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Using the Ionosphere as a Laboratory for Plasma Turbulence

A plasma is the state of matter when it is ionized, that is, it consists of free electrons which carry a single negative electric charge, and ions, which usually carry one or more positive charges, and are much heavier than the electrons. For most purposes, plasmas are theoretically described in terms of classical physics, which means Newtonian mechanics fusioned with classical electromagnetism, i. e., Maxwell's equations. Mechanics is the principles of what motion results from given forces. Electromagnetism is about what force fields result from given charge and current distributions. In plasma dynamics, the electromagnetic force fields put the charged particles into motion, and thereby change the local charge and current distributions, leading in turn to modifications of the electromagnetic force fields. So, plasma dynamics is the interplay resulting from this fusion of the two basic theories of classical physics.

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From the point of view of basic research, there were good reasons to expect that a broad range of new phenomena would reveal themselves through this fusion. From the point of view of practical applications, plasma physics has to a large extent been driven forth by the perspective of confining a plasma to create conditions for thermonuclear fusion. This has so far not been successful. On the other hand, the study of plasma processes has been very important in space research during the last 4–5 decades. Recently there have also been some developments towards various industrial applications.

Even if the basic theoretical framework of plasma dynamics is clear and uncontroversial, a sound development requires a good interaction between experiment and theory. However, to build good plasma experiments has not been an easy task, and so, creative experimental setups have been crucial for the development of plasma physics. This contribution aims at describing a particular, fairly non-standard, experimental setup, which in the author's opinion has been quite successful in establishing contact between theory and experiment in the case of a fairly complex plasma process.

The setup has the following ingredients: (i) The plasma of the *ionosphere*, which is the ionized layers of our atmosphere from approx. 60 to several 100 km altitude. (ii) A *radar system* which is used for studies of the ionosphere. Such a radar system, EISCAT (European Incoherent SCATter radar system), operates in northern Scandinavia, with transmitters in Tromsø, and receivers in Tromsø, Kiruna, and Sodankylä. (iii) A powerful radio transmitter, *Heating*, which is used for active drive of plasma processes in the ionosphere. Such a powerful radio transmitter is located next to the EISCAT transmitters. A similar setup exists at the Arecibo observatory in Puerto Rico, but at the moment, that combined facility is not operating.

The Heating facility at Tromsø operates at frequencies in the range 4–8 MHz. In this frequency range, the radio wave is strongly modified by the ionospheric plasma. In the present case, where it is also very powerful, it also has a potential for driving processes in the plasma, as we shall describe in slightly more detail below. The EISCAT radars, in comparison, operate at 224 MHz (the VHF radar) and 929 MHz (the UHF radar). In this frequency range the propagation of the radio wave is not affected by the plasma. However, a tiny fraction of the incident energy flux is *scattered* back by *fluctuations* in the plasma. It is this backscattered signal that is received and analyzed by the receiving system of the radars.

The process: "Radio driven Langmuir turbulence".

In order to describe the theory of the actual process, as well as the theory of the measurements, from first principles, one would probably have to write a whole book, with much heavy mathematical derivation. Here, we shall be content with indicating a few concepts of general classical physics.

(i) *Oscillations.* In a simple mechanical system containing *inertia* and a *restoring force*, oscillations will result. Examples: a) A spring where the restoring force is proportional to the displacement ("Hooke's law"), and a mass point attached to the spring. A straightforward text book analysis of this system leads to the formula $\omega = \sqrt{k/m}$ for the frequency ω, in terms of the spring constant k and the mass m. b) A pendulum. Here the frequency turns out to be $\omega = \sqrt{g/l}$, where g is the acceleration of gravity (approximately 9.8 m/sec^2) and l is the length of the pendulum. c) *Space charge oscillations of a plasma:* If an excess or a deficit of electric charge arises somewhere in the plasma, electric forces arise, since similar charges expel each other and opposite charges attract each other. This will set the lightest elements of the plasma, which are the electrons, into motion. But since the electrons also have inertia, oscillations result. The frequency of these space charge oscillations, or *Langmuir oscillations* (after the American physicist and chemist Irving Langmuir 1881–1957, Nobel Prize in Chemistry 1932) is called the plasma frequency $\omega_{pe} = \sqrt{4\pi e^2 n_e / m_e}$, where n_e is the electron density, m_e the mass of the electron, and e is the charge of the electron (in suitable units! This version is in old-fashioned Gaussian units.)

(ii) *Equilibrium; stationary state.* Equilibrium refers to a state where everything is at rest, or not changing, meaning that all forces are in balance. Stationary state refers loosely to a state where the system is changing in some regular way. In fluid dynamics, the term *laminar flow* may be seen as an example.

(iii) *Stability, instability.* Some equilibria or stationary states are *unstable*, which means that some small disturbance of the state grows. We know examples of this from everyday life: e.g. the instability of the inverted pendulum (with stiff support). Everybody has tried to balance an upside-down rake. Another example is waves coming up on the surface of water as a result of wind blowing over it. The latter is an example of an instability in a system with infinite degrees of freedom. Equilibrium and stability/instability can be defined in purely mathematical terms, within the discipline called *dynamic systems*.

(iv) *Saturation* refers to the ultimate state developed from an instability. We are very far from any general mathematical theory of the "saturation" of an instability. In physics, the principle of conservation of energy gives an overall point of view: Energy delivered *into* the system, feeding the instability, must be *dissipated* by the turbulent process.

(v) *Turbulence.* We shall not put any effort into defining this term, but merely state that one possible (but not the only!) point of view on turbulence could be as the saturation of an instability, provided that this state is complex enough. There are many examples where an instability results in a fairly regular motion; then it is not turbulence.

(vi) *Resonance.* When a system which has an internal mode of oscillation, such as the examples above, is exposed to an external periodic forcing with frequency near the internal frequency of oscillation, we have a situation of resonance. Strong oscillation at the forcing frequency may result. This is, for example, the principle of antennas.

(vii) *Langmuir turbulence.* A system with an electron beam being shot into a plasma, is unstable, and it is Langmuir oscillations which in that case grow up. Therefore, it is called Langmuir turbulence. A saturation theory from the 1960s assumed that Langmuir turbulence is saturated by

(viii) *cascades,* which roughly means that the wave originally growing up, by a resonant process gives rise to new waves at other (lower) frequencies. These waves can in turn cascade to even new waves and so on.

(ix) *Cavitation.* Zakharov [1] demonstrated theoretically that a phenomenon called *collapse* can occur in the Langmuir system. This means that the plasma fields contract to a point (similar to a black hole?). Another, indeed different, phenomenon, is the self cavity resonance. Both of these processes occur in what we call cavitation.

(x) *Parametric instability.* An example is a pendulum for which the point of support makes vertical oscillations. This is a permissible movement (a stationary state), but it turns out to be *unstable* when the frequency is nearly twice the pendulum's internal frequency, leading to growing pendulum motion. A related example is the swing. Another example is a cup of water (or coffee) oscillating vertically. At certain frequencies, one can see standing concentric water (or coffee) waves in the cup.

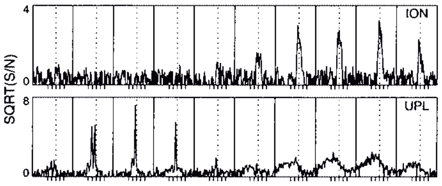


Figure 1. Example of results from experiment on radio-driven Langmuir turbulence in the ionosphere, from [6], using the EISCAT VHF radar and the Heating facility. The vertical lines in each panel separate height bins, where each height bin is 300 m. The data within each height bin are spectra, where the tick marks on the axis represent 5 kHz. The spectra in the lower panel to the left are typical cascade spectra. ("UPL"="Upshifted Plasma Line"; the spectra are shifts to the radar frequency + the Heating frequency.) Those to the right (both panels) resemble those predicted from cavitation cases. The upper panel is "Ion line", in those data the frequencies are shifts from the radar frequency.

(xi) *Radio driven Langmuir turbulence.* It was theoretically predicted in the 1960s that an incident radio wave could drive up Langmuir oscillations by a parametric insta-

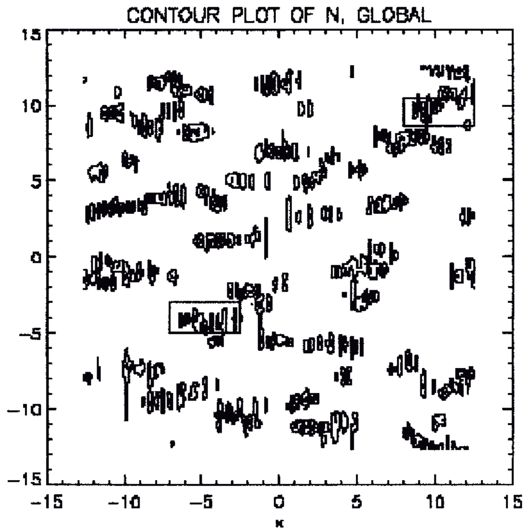


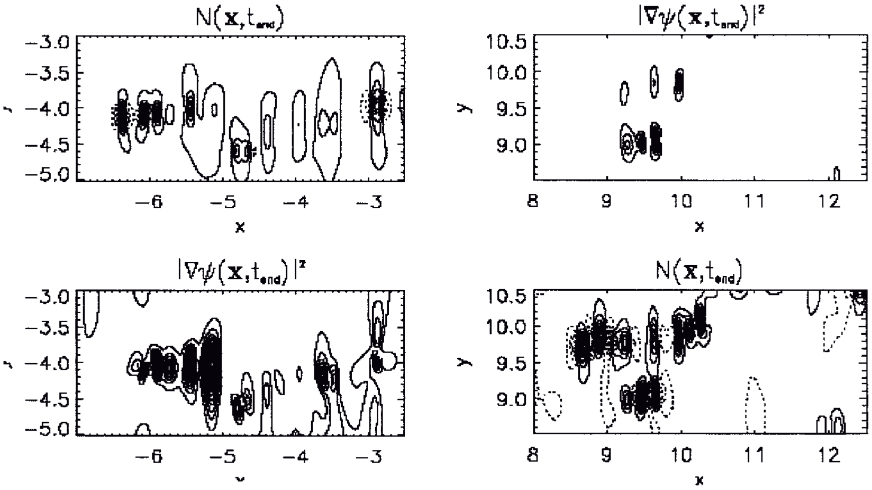
Figure 2. Contour plots of the state at a fixed time for a numerical run of the driven and damped Zakharov model, from [10]. N: dimensionless (relative) plasma density perturbation. Dotted (whole) contours represent positive (negative) values. $\nabla\psi$: electric field of the Langmuir turbulence. The upper part shows the whole numerical cell, while the lower part is magnifications of the regions indicated. The horizontal direction is along the ambient magnetic field, and the driving electric field polarization is along the magnetic field. Three features may be noticed: (i) The anisotropy of the cavitations (predicted in Russian works in the 1970s, but to my knowledge not noticed in such a numerical

bility in a plasma. The process takes place near the locus where the plasma frequency is equal to the radio wave frequency. The theory of its saturation resembles the Langmuir turbulence, and this justifies its name.

The experiments

Experiments of the kind described in sect. 1 above at Arecibo [2] around 1970, demonstrated the existence of this parametric instability. Experiments continued in the 1970s and 1980s. A saturation theory based on cascades occurred [3], but was not without problems when compared with experiments. Alternatives based on cavitation and the so-called Zakharov model occurred during the 1980s. In my opinion, the correct picture of this process was described by DuBois and co-workers from 1985 [4] and onwards. Around 1990 there was a state of confusion and controversy. In theoretical work initiated at Tromsø [5], it was demonstrated that cavitation was to be expected in the upper part of the excited plasma volume (or: highest density), while cascade was to be expected further down. But the cascading process is not necessarily observable by the radars. These predictions were demonstrated in some nice experiments at Arecibo [6], and later at Tromsø [7], from which Figure 1 is taken. A particularly nice study at Arecibo was published in [8], and finally we mention the very thorough experimental study [9] from the Tromsø facilities. The paper [10] contains an overview of the theory based on the damped and driven Zakharov model, and a series of 2-dimensional numerical runs of that model. Figure 2 shows one example.

Much of the work using the kind of radar installations that exist at EISCAT and at Arecibo, is “geophysics”. This means that one is interested in what *is there,* and the activity should be described as *observations.* The study described above, differs in many respects from that kind of work. In many ways one *designed* the experiments to test hypotheses. For that purpose, one needed as pure and controlled conditions as possible. Nice “ionospheric weather” (at Arecibo, the experiments were done



context), (ii) the tendency that the cavities come in "streets" along the magnetic field; so far unexplained; and (iii) a tendency of upstew at each side of the cavity along the magnetic field (dotted lines in the n plots); this supports the trapping, and makes the cavitation dynamics more similar to the 1D picture.

during night time); "cold start", meaning that one turned on the heater for a very short time and then turned it off for a long time, and made many repetitions, in order to secure undisturbed conditions; but most of all: very clever experimental procedures (which we cannot describe in detail here) to obtain simultaneous *height* and *spectral* resolution. For these reasons, this work really deserves the name plasma *experiments*.

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