground-based coherent (e.g. SuperDarn network) and incoherent scatter radar (e.g. EISCAT, Arecibo) to satellites and sounding rockets instruments. Ground-based radars allow the continuous determination of the density, temperature and velocity of the ionosphere in the E and F layers, providing complementary data to the *in situ* observations of the space missions.

As will be described below, the Langmuir waves are well documented in the Earth environment. From Mars and Venus, they are mostly used as a tool to diagnose the plasma density. To our knowledge, no specific investigations on these waves have been reported in the ionospheric environment of the other planets.

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In the Earth environment, the characteristics of the Langmuir waves differ with the altitude where they are observed. At low altitude (<400 km) they appear as short bursts of 100 ms, with amplitude of 50 mV $m^{-1}$. At higher altitudes (600 to 2000 km), the intensity of the waves varies from a few mV $m^{-1}$ to 500 mV $m^{-1}$ (and some exceptional bursts at 1 V $m^{-1}$), with bursts lasting only a few milliseconds for the most intense waves and only a few seconds for those with low intensity. Their frequency ranges from 0.1 to 10 MHz. The waves are associated with electron energy between 50 and 5000 eV. McFadden et al. (1986) reported the observations of electron distribution functions in auroral arcs, showing the presence of electron beams. The correlation with the occurrence of Langmuir waves was significant. Burinskaya et al. (2003) and Schlatter et al. (2014) provided further evidences on a correlation between the enhancement of the Langmuir activity and the geomagnetic activity, in particular when the $K_p$ index reaches values of 3 or greater. Also (Ergun et al. 1991; Kletzing et al. 2005) confirmed the presence of unstable electron distribution function.

The Langmuir waves appear highly modulated. Numerous theories have been provided to explain the modulation of the wave-packets. Stasiewicz et al. (1996), Khotyaintsev et al. (2001) and Lizunov et al. (2001) proposed that parametric decay with lower hybrid waves for the low frequency signal takes place in the topside polar ionosphere. As for Forme (1999), they proposed a model of parametric decay based on ion acoustic waves, since they noted an increase of the ion acoustic turbulence associated with burst of Langmuir activity on the topside ionosphere. Defining which low frequency signal is involved in the decay is crucial to follow the transfer of energy toward other particle species. LaBelle et al. (2010) suggested that linear growth and mixing of Langmuir modes better explain the different characteristics of the waves (including their modulation but also the distribution of their amplitude), at least for the cusp waves at high altitude. Burinskaya et al. (2003) ruled out the role of the decay in the polar cap and defended a model based on resonant wave scattering off density fluctuations. Several statistical analysis of the Langmuir envelope electric field distribution have been performed in the polar cap (Cairns and Menietti 2001; Samara et al. 2008). They found a good agreement with the lognormal shape of the amplitude expected from the SGT.

Concerning unmagnetized planets, the Mars ionosphere has been subject of numerous studies for its importance in the communication with rockets in orbit around the planet and the peculiar solar wind-planet interaction. In the frame of the present paper, Langmuir waves are used from radar sounding to determine the vertical profile of density. However, plasma waves in general are thought to contribute to Mars's atmosphere loss in participating in the ion heating (Ergun et al. 2006). The role of Langmuir waves is minor compared to other plasma waves like shear Alfvén waves or ion cyclotron waves, except maybe in the regions where the crustal magnetic field is not negligible, through coupling with lower hybrid modes as in the Earth case. Concerning Venus, if the ionosphere is also largely studied, the Langmuir waves seem to play a minor role compared to whistler or lower hybrid waves. The only paper referring to the presence of Langmuir waves in the upper side of the Venus ionosphere is the one of Ho et al. (1994).

### 3.2. *Magnetotail, plasma sheet boundary layer*

The other region where Langmuir waves frequently occur is the plasma sheet boundary layer in the magnetotail (see Fig. 3). They were first revealed from the GEOTAIL mission (Kojima et al. 1997). The waves appear as highly modulated wave-packets around $f_{pe} \approx 2$ kHz (the local cyclotron frequency is $f_{pe} \approx 200$ Hz). A comprehensive

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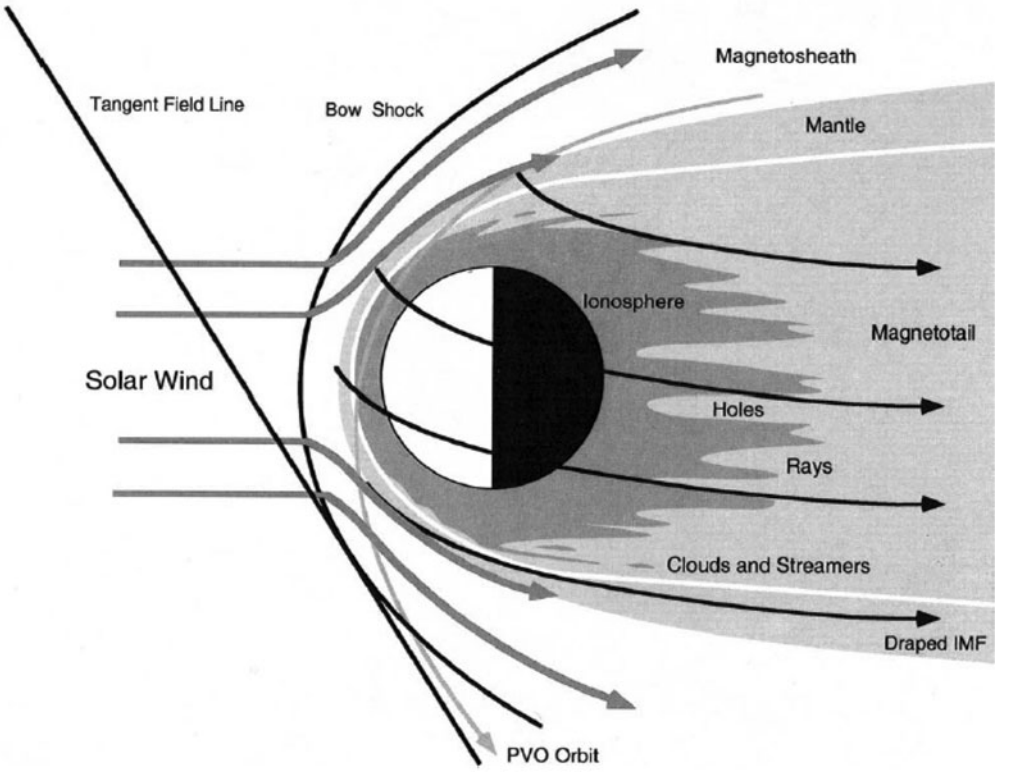



FIGURE 4. Sketch of the solar wind-planet interaction in the case of an unmagnetized planet (from Strangeway 2004).

study of the almost monochromatic waves performed by Kellogg and Bale (2004) from WIND measurements showed that the waves preferentially occur in the outer region of the tail (i.e. farther from the Earth) with amplitudes of about 10 mV $m^{-1}$, amplitude that can reach higher values for larger distances to the Earth. The enhancement of the Langmuir activity was clearly related to the increase of the electron energy flux of electrons of 100–500 eV. Electron beams of typically 1 keV and large density (5% to 13% of the background density) have been also reported (Zheng et al. 2012) and interpreted as electrons originated from the ionosphere and accelerated along magnetic field lines towards the plasma sheet.

The magnetotail is one of the magnetospheric regions where magnetic reconnection occurs. The breaking of the frozen-in condition for reconnection to proceed involve electrons plasma waves. Farrell et al. (2002) and Deng et al. (2004) showed occurrence of wave activity close to the plasma frequency near reconnection sites in the magnetotails. Instead of Langmuir waves, the polarization analysis performed on the waves showed that they are upper hybrid waves (and not a parallel-propagating Langmuir waves). Also Kellogg and Bale (2004) studied the correlation between the presence of Langmuir waves and the auroral index AE (related to substorm activity) and auroral kilometric radiation (AKR, an indicator of the auroral activity), to link the presence of the waves to magnetic reconnection events. The results were not fully conclusive even if some correlation seems to occur. New indications of the presence of electron beams associated with magnetic reconnection were provided by Cai et al. (2009). They indeed measured bumps on the tail of the electron distribution functions,

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bumps generated by different mechanisms of electron acceleration at the front shock associated with the ion jets.

Ho et al. (1993) reported observations of Langmuir activity in the magnetotail of Venus. The density of the plasma around the planet is about 10 $cm^{-3}$ leading to a plasma frequency of ≈30 kHz. They showed that waves at this frequency are frequently observed and interpreted them in terms of Langmuir waves. Unexpectedly, the authors also observed an increase of wave activity in their 5.4 kHz channel. They identify these waves also as Langmuir wave. This low frequency gave an estimate of the local density indicating to 0.3 $cm^{-3}$, that is much below of the detection threshold of the particle dedicated instrument. Together with this very low density, they estimate the temperature to be about 13 eV.

### 3.3. *Planetary foreshock*

The presence of an obstacle in the supersonic, super-Alfvénic solar wind generates the formation of a shock ahead of the object, at least when it is unable to absorb the solar flow (as in the case of the Moon and asteroids). A shock slows down, heats and deflects the solar wind. One of the key questions regarding the planetary shocks is the physics governing its formation, in particular since the medium is collisionless (the width of the shock is much smaller than the collision mean free path). The formation of a shock depends on several parameters (like the $\beta = 8\pi n k_B T/B^2$ of the plasma, the Alfvénic Mach number, the electron and ion gyroradius compared to the size of the obstacle, the orientation between the solar wind magnetic field and the solar wind flow etc). The presence of a magnetosphere around the object also deeply modifies the physical processes governing the formation of the shock. Of particular interest is the foreshock region, that is the region upstream of a planetary shock, magnetically connected to it and filled with backstreaming particles Eastwood et al. (2005). These particles provide free energy to destabilize the plasma and generate waves, in particular Langmuir waves.

The plasma waves allow energy and momentum transfer between the solar wind and the upper region of the obstacle (either the ionosphere or the magnetosphere). In spite of the diversity of the planets (size, presence of a magnetosphere or not, distance to the Sun), plasma waves have been observed in all the foreshock regions: on Venus by the Pioneer Venus Orbiter and a flyby of Galileo (Crawford et al. 1990; Hospodarsky et al. 1994), Earth from several spacecraft and in particular ISEE-1 and 2 and OGO-5 for the first missions (Scarf 1971; Lacombe et al. 1985; Kasaba et al. 2000), but also GEOTAIL and CLUSTER, Mars mainly from Phobos 2 (Grard et al. 1989; Trotignon et al. 1991; Skal'Skii et al. 1992), and also the four giant planets observed during the flyby of Voyager 1 and/or 2, Jupiter visited also by Ulysses (Kurth et al. 1980; Canu et al. 1993), Saturn explored by the Cassini mission (Gurnett et al. 1981; Kurth et al. 1983), Neptune and Uranus (Gurnett et al. 1986, 1989; Kurth et al. 1989), and to the outermost region of the heliosphere, the terminal shock (Gurnett and Kurth 2005).

The electrons and ions of the solar wind are accelerated at shocks. Langmuir waves witness the presence of such acceleration of the electrons. The energization of the particles at shock leads to the formation of electron beams that propagate backward to the solar wind along the magnetic field lines (Kellogg 2003). They provide the free energy to destabilize the plasma through the bump-on-tail instability, thus generating Langmuir waves (Fitzenreiter et al. 1984; Bale et al. 1997). Figure 5 displays an example of observations at Venus where Langmuir waves are clearly observed along the magnetic field line tangent to the shock. The extension of Langmuir waves along

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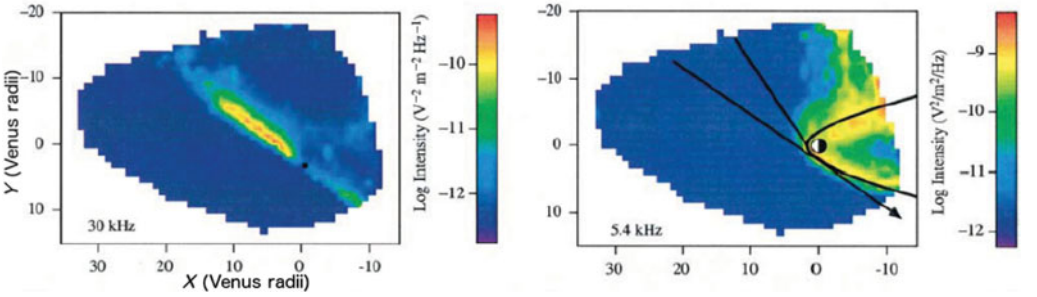



FIGURE 5. Plasma waves observed upstream the Venus bow shock (adapted from Strangeway 2004). The left panel displays the extension of the Langmuir waves emission (observed at 30 kHz). The emission is visible along the tangent to the bow shock, as can be checked with the right panel that displays in black lines the main frontiers around the planet (bow shock, tangent to the shock and electron foreshock) together with the ion acoustic waves emission. The maps are drawn in the Venus Solar Orbital (VSO) coordinate system, i.e. the analogous to Geocentric Solar Ecliptic Coordinates.

this line indicates the efficiency of the energization process. If at Venus the intensity of the waves strongly decreases after 15 Venus radii, Langmuir activity is still observed at a distance beyond 100 Earth radius (Greenstadt et al. 1995). The difference comes from the curvature of the shock that controls the energization process (Strangeway 2004). Thus, more than microscopic parameters, the macro-scale properties seem crucial in the extension of the Langmuir wave activity. Also, the intensity decrease of Langmuir waves as we go deeper towards the ion foreshock region is due to the presence of electron beams of lower intensity (Filbert and Kellogg 1979). Thus, the extension of the area where these waves are observed reflects the dispersion in velocity of the electron beams and gives some constraints on the possible mechanisms for the energization of the electrons (Fitzenreiter 1995).

Electromagnetic radio emissions at $2f_{pe}$, the harmonic of the plasma frequency, are detected in the vicinity of the Earth (Anderson et al. 1981; Hoang et al. 1981; Lacombe et al. 1988; Kasaba et al. 2000) and Venus bow shock (Strangeway 2004). The observations show that the electron foreshock is the source of the energy and that the intensity of the electromagnetic waves is related to the intensity of Langmuir waves. Therefore, the decay of Langmuir waves through wave coupling (parametric decay and coalescence of the mother and daughter waves) has been naturally proposed to explain these emissions (Fitzenreiter et al. 1984; Soucek et al. 2005; Sigsbee et al. 2010). Robinson and Cairns (1995) showed that the heliocentric decrease of the maximum amplitude of the Langmuir field was consistent with the threshold of parametric decay at all the planet, from Venus up to Neptune.

The Langmuir wave activity in the sunward and anti-sunward regions of the shock is asymmetric: enhanced in the former and it is much reduced in the latter. This asymmetry is well pronounced at Venus, but not so clearly identified at the Earth foreshock. Recently, Pulupa et al. (2011) provided new evidence on the existence of such asymmetry in the Earth environment from a statistical analysis of observations from the WIND mission. They explained such asymmetry by the role played by the electrons of the strahl of the electron distribution function. The presence of such an enhanced electron tail favors the formation of energetic electron beams with a sufficient derivative in the distribution function for the bump-on-tail instability to proceed. The role of the electron strahl in the formation of Langmuir waves has also been recognized in the context of interplanetary magnetic holes (see Sec. 4.1 below).

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Langmuir waves provide estimates of the electron density at the electron foreshock. The accuracy of the estimation depends on the correction from thermal terms on the dispersion relation (see (2.1)). Trotignon et al. (1992) deduced electron density between 0.5 to 19 $cm^{-3}$. Also Went et al. (2011) from the electron density and, assuming a constant solar wind speed, gave an estimate of the solar dynamics pressure, a key parameter in the model of shock position ahead of a planet. The density fluctuations can also be inferred from the ponderomotrice force generated by the waves on the electrons (see (2.2)). Using this effect Henri et al. (2011b) estimated the fluctuations of the electron density in the Earth foreshock and the (non-connected to the bow shock) solar wind to vary from $10^{-4}$ (the detection limit of the instrument) to a little less than $10^{-2}$, values in agreement with the expected saturation levels.

Up to now, only nonlinear processes have been invoked to explain the saturation of the linear growth of Langmuir waves in the planetary foreshock. Yet, such saturation mechanism can hardly account for the very bursty nature of Langmuir waves as revealed by the waveform measurements, and the low level of the wave amplitude. Cairns and Robinson (1999); Boshuizen et al. (2001) in the Earth foreshock and Boshuizen et al. (2004) for the foreshock region of Saturn, Neptune and Uranus showed that the probability distribution of the electric strength of Langmuir waves agrees with the lognormal distribution expected from the SGT. However, Krasnoselskikh et al. (2007) and Musatenko et al. (2007) recently provided probability distribution of the wave energy density in the Earth foreshock and showed a discrepancy from the SGT expected lognormal shape.

## 4. Langmuir waves in the interplanetary medium

Langmuir waves are also detected in the interplanetary medium, outside any planetary environments. If they are particularly intense during solar activity periods (generated by fast electron beams from solar flares or interplanetary shocks), they are also encountered in the quiescent solar wind, in particular in magnetic holes.

### 4.1. *Quiescent solar wind*

Several NASA and ESA missions have been dedicated to the exploration of the heliosphere. After the first Pioneer missions, Helios explored the inner heliosphere down to about 0.3 A.U., Voyager, 1 and 2 reached the outer limits of the solar system, ISEE-3 observed the solar wind from the Sun–Earth Langrange point L1 and was sent to the encounter of the comet Giacobini–Zinner, and Ulysses was the only mission sent outside the ecliptic plane. These former missions are now stopped. Still, WIND is providing detailed measurements from the Lagrange point L1 and STEREO scan the interplanetary medium along the Earth orbit but at large angular distances from the Earth. Equipped with more and more powerful plasma instrumentation, in particular radio receptors, all these probes have provided measurements of Langmuir waves in various plasma conditions.

Outside periods of solar activity, Langmuir waves are predominantly observed in magnetic holes, i.e. localized magnetic depressions inside magnetic discontinuities, in pressure equilibrium (Turner et al. 1977). The holes last from a few tens of second up to half an hour (Stevens and Kasper 2007, and references therein). Figure 6 displays such an event observed by STEREO. The question of the Langmuir waves formation inside magnetic holes is also related to the origin of the magnetic structure. From the analysis of Ulysses measurements, Lin et al. (1996) first revealed the presence of the Langmuir waves in magnetic holes. They also showed that the amplitude of

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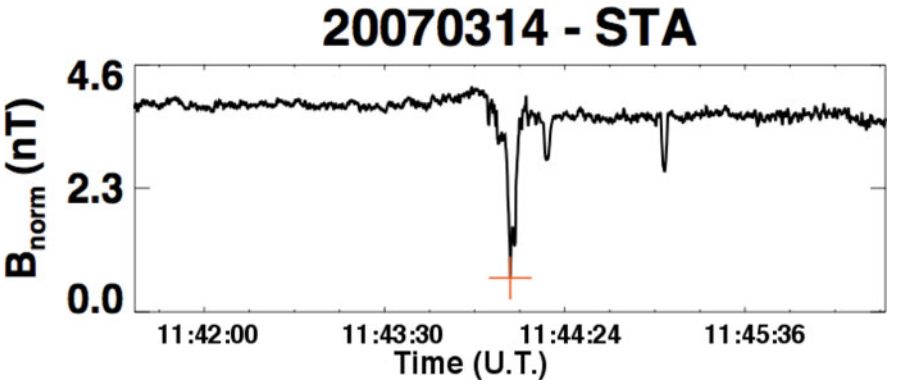



FIGURE 6. Example of a magnetic hole observed by STEREO-A/IMPACT. The red cross indicates the time when Langmuir waves were observed from the TDS mode of the WAVES instrument.

magnetic field depression gradient, rather than the amplitude of the hole itself, is a key parameter for the development of Langmuir waves. Studying the dependence of the Langmuir wave activity with the heliographic latitude, MacDowall et al. (1997, 2001, 2003) reached the following conclusions: (i) the intensity of the electric field is much higher outside a band of $\pm 20^{\circ}$ in latitude; (ii) at high latitude, the wave activity is more likely observed in magnetic holes or other magnetic field discontinuities; (iii) the probability of wave activity is higher outside the streamer belt than inside (magnetic holes are more common in the high-latitude solar wind); (iv) the electric field intensity is higher closer to the sun and shows a tendency to decrease with the distance to the sun (but also a more surprising increase seems to occur at about 5 AU). All the proposed mechanisms for the formation of magnetic holes are adiabatic, thus very slow. The presence of high-frequency electrostatic waves inside these magnetic dips is thus puzzling. Indeed, Langmuir waves usually require time dependent fluctuations of the electron distribution function, hardly compatible with a slow formation of magnetic holes. MacDowall et al. (1995, 1996) proposed that adiabatic focusing of thermal electrons – conservation of the magnetic moment – may lead to counterstreaming electron beams and Langmuir waves. Recently Briand et al. (2010) showed clear evidence on the key role played by the energetic electrons (the strahl) in the generation of the waves. They proposed that the electrons of the strahl, rather than the electrons of the core distribution, are the ones submitted to a magnetic focusing to produce beams, then the waves.

### 4.2. *Transient phenomena*

Langmuir waves have been intensively studied in the frame of solar radio emissions, and more specifically associated with Type II and Type III radio emissions (Fig. 7). These electromagnetic emissions, related respectively to interplanetary shocks and solar flares, are emitted near the electron plasma frequency $f_{pe}$ or its harmonic $2f_{pe}$. The faster time-frequency drift of Type III emissions proves that the electron beam velocity is higher than in the case of Type II.

The basics of the mechanism at the origin of these radio emissions were proposed by Ginzburg and Zheleznyakov (1958). Electrons are accelerated at the reconnection sites during solar flares or by fast Fermi mechanism at interplanetary shocks. As the electron beams propagate along the interplanetary magnetic field, they locally destabilize the plasma through the bump-on-tail instability. The generated Langmuir

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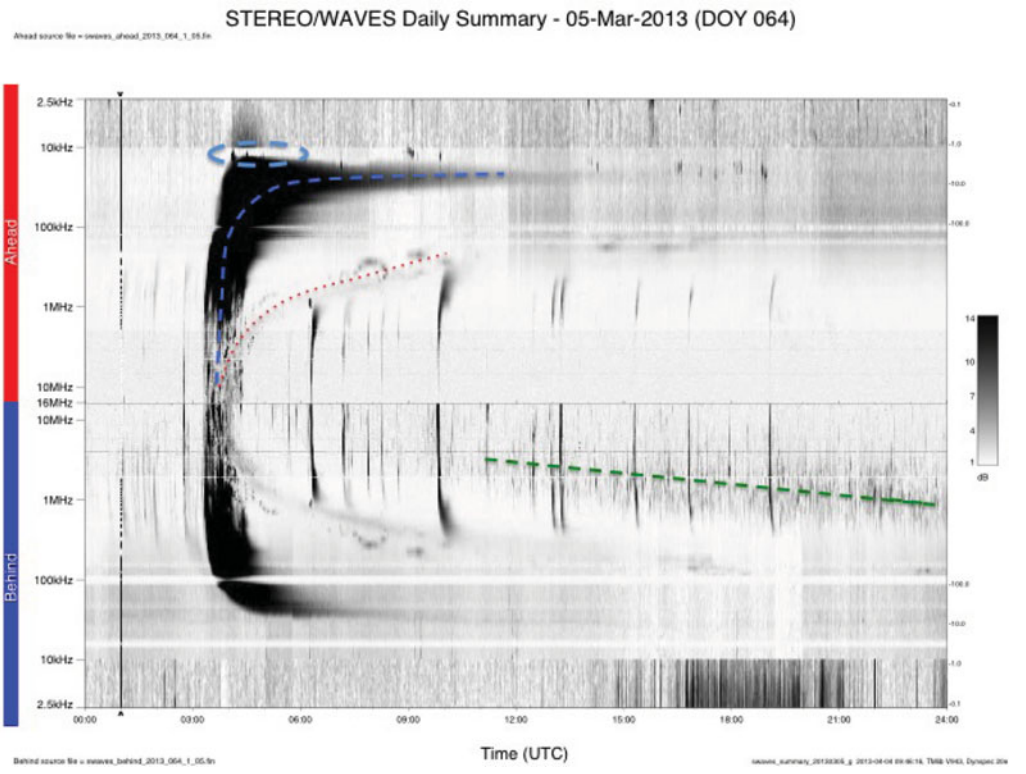



FIGURE 7. Example of the main solar radio emissions related to: (i) flare (the so-called Type III emission – underlined in dashed blue line), (ii) Interplanetary Coronal Mass Ejection (Type II emission – in dashed red) and (iii) solar active regions (Type III storm - in green) obtained by STEREO/WAVES instrument. The blue circle shows the presence of Langmuir waves associated with the type III emission. The intensities are represented in reversed black-white color code: the darker, the stronger. Time (in hour of the day in UTC) is in abscissa, and frequencies in ordinate. AHEAD means observations from STEREO-A (ahead of the Earth), while BEHIND means observations performed by STEREO-B, behind the Earth. The dark signal on STEREO-B below 10 kHz are typical of dust impact on the antenna.

waves are then converted to electromagnetic waves through the nonlinear mechanisms presented in Sec. 2. Since the density decreases with the heliocentric distance, so does the plasma frequency, explaining the time-frequency drift toward lower frequencies. For a complete review of the characteristics of the Type III bursts, see the recent review of Reid and Ratcliffe (2014).

4.2.1. *Solar flare related emissions.*

The electron acceleration at the origin of the Type III emissions takes place at magnetic reconnection sites in the high solar corona. Still no *in situ* observations of the electron distributions have been possible so close to the Sun. Only indirect evidence of such acceleration processes are given by X-ray emissions associated with solar flare. Also, bumps in the electron distribution function were observed in the interplanetary medium Lin et al. (1981, 1986). Even if the time resolution of these observations was poor compared to the evolution of the waves – limiting the accuracy of quantitative studies – these data provided a new support to the physical scheme of radiation emission described above. Finally and more crucially, the presence of Langmuir waves also provides fundamental information. Langmuir waves associated

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with Type III burst were first mentioned by Gurnett and Anderson (1977) in the range 20–100 kHz. The intensity of the waves decreases from a few tens of mV $m^{-1}$ at small radial distance to the Sun ($r \approx 0.3R_{\odot}$), following a power law of the form $r^{-3.5}$ (Fig. 4 of Gurnett et al. 1978). These observations already revealed the bursty character of the waves, lately confirmed by waveform measurements from WIND mission. Since then, the simultaneous detection of Langmuir waves and low frequency waves were reported several times from spectrum analyzer. However, the fundamental laws (moment, energy conservation and phase locking) have been checked only recently (Henri et al. 2009; Briand et al. 2014). Such analysis was possible owing to the 130 msec waveforms of STEREO/WAVES Time Domain Sampler (TDS). Such long waveforms – compared to the 15 msec of most the WIND data – allowed the simultaneous detection of high and low frequency signals. But most of all, the waveforms keep the information on the phase of the waves. These observations were completed by numerical simulations that proved that the amplitudes of the waves were indeed sufficient for the parametric decay to occur Henri et al. (2010a). The second paper also provided important support on the coherent character of the decay. The next step nowadays is to develop simulations of Type III radio emissions, including both the small scales of the kinetic physics and the large scale of the electromagnetic domains (Li et al. 2006, 2008; Pal Singh et al. 2012), fluctuations of the density or the ion/electron temperature (Li et al. 2011a,b), but also the non-Maxwellian character of the electron distribution function (Li and Cairns 2013).

4.2.2. *Interplanetary shocks.*

Interplanetary collisionless shocks are caused either by solar transients (interplanetary coronal mass ejections) or corotating interaction regions. A comprehensive review of collisonless, non-relativistic shocks can be found in Treumann (2009). Conversely to the standing planetary shocks, IP shocks are traveling ones. They thus crucially participate to the plasma heating, the generation of turbulence and the energy dissipation of the collisionless interplanetary medium over large distances. An example of plasma heating at IP shock has been provided by the analysis of the evolution of the electron distribution at the shock transition from WIND measurements (Fitzenreiter et al. 2003). One of the questions regarding the physics of the interplanetary shocks is the mechanism of energization of the electrons. Several mechanisms have been proposed that strongly depends on the nature of the shocks, in particular in the character quasi-parallel ($\theta_{b,n} < 45°$) or quasi-perpendicular of the shock (see the review by Treumann and Terasawa 2001). Since Langmuir waves are the signature of the acceleration, it is fundamental to observe them. Also, the remote observation of Type II emissions can help since they result from the Langmuir wave mode conversion. Determination of the site of these emissions (nose of the shock or flank, upstream or downstream) through direction finding technics are thus crucial.

In a statistical study from *in situ* measurements (WIND and Ulysses), Thejappa and MacDowall (2000) showed that Langmuir waves only occur in the upstream part of supercritical shocks. These results were confirmed by a more recent statistical studies Pulupa et al. (2010). These last authors also showed that the velocity of the shock, expressed in the Hoffman–Teller frame, was the best predictor of the Langmuir wave activity at fast forward shocks. The predominance of Langmuir waves in quasi-parallel or quasi-perpendicular shocks is however still controversial: Thejappa and MacDowall (2000) claimed that the two types of shocks produce the waves, while Pulupa et al. (2010) seem to privilege quasi-perpendicular ones.

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## 5. Conclusions

Langmuir waves are fundamental waves when studying the dynamics of the electrons, in particular in collisionless plasma where waves are suspected to play the role of collision. In this paper, the main physical mechanisms involving Langmuir waves have been reviewed, from their generation to their saturation and decay. Then, these theories have been compared to the observations in several heliophysical environments. From these confrontations, several subjects of high interest at the present time arise.

First, the role of the density fluctuations in the development of Langmuir waves is one of the most debated subjects. The density fluctuations can indeed (i) stochastically change the growth rate of the waves (SGT theory) and explain the clumpy aspect of the wavepackets, (ii) trapped Langmuir waves to explain some very localized waveforms (eigenmode model) and (iii) allow the linear mode conversion of Langmuir waves to electromagnetic waves. Numerous efforts are thus devoted to understand the growth and decay of the waves in inhomogeneous plasma as a fundamental problem but also to increase the diagnostic potential of the waves.

Then, Langmuir waves are studied in the frame of magnetic reconnection and collisionless shocks. They are first the tracers of electron acceleration, either at reconnection exhausts or ahead of shocks. They play an important role in the local change of the plasma properties in particular in the development of the turbulence, crucial actor in the two processes. The investigations on all these subjects are based on space exploration, laboratory experiments and numerical simulations.

In this review, the focus was given on several specific heliospheric regions where Langmuir waves were intensively observed (ionosphere, plasma sheet boundary layer, planetary foreshocks and interplanetary medium). Yet, increase of the Langmuir activity was also reported during the Vega's encounter with the Halley's comet (Grard et al. 1986) and with ICE† at Giacobini–Zinner (Kennel et al. 1986). In the future, several space missions should provide unprecedented data in almost unexplored regions of our heliosphere. The ESA Rosetta probe has been successfully woken up in January 2014. In August 2014, it reached its final objective, the Churyumov–Gerasimenko comet. The probe will now follow the comet along its trajectory for at least two years. Equipped with a specific plasma instrument package (RPC, Carr et al. 2007), it will contribute to a better understanding of the interaction of the solar wind with a comet, in particular during the increase of its activity as it gets closer to the Sun. Then, the solar corona will be visited by Solar Orbiter (ESA – Launch 2017) and Solar Probed Plus (NASA – Launch 2018). This last mission will explore the smallest heliocentric distance ever reached (10 solar radius), allowing plasma parameters to be measured very close to reconnection sites of solar flares and around the altitude of the solar wind acceleration.

Mercury has been visited twice but the payloads did not include instruments for full plasma waves studies. So, the investigations on the dynamics and physical processes taking place in the magnetosphere of the planet are scarce. The ESA/JAXA Bepi Colombo mission, with its instrumental package PWI, will fill this gap when the probe will reach the planet in 2020 (Kasaba et al. 2010). The magnetosphere of Saturn has been intensively studied owing to the instrumentation onboard of Cassini mission. The ESA JUICE mission foreseen for a launch in 2022 will be equipped with a specific

† ICE is the name of the former NASA-ISEE-3 mission during its extension towards the comet Giacobini–Zinner.

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plasma package (RPWI) to explore the magnetosphere of Jupiter from 2030 (Grasset et al. 2013). Regarding the outermost planets of the solar system, our knowledge on the dynamics of their magnetosphere is limited to the information provided by the Voyager probes during their flyby. However, the inclination of the magnetic axis of Uranus and Neptune compare to their rotational axis as well as their long revolution period and their distance to the Sun make them very interesting to study, next to the interest for the atmosphere and internal structure of each planet (Arridge et al. 2012).

Besides space missions, laboratory experiments contribute substantially to the understanding of the fundamental processes related to electron plasma waves. For example, Dylov and Fleischer (2008) tested the bump-on-tail instability through optical system. Also, the nonlinear evolution of Langmuir wave is a well-known problem in the context of the laser-plasma interactions, and in particular in the frame of inertial laser confinement. Several instabilities are studied that invoked the dynamics of the ions (stimulated Brillouin scattering), or the electron dynamics (Stimulated Raman Scattering). One major problem is the saturation of the SRS. Several alternatives theory to the classical Langmuir decay have been proposed that could be of interest for the heliophysics community (see Friou et al. 2013, for a recent discussion and references). Also, the role of inhomogeneity in the SRS has been widely explored (Chapman et al. 2010). The two communities could gain in working together since, in normalized units, their plasma characteristics are sometimes very similar (same range of $T_e/T_p$ and $k\lambda_D$).

Finally, numerical simulations are unavoidable to thoroughly understand the details of the physics (and also to design the space instruments or laboratory experiments). Regarding Langmuir waves related physics (generation, decay), most of the numerical studies have been restricted to one spatial (and velocity) dimension. Multi-dimensional simulations are however mandatory. The computing facilities now available allow simulations to be performed that can incorporate more physics and deal with large scale behavior. One of the major challenges for the next years is to incorporate kinetic treatments in restricted areas of large scale global simulations.

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