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INTERPRETATION OF LABORATORY
EXPERIMENTS OF INTEREST TO
SPACE PHYSICS

Lars P. Block

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Department of Plasma Physics
Royal Institute of Technology
100 44 STOCKHOLM 70
Sweden

INTERPRETATION OF LABORATORY EXPERIMENTS OF INTEREST TO SPACE PHYSICS

Lars P. Block
Department of Mechanics and of Plasma Physics
The Royal Institute of Technology
S-10044 Stockholm, Sweden

The merits and limitations of experiments designed for studies of: 1) solar wind interaction with magnetospheres (terrella experiments) and non-magnetized bodies, 2) neutral lines and sheets, 3) wave-particle interactions, 4) anomalous resistivity, 5) double layers, 6) magnetically field-aligned electric fields in strong magnetic mirrors, and 7) the critical ionization velocity of a plasma moving through natural gas, are discussed.

1. INTRODUCTION

Although theoreticians have a firm belief in their theories, that belief is not always shared by nature. It is, therefore, necessary to check the theories with observations.

Unfortunately, it is not always possible to build a sound theory based on in situ observations in space, only. Laboratory simulation of the phenomena may, however, provide additional information of great importance, if a correct interpretation and scaling to space dimensions can be achieved.

In discussing laboratory simulation of space phenomena it is advantageous and customary to distinguish between configuration and process simulation (Fälthammar, 1974).

The aim of configuration simulation is to study specific phenomena in a geometric model of a certain region of space, e.g. the magnetosphere, the neutral sheet, or the interaction of a space-craft with the surrounding medium.

In process simulation experiments some interesting basic process is in focus, regardless of geometry. The influence of different geometries may, in fact, provide additional clues for understanding the mechanisms of the process in question. The kind of process to be studied range from simple particle collisions, i.e. determination of cross-sections, to intricate collective plasma phenomena, such as shocks, waves, anomalous resistivity, etc. Experiments to determine basic constants and cross-sections will be ignored here, regardless of their importance to space physics.

2. LIMITATIONS

It is always necessary to consider, in detail, the conditions and limitations for the application of laboratory experience to space phenomena. The most important limitations, applicable to most or all experiments are discussed here. It must, however, be emphasized that additional restrictions may apply in many cases. Because of the large variety of experiments and phenomena it is impossible to cover them all in a single article.

2.1 Scaling

Scaling is important, in particular to configuration experiments.

The Boltzmann equation is usually taken as the basis for scaling considerations, due to its vital importance for plasma phenomena. The invariability of elementary particle properties makes it necessary to leave potentials, temperatures, in fact all kinds of energies, and hence also velocities unchanged. This means that lengths and times must obey the same scaling ratio. Table 1 presents the scaling laws for some important plasma parameters according to Boltzmann scaling (often somewhat inadvertently called Vlasov scaling).

Length, time, resistivity	vary as L^{+1}
Particle energy, velocity, potential, temperature	vary as L^0
Particle density and pressure, electric and magnetic field, frequency	vary as L^{-1}
Magnetic pressure, space charge density, current density	vary as L^{-2}

Table 1. Plasma Scaling Laws

According to the Table kinetic and magnetic pressures scale differently. Kinetic pressure scaling is derived from the facts that collision frequencies should scale inversely with L as all other frequencies, but cross-sections are invariant. Thus, the ratio between kinetic and magnetic pressure cannot be retained, as would often be desirable. Another difficulty is that plasma frequency must vary as $L^{-1/2}$ provided the particle density varies as L^{-1} .

These are only two examples of a fundamental difficulty with scaling. Another difficulty is the impossibility to achieve the large magnetic fields necessary when the scaling ratio is very large. For instance, if the whole magnetosphere is scaled, magnetic fields of the order of 10^8 gauss or more would be necessary.

Valuable information may, however, be obtained from simulation experiments if qualitative scaling can be achieved. This means that relevant dimensionless numbers should be kept qualitatively the same in the laboratory as in space. Those much smaller or larger than unity in space retain this property in the model, but not necessarily by the same order of magnitude (Block, 1967; Schindler, 1969; Podgorny and Sagdeev, 1970). However, a deeper understanding of the physical processes may often be gained by investigating their dependence on these dimensionless numbers, especially in the neighbourhood of unity.

2.2 Boundary conditions

Many theories are based on assumptions of, e.g., a homogeneous, infinitely extended medium. Such simplifying assumptions are often necessary to make the problem mathematically tractable, but it is likewise often misleading and cannot always be applied to natural phenomena, because the boundary conditions are of decisive importance. This is also a problem for the application of laboratory phenomena to space conditions. A laboratory plasma is usually bounded by material walls which do not exist in space. It is fortunate that a plasma screens itself from the influence of solid or liquid materials by a sheath with a thickness of the order of the Debye length. Nevertheless, care must be taken to account for the influence of walls or other boundaries.

The technological difficulties to achieve proper scaling makes it sometimes necessary to pulse the plasma-producing discharge. If the pulse-time is too short, only transient phenomena may have time to develop and a steady state is never reached.

The above consideration will now be applied to some specific experiments.

3. CONFIGURATION SIMULATION

The most typical configuration simulation experiments are perhaps the classical terrella experiments, aimed at simulating the entire magnetosphere and its interaction with the solar wind. This is very difficult, not only due to the large scaling ratio ($\sim 10^8$) but also because of the very great differences between the plasma parameters in different regions, from the cold, dense, weakly ionized E-layer to the hot dilute and fully ionized outer magnetosphere.

3.1 Terrella experiments.

The most ambitious experiments so far have been made at the USSR Institute for Space Research in Moscow (Podgorny and Dubinin, 1972, 1974; Podgorny et.al., 1973; Dubinin and Podgorny, 1974; Dubinin et.al., 1975). They have been able to simulate an impressive number of phenomena, such as the bow shock including the spectrum of magnetic fluctuations, the precipitation pattern of electrons with typical auroral energies, the tail, the plasma sheet, the polar clefts with the entry of magnetosheath plasma into the magnetosphere.

They have been able to achieve qualitative scaling in virtually every important respect except for the ion Larmor radius in the plasma wind, which is only slightly less than the terrella-magnetopause distance.

There is always an uneasy feeling of uncertainty about the applicability to space conditions of terrella experiments, as well as many others. However, Dubinin and Podgorny (1974) express an utterly sound philosophy which in a somewhat generalized form reads as follows:

The main objectives of terrella experiments are (1) to reproduce as many magnetospheric phenomena as possible, and (2), if the first objective is reasonably successful, to study and reveal the physics of the model phenomena in the hope that this will help our understanding of the corresponding space physics.

In a simplified way it has been said that the study of the magnetosphere can be divided into two epochs, the exploratory epoch which is practically over now, and the physics epoch which has just begun. The same can be said about the magnetospheric model experiments. The first objective mentioned above corresponds to the exploratory phase which has been successfully carried out by Podgorny and coworkers. The second objective, to understand the physics, must now be vigorously pursued in close cooperation between space observations and model experiments. Results from the laboratory can be tested in space. Corresponding phenomena in space and in the model may or may not be due to the same mechanisms. A continued space-model comparison should result in an earlier understanding of the physics behind the phenomena.

Fig 1. Power Spectrum For Magnetic Fluctuations. Dots Reproduce Results From Terrella Experiment Of Podgorny et.al. (1973). Curve Gives OGO-3 Results In The Bow Shock (Olson et.al., 1969) And Rings Give Spectra In The Magnetosheath (OGO 1).

Fig.2. Power Spectrum For Electric Fluctuations In The Shock Wave Of The Terrella Experiment Of Podgorny et.al. (1973).

Two results of the terrella experiments suggest a follow up in space. Podgorny et.al. (1973) found microfluctuations in the bow shock. The power spectrum of the magnetic fluctuation agreed fairly well with that measured in space (Olson et.al., 1969) as shown in Figure 1 where the ion gyro frequency is taken as unit of frequency, and the magnetic energy density as unit of energy density. The electric field fluctuation spectrum was also measured in the model (Figure 2) but remains to be measured in the bow shock in space.

The second result (Dubinin and Podgorny, 1974) of interest is that plasma intrusion into the magnetosphere occurs not only through the polar clefts but also through equatorial gaps around dawn and dusk. This may be much more significant in the model than in space, due to the relatively much larger ion gyro radii in the model. However, satellite experiments designed to check the importance of equatorial gaps in the magnetopause are desirable.

In view of the successful modelling achieved by Podgorny and collaborators it now seems more desirable than ever to pay attention to terrella experiments when planning satellite experiments. It even seems worth while for other research groups to begin new or resume earlier experiments (Danielsson and Lindberg, 1964, 1965; Kawashima, 1971).

3.2 Solar wind - nonmagnetized body interaction.

A non-magnetized body in plasma wind may simulate a comet, the Moon, Venus or any other non-magnetized planet, as well as a spacecraft. Interpretation is more uncertain here than in the case of terrellas, due to the more limited number of experiments. Many features observed at the Moon are reproduced by Andriyanov and Podgorny (1975), such as a Mach cone with increased magnetic field and decreased plasma density in the wake of a lunella or "venella" (small Venus). However, the large ion gyro radius causes too fast diffusion into the wake. The authors point out that, in the experiment, pressure balance across the Mach cone boundary cannot be accounted for by

magnetic field and temperature alone. A conclusion, not drawn by the authors, is that effects of the plasma flow geometry are important.

To simulate solar wind-Venus interaction Andriyanov and Podgorny use a wax ball which evaporates an extended atmosphere when hit by the plasma wind. The interaction with an artificial ionosphere can thus be studied. The decisive importance of the wind magnetization for creating a shock, seen as a well-defined interaction surface, is demonstrated. However, proper interpretation has to await much more detailed investigations.

Kristoferson (1975) has employed a slower but more fundamental approach by studying spectroscopically in great detail the "atmospheres" evaporated from solid obstacles made of different materials. Such studies may enable the best choice of venellas, lunellas, and so on.

Both Andriyanov-Podgorny and Kristoferson are aware of the importance of the critical ionization velocity effect for plasma-neutral gas interaction in this context. This is further discussed in section 4.4 below.

Experiments to simulate interaction between a plasma flow and a spacecraft have been made by Illiano and Storey (1974). Oran et.al. (1975 a,b) among others. These works will not be discussed in detail here. Their importance is obviously very great, and their interpretation is fortunately relatively simpler than terrella experiments because of the small scaling ratio and less inhomogeneous conditions. The main (certainly not unexpected) experimental result is an increased plasma temperature in the wake of the obstacle.

3.3 Neutral line and sheet experiments.

Bratenahl and collaborators have made a series of experiments designed to simulate substorms and solar flares under the assumption that these are associated with the formation of an x-type neutral line (Bratenahl and Yeates, 1970; Baum et.al., 1973 a,b,c; Baum and Bratenahl, 1973, 1975). Similar experiments with somewhat different results have been made by Ohyaabu et.al., (1974). These experiments may be regarded either as configuration or as process simulation, since a fundamental process occurring in a certain field configuration, most likely existing in space, is studied in the laboratory.

The experimental setups are shown in Figures 3 and 4. The magnetic field is created by parallel currents through one or more pairs of rods. An oppositely directed current flows through the plasma between the rods, i.e. along the neutral line or sheet. The two experiments differ in that Ohyaabu et.al. first excite the main magnetic field by discharge of a slow capacitor bank through four pairs of rods, then inject a plasma from an external plasma gun, and finally supply the neutral sheet current from a fast bank. Bratenahl et.al. use just one bank, discharged through one pair of rods in series with the neutral line plasma current that produces the plasma without aid of a gun.

In both cases a mode of normal plasma current conduction is followed by a mode of "anomalous resistivity" as seen from a vastly increased discharge voltage and decreased current. However, in the case of a neutral line with no pre-produced plasma (Bratenahl et.al.) the electron and ion temperatures remain low (a few eV), whereas the pre-produced plasma in the neutral sheet is claimed by Ohyaabu et.al. to be heated to a few keV.

Fig.3: Schematic View Of Neutral Line Experiment Of Bratenahl And Yeates (1970). Figure a: Side View Of Apparatus With Current Directions, Shaded Areas Indicating Insulator Sleeves On Conductor Rods. Figure b Shows Magnetic Vacuum Field (Top View) Around Conductor Rods Shown As Small Circles With Crosses.

Fig.4. Schematic View Of Neutral Sheet Experiment Of Ohyabu et.al. (1974). The Eight Conductor Rods Carry The Current In Parallel Towards The Left With The Rightward Return Current Through The Plasma Between The Rods.

Assuming that the Joule heating is balanced solely by heat conduction along the magnetic field one finds that in Bratenahl's case the heat conductivity would have to exceed the normal value (Spitzer, 1962) by about a factor 5000. In Ohyabu's case the conductivity must be reduced by a factor of at least $2 \cdot 10^5$. Although turbulence should reduce the heat conductivity, such a large factor seems excessive. Ohyabu et.al. have measured the temperature of plasma ejected sideways from the discharge. Hence, it seems unavoidable to conclude that the main discharge plasma is much colder than the ejected plasma.

On these grounds it seems rather difficult to interpret the results of Ohyabu et.al. In their case the high voltage-current ratio may possibly be due to anomalous electric and thermal resistivity, i.e. turbulence, but in Bratenahl's case double layers, which accelerate the particles without heating them (Block, 1975), are almost certainly built up. Baum et.al. (1973b) erroneously exclude this possibility on the grounds that the conductivity would be too low by five orders of magnitude. This is due to a fundamental mistake. Apart from an error in their "conductivity" formula (the Child-Langmuir law) they assume the layer thickness to be equal to the separation between the electrodes. One percent of that would be more appropriate and would fit the data very well.

It should be possible to discriminate between double layers and anomalous resistivity in these experiments by more detailed measurements of the electric field and particle velocity distributions.

4. PROCESS SIMULATION

The virtue of process simulation can be expressed in terms of the following rules:

- a) New theories should as far as possible be tested in laboratory.
- b) Theoretical processes which cannot or have not been reproduced in the laboratory should often be met with scepticism when applied to space plasmas.
- c) Most plasma processes observed in the laboratory are probably of importance in space.
- d) Proper application of a laboratory process to space conditions requires a theoretical understanding of its dependence on all plasma parameters and boundary conditions.

These rules may seem self-evident, but they are unfortunately not always obeyed, since too many theoreticians are not aware of the multitude of plasma phenomena not understood theoretically, and too many experimentalists are unaware of appropriate theories. There is of course at least a partial excuse: paper proliferation.

4.1 Wave-particle interactions

An enormous amount of wave-experiments have been made. Unfortunately, most of them lack measurements of particle velocity distributions. Theoretical values for the onset of various instabilities are usually based on Maxwellian velocity distributions. However, Jentsch (1976) has shown that the

limiting electron drift velocity for onset of the ion-acoustic instability can easily be increased by a factor 100 with suitably shaped, not unrealistic velocity distributions. Thus, velocity distribution measurements are mandatory for correct interpretation of wave-particle interaction experiments.

Boundary conditions may also cause difficulties. Theories considering infinitely extended plasmas may be irrelevant to laboratory plasmas confined by walls or to line and sheet currents in the ionosphere since some waves emitted by current-carrying particles may escape the plasma or interact with particles outside the current channel.

Apart from these general considerations I wish to draw attention to an experiment on large amplitude whistlers (Stenzel, 1975). In a very large magnetized quiescent plasma a whistler wave is launched. With sufficient amplitude non-linear wave particle interactions cause self-ducting, allowing the wave to propagate nearly undamped along the magnetic field. The importance of this effect both to natural whistlers and to the possibility of exciting controlled whistler waves from spacecrafts should be studied. Stenzel's experiment was in fact inspired by suggestions to launch whistlers from space-crafts.

W. Bernstein et.al. (1975) have set up a contrastreaming beam configuration consisting of a primary monoenergetic magnetically field-aligned electron beam (50 eV - 5 keV) which produces a secondary beam of back-scattered electrons. They observe emissions at $(n+1/2)f_{ce}$ and suggest that the same mechanism could produce the observed $(3/2)f_{ce}$ auroral emissions.

4.2 Anomalous resistivity and double layers.

For detailed reviews of anomalous resistivity and double layers see Block (1975) and Block and Fälthammar (1976).

In section 3.3 it was argued that neutral line experiments may in some cases be best interpreted in terms of anomalous resistivity, in other cases double layers seem to fit best into the picture. The basic difference between the two mechanisms is that anomalous resistivity leads to local heating, but double layers only accelerate the particles without heating them. Of course, the beam of accelerated particles may in some cases soon be dispersed, i.e. strongly heated, through beam-plasma interaction. In that case it may be very difficult to discriminate between the two processes.

Hundreds of experiments on both mechanisms have been reported in the literature. I therefore only mention one of each kind, not claiming that all other experiments are less important.

Fig.5. Potential Fluctuations Across Double Layers In Experiments Of Babic And Torvén (1974). Scales Are: Abscissa 5 μ sec/div, Ordinate, 100 Volts/div.

Babic and Torvén (1974) have studied fluctuating double layers. The potential drop across a double layer in a low-pressure discharge is usually fluctuating considerably (Figure 5). The fluctuations cause the double layer to disappear and reappear at rather regular intervals. The typical period for the fluctuations is about 20 ion plasma periods, i.e. the lifetime of a double layer and the time to recreate it is of that order. The spectrum of the fluctuations have not yet been measured by these authors but that should of course be done. It is obvious, however, that most of the power lies below the ion plasma frequency (about 10 MHz) but there is evidence that some radiation in the GHz-regime is emitted (Torvén, private communication).

An important observation is that if a metallic probe is inserted in the plasma, the double layer has a strong tendency to attach itself to the probe. To avoid this, capacitive probes on the outside of the discharge are used.

The strong double layer fluctuations may easily be mistaken for turbulence, but the basic difference is that the electrons are not appreciably heated, just accelerated in a linear fashion. Hence, it is not safe to draw conclusions just from measurements of potential fluctuations.

Hamberger and Jancarik (1972) have measured electrostatic fluctuations in a plasma that is supposed to be turbulently heated. They simply use an electric double probe, measuring the potential fluctuations between two points close together in the plasma. From the measured fluctuation spectra they draw far-reaching conclusions concerning the nature of the assumed turbulence. These may be correct or incorrect. The observational evidence is certainly valuable, but only as a relatively small piece among many other data, necessary for a reasonably safe interpretation. The fluctuations may be associated with a double layer attached to the probe.

Another possible interpretation is that they only see the transient formation of a double layer. The duration of their experiment, 250 ns, is not long compared to the formation time for a double layer. It should be sufficient for higher densities of hydrogen when the ion plasma frequency f_{pi} is hundreds of MHz, but for lower densities of argon with $f_{pi} < 100$ MHz the steady state may not be reached, provided it consists of double layer.

It should be pointed out that numerical computer experiments indicate a formation time for double layers of the order of one ion plasma period, i.e. much shorter than the time observed in the experiment of Babic and Torvén, mentioned above. For further details, see Goertz and Joyce (1975).

Fig.6. Equipotential Surfaces (In Principle) In The Neighbourhood Of A Double Layer. The $E \times B$ Plasma Drift Has A Stabilizing Effect On The Layer In Space. In Most Laboratory Double Layers The $E_{\perp}$ -Region Is Outside The Plasma And Hence Does Not Stabilize.

An ionospheric double layer is probably more stable than a double layer in a straight discharge tube (such as that used by Babic and Torvén) for two reasons. Firstly, if the cross section of the discharge tube is varying along the tube the double layer is stabilized at a point where the cross-section is small. Such a variation in cross-section can be achieved by an inhomogeneous longitudinal magnetic field. The analogy with a geometric flux tube is obvious.

Secondly, the large extent of the ionosphere transverse to the magnetic field means that the double layer equipotentials must be shaped as shown schematically in Figure 6. Thus, in the region where the equipotentials are parallel to the magnetic field there must be an appreciable amount of $\vec{E} \times \vec{B}$ -drifting plasma. The corresponding kinetic energy must have a strongly stabilizing effect on the double layer. In the laboratory the equipotentials simply spread out in plasma-free space outside the tube.

4.3 Differential pitch-angle distributions in magnetic mirrors.

Alfvén and Fälthammar (1963) and Persson (1963, 1966) showed that if the electron and ion pitch-angle distributions were different in a magnetic mirror field an electric field along the magnetic field must exist. The potential difference that can be maintained is of the order of the particle energy times the mirror ratio.

The most critical problem about this mechanism is the stability of the differential pitch-angle distributions. The plasma must of course be essentially collisionless, as is the case in the magnetosphere. Extremely great differences in the pitch-angle distributions have been observed in the magnetosphere (e.g. McIlwain, 1971, 1975) for keV-particles. However, if cold particles are included, the total pitch-angle distributions may be more alike for electrons and ions, although it appears that cold plasma is essentially absent during the presence of the keV-plasma clouds.

Consequently, laboratory experiments to test the stability of differential pitch-angle distributions with finite $E_{\parallel}$ are of great importance. Such experiments have been made by Hopfgarten et.al. (1972) and Geller et.al. (1974). Especially the latter show very convincingly how a finite $E_{\parallel}$ can be maintained, provided the plasma is sufficiently collisionfree in the magnetic mirror field and the density of cold plasma can be kept below about 1 % of the hot, anisotropic plasma density. Very good quantitative agreement with theory was obtained for both magnitude and distribution of the electric field.

The importance of this type of $E_{\parallel}$ in the ionosphere-magnetosphere system is probably much greater than has previously been realized (Block and Fälthammar, 1976). A very strong reason for that is that while the Birkeland-currents are confined in thin sheets the region with finite $E_{\parallel}$ must be much more extended due to the approximate validity of $\text{curl } \vec{E} = 0$. Hence a mechanism that can maintain $E_{\parallel}$ without a net current is needed. The mirror effect provides such a mechanism (Lennartsson, 1975).

4.4 Plasma-neutral gas critical ionization velocity.

Experiments by Angerth et.al. (1962), Wilcox et.al. (1964), Danielsson (1970), Danielsson and Brenning (1975), and several others have shown that if a plasma moves relative to a neutral gas with a velocity exceeding a certain

critical velocity v_c the plasma-neutral gas interaction is very much stronger than below that velocity. The rate of ionization increases by at least an order of magnitude at the critical ionization velocity defined by

$$\frac{1}{2} m_n v_c^2 = eV_i$$

where m_n and V_i are the mass and ionization potential, respectively, of the neutral gas atom. For a review of the experiments, see Danielsson (1973). A theoretical review was given by Sherman (1973). Among later work Raadu (1975) may be mentioned. Alfvén (1942, 1954) originally suggested its existence.

Hydrogen has the highest critical velocity, about 60 km/s. Most other common gases have critical velocities in the range 1-20 km/s. The effect must therefore be important for the interaction between the solar wind and comets and planetary atmospheres. It could also be important in the auroral ionosphere. At sufficient altitude in the low magnetosphere there should be no interaction due to lack of neutral gas. Hence the plasma velocity can exceed v_c . If the magnetic field lines are equipotentials, or more generally, if the generator of the Birkeland current system is in the magnetosphere, the plasma velocity E/B is decreasing with decreasing altitude. At some altitude where the neutral gas density is sufficient for the critical velocity effect, the plasma velocity relative to the neutral gas must be limited to v_c . Further down, the plasma velocity must be still lower. In fact, all measurements of $E_{\perp}$ in the E-layer have shown that $E_{\perp}/B < v_c$.

The strong interaction region is probably situated above the F-layer, since the experiments have shown that the effect is operating at surprisingly low densities. Very few collisions can trigger instabilities that heat the electrons, which can then ionize the neutral particles (Sherman, 1973).

The theory of the critical ionization velocity is far from complete. It is beyond the scope of this paper to go into further details. The purpose of including the critical velocity effect here is only to draw attention to it among magnetospheric and other space physics workers. It is certainly of great importance and has been overlooked.

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Royal Institute of Technology, Department of Plasma Physics,
Stockholm, Sweden

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The merits and limitations of experiments designed for
studies of:

1) solar wind interaction with magnetospheres (terrella
experiments) and non-magnetized bodies, 2) neutral lines
and sheets, 3) wave-particle interactions, 4) anomalous
resistivity, 5) double layers, 6) magnetic field-aligned
electric fields in strong magnetic mirrors, and 7) the
critical ionization velocity of a plasma moving through
natural gas, are discussed.

Key words Anomalous resistivity, Critical ionization velo-
city, Double layer, Electric field, Ionosphere, Laboratory
experiment, Magnetic field, Magnetic mirror, Magnetosphere,
Neutral line, Neutral sheet, Plasma Scaling, Simulation,
Solar wind , Terrella, Wave-particle interaction