ACTIVE AND LABORATORY EXPERIMENTS IN SPACE PLASMA PHYSICS

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Abstract. This report focuses on active experiments in space as well as laboratory experiments which are directly related to space phenomena. The active experiments involve particle releases in the CRESS and AMPTE missions. Unexpected results such as the motion of the plasma triggered several interesting computer simulations and a laboratory experiment which will be reviewed. Critical Ionization Phenomena will be discussed in this context. A recent release over Arecibo was used to create a “plasma lens” to focus radiation from the HF heater beam. The higher power triggered several nonlinear processes. Advances in plasma sources and diagnostics have made it possible to scale many laboratory experiments. Discussed here are experiments on Alfvén waves generated by a localized source, 3D magnetic field line reconnection, three dimensional magnetized double layers and simulations of a tethered satellite.

Key words: Active experiments, laboratory experiments, Ba releases, CIV phenomena, tethered satellite, Alfvén waves, double layers, laser target, magnetic field-line reconnection, whistler waves, cavitons, ionospheric modification

The modification of space plasma by the injection of chemical compounds is rather new, most experiments have taken place in the last decade. There is, however a history of terrestrial ionospheric modification experiments using high power radar facilities.1 Since the work of Langmuir2 many basic laboratory experiments have studied the linear properties of waves and a host of processes such as beam plasma instabilities, parametric decay, mode conversion and so on. In addition investigations of nonlinear effects such as wave filamentation and ducting, soliton formation, shock waves, particle trapping in waves and nonlinear saturation have been done, sometimes in great detail, in the laboratory. There is an ongoing effort to study Langmuir wave collapse and a great many laboratory experiments on caviton formation have been executed in the past, especially in the early 1970s.3 Although many (perhaps all) of these phenomena occur in space the body of experimental work has been, in general, passed over by the community of space oriented plasma physicists. One reason for this is that in the past, it was not always possible to scale combinations of laboratory plasma parameters to properly scale processes which occur in a specific region of space. We do not imply that it is possible to scale anything (such as the entire earth-ionosphere-magnetosphere) in a single experiment. But just as rockets are launched to study processes in a given region, a modern laboratory experiment can be designed to study the same processes in detail unavailable to rockets or satellites. Examples are the interaction with whistler waves with density striations and the formation of double layers.

The field addressed by this reporter review has become quite broad and outgrown the room necessary to give justice to both active experiments in space and terrestrial
laboratory work. We will therefore discuss some of the recent interesting work in both of these areas, and apologize for any omissions.

The active experiments to be reviewed are chemical releases of the AMPTE and CRESS missions. The former occurred nearly nine years ago. The AMPTE plasma cloud moved in an unexpected direction, and was subject to an instability which deformed it. The questions raised have generated interesting physics done only in the past few years. We will discuss this new work here. In addition a recent CRESS release was used in a novel experiment to focus a microwave beam launched from the ground.

Development of large, magnetized plasma sources\(^4\) have enabled studies of Alfvén waves and their filamentation has been observed. Double layers have been produced in the laboratory and studied for years in unmagnetized plasmas\(^5\); we will report on recent work in a magnetized case. We will also report on experiments on the critical ionization phenomena. This is relevant to chemical releases, and possibly processes which occur near the space shuttle and rockets. We will review an experiment in which a plasma source developed for use in Thermonuclear Fusion was modified to study three dimensional magnetic field line reconnection. Finally a series of experiments on the collection of currents to electrodes placed on different magnetic field lines may predict what will occur when a tethered satellite is deployed for electrical power generation.

1. Chemical Releases

The idea behind active experiments in space is to disturb the environment in a known way, and from the response learn more about the plasma physics of that region.\(^6\) This could be a first step toward plasma utilization or control. One such release, which received much publicity was the "Christmas Comet", part of the AMPTE (Active Magnetospheric Particle Tracers Explorer) mission. The series of releases took place in 1984–85 and was an international effort. The "Christmas Comet" was launched on December 27, 1984. The Barium cloud which was rapidly (30 sec) ionized by solar radiation was observed by aircraft. A small fraction, less than one percent of the ions, are produced by Critical Ionization Phenomena.\(^7\) We will have more to say about this later on. The satellite from which the two Ba canisters were released had instruments which measured magnetic field, plasma density and particle energy spectra. One of the canisters was fired away from the craft which then overtook the Ba plasma it produced. Magnetic probes detected the plasma formed diamagnetic cavity, magnetic field expelled from the cloud, a precursor signal, and evidence for surface currents on the cavity. The initial motion of the cloud was in an unexpected direction. Instead of moving with the solar wind the cloud moved transverse to it in a direction antiparallel to the solar wind electric field. This is illustrated in Figure 1.
Although the release promised to shed light on the behavior of comets, the initial $V_{sw} \times B_{sw}$ ($sw =$ solar wind) drift direction and early disintegration was the “hot topic”. A snowplow model by Chapman underscored the importance of a hybrid description of the plasma and momentum transfer.

The problem was attacked by the UCLA simulation group which developed a fully three dimensional code. The electrostatic code treats the electrons as a fluid and the ions kinetically. It models the solar wind at 8.4 million spatial locations, and a Li or Ba release at 250 thousand initial positions on a grid. The simulation was run at the Cornell supercomputer center using an equivalent of 2 CPU years and 1 Gbyte of ram memory. (The code actually was highly parallelized and used twelve processors.) The gross motion shown in Figure 1 was simulated. In addition the simulation showed that a jet of ions, postulated by Harendhel, emanated from the release and was responsible for its sideways motion. The simulated Ba cloud, draped magnetic field is shown in Figure 2.
Fig. 2. Simulation results of artificial comet. The comet shown in the center is moving through the IMF shown as parallel rods. The field is highly distorted in the vicinity of the comet. Ions jetting from the comet which are responsible for its skidding are seen in other views. For color reproduction of this figure see color section, p. 488.

Parameters:

\[ V_o = 1 \text{ km/s} \]
\[ \rho_i = 230 \text{ km} \]
\[ R_b = 230 \text{ km} \]
\[ \lambda_4 = 40 \text{ km} \]

Plasma Regime:

Large Larmor radius
\[ (\rho_i >> L_n \sim \lambda) \]
Sub-Alfvenic
\[ (M_A = 10^{-2}) \]

Fig. 3. Evidence of an instability in the Large Larmor Radius (LLR) or Hall MHD instability in a photograph of the AMPTE Ba release. For color reproduction of this figure see color section, p. 488. (from P. Bernhardt et al, J. Geophys. Res. 92, 5777 (1987)).
LLR DEVELOPMENT (LATER)

$B = 5 \text{kG}$; Al target; $V_0 = 6 \times 10^7 \text{ cm/s}$ [Shot # 89-0567]

Instability Remains Robust and Becomes Erratic

Fig. 4. Laser-Target experiments which simulate the LLR ripple instability. A single shot sequence of four images of the instability development. The target was irradiated from the right hand side. The dark circle in the center is due to light blocked by a solid shield. The two straight objects coming from the top are magnetic probes.

2. Modeling of Instability during Ba Release

The AMPTE experiments have also triggered an experimental and theoretical program at the Naval Research Laboratory (NRL). A photograph taken of a Ba release from the Active Magnetospheric Particle Tracer Experiment is reproduced in Figure 3. It shows the cloud is unstable with respect to density clumping. As indicated in the figure the Ba$^+$ gyroradius is roughly the size of the cloud and its drift is sub-alfvenic. These conditions are satisfied in a laser (Nd-glass, $30 \text{J}$, $10^{13} \text{ W/cm}^2$) target (Al $2\mu\text{m}$, $Z_{\text{eff}} = 10$, thick $1 \text{ mm}$ dia) experiment. The plasma density next to the target ($1.0 \times 10^{14} /\text{cm}^3$) and the background magnetic fields employed ($1 - 1.0 \text{ T}$) are many orders of magnitude higher than those in space ($n_{\text{Ba}^+} = 10^5 /\text{cm}^2$, $B = 10 \text{ nT}$). The plasma expansion velocity is $6.2 \times 10^7 \text{ cm/sec}$ which makes the flow sub-alfvenic. The density scale length, $L_n$, is $1.0 \text{ cm}$. For these parameters the laboratory interaction region is ten centimeters instead of several
term set to zero no instability was observed. The development of this theory will be useful in modeling like regimes in the laboratory and in space. One of these is the reconnection region in the Earth's magnetotail.

An alternate formulation of the theory of this instability has been done by Winske. In this work the free energy for the instability is provided by a relative electron-ion cross field drift which occurs because the plasma is decelerating and a density gradient induced drift. Under different conditions these terms can add or subtract but in any case the instability growth rate is near the lower hybrid frequency. A computer simulation of an expanding plasma cloud, in a background field in which the electrons are magnetized, but ions are not, produces flute structure similar to those in Figure 5.

3. Particle Releases as Wave Focusing Tools

Until this year all particle releases in space were initiated to study the expanding test plasma and its effect on the background plasma. A novel experiment was performed in May of 1992 in which a particle release was used to form a "plasma lens" and subsequently focus ground based microwaves. Thirty kilograms of CF$_3$Br
Fig. 5. Simulation by Huba et al. of CREEES G10 mission. The released mass was 5 kg of Ba in an ambient field of 135 nT at 5 earth radii. The Alfvén Mach number is 0.1. Computed density and magnetic field is shown at four times after the release. For color reproduction of this figure see color section, p. 489.
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was released in the F region within 5 km of the center of the Arecibo HF heater beam. The geometry for this experiment is shown in Figure 6. The chemical release resulted in the formation of an ionospheric hole. The plasma density was reduced due to dissociative attachment and the subsequent recombination of Ba\(^+\) and O\(^+\). The processes was effective enough\(^{20}\) to produce a density cavity 30 km in diameter and densities of order 1/4 the ambient density (4 \times 10^4/cm\(^3\)) in that region (300 km). The density cavity was used as a lens to focus the 5.1 Mhz (HF) Arecibo heater radar. This enabled the effective radiated power to be increased from the nominal 50 MW to an astounding 5 GW! The wave fields were strong enough to drive nonlinear processes. The diagnostics consisted of Langmuir probes, DC to 10 MHz electric field probes and an electron energy analyzer mounted on a rocket. The rocket was timed to travel through the perturbed region (Figure 6). Other diagnostics included a 430 Mhz ground based radar.

The local plasma density was measured by Langmuir probes on the rocket. Before the rocket reached the cavity the plasma density as a function of time (rocket height) reflected the rocket spin and fine scale irregularities associated with the Arecibo heater. When the rocket entered the intense field region, very narrow microcavities were observed. This is shown in Figure 7a. The cavities are as small as 1 meter across (\(\lambda_{dc} \approx 5\) cm, \(R_{ce} = 3.5\) cm, \(R_{ci} = 6\) m) and were formed by the action of the HF wave. The rocket provided in situ measurements of the spectrum of the electric fields in this region as displayed in Figure 7b. The upper insert is the high frequency plasma wave spectra, the lower depicts lower frequency electric fields presumably associated with ion acoustics waves. The waves are observed to be coincident with the cavities, This is strong evidence for parametric decay\(^{21}\) of the electromagnetic pump into a an electron plasma (Langmuir) wave and an ion acoustic wave. Incoherent backscatter data at 430 MHz corroborated the rocket observations. The authors\(^{16}\) conclude that the data is consistent with Langmuir waves trapped in field aligned density cavities\(^{22}\) and not strong Langmuir turbulence.

The regime in which these experiments have been undertaken is one in which the ion Larmor radius is of the order of the density striation width. This interesting regime has not been, as yet, fully explored in the laboratory. There have been extensive laboratory experiments in which electromagnetic radiation has been incident on a density gradient on which \(f_{\text{radiation}} = f_{\text{pe}}\). Some of the effects observed in great detail were mode conversion and electric field enhancement,\(^{23}\) the generation of density cavities and ion acoustic waves, fast ions, and electrons,\(^{24}\) and magnetic field generation.
IFH ROCKET DATA NEAR 5.1 MHz REFLECTION

$N_e \times 10^5 (\text{cm}^{-3})$

1.2
1.6
2.0
2.4
2.8
3.2
3.6
Fig. 7.  a. Electron density measured by a Langmuir probe on the IFH rocket. Density fluctuations are evidence of a) rocket spin (b) microcavities (c) spikes (d) and heater induced cavities. The time indicated is time after launch. b. Measured spectra of Langmuir waves near 5.1 MHz and ion acoustic waves by electric field probes on the IFH rocket. The data indicate that the waves are trapped inside the density cavities. For color reproduction of this figure see color section, p. 490–491.
LABORATORY EXPERIMENTS (1960-1987):

Fig. 8. A comparison between the theoretical critical ionization velocity, $V_c$, and the measured $E/B$ values from discharge experiments. The shaded boxes correspond to different gases and are centered at the theoretical value $V_c$. In order of increasing values of $V_c$ the gases are Xe, Kr, CO₂, O₂, Ar, CO, NH₃, H₂O, Ne, D₂, He, and H₂.

4. Critical Ionization Velocity Phenomena

The CIV effect was proposed by Alfvén over thirty years ago. He postulated that if the relative velocity of a plasma and a neutral gas exceeded

$$V_{\text{crit}} = \sqrt{\frac{2eU_i}{m_n}}$$

there would be a strong increase of the ionization rate of the neutrals $n$. Here $U_i$ is their ionization potential. In the past decade there has been a great deal of laboratory work, and theory on this topic. Much of this is condensed in recent review paper. Although the concept is simple the physics of what occurs during this process is not. The process has been verified in the laboratory using homopolar devices. These machines have crossed electric and magnetic fields so that stationary neutrals within them may interact with drifting ions. Figure 8 compares $V_{\text{crit}}$ with the measured $E/B$ ion drift velocity in which CIV was observed. The experiments were conducted using a variety of different neutral gases and performed by three different groups. For the most part the experimental values for $V_c$ lie within 50% of the theoretical ones. It has been established that the parameter $V_A/V_{\text{neutrals}}$ ($V_A$ is the Alfvén speed, $V_{\text{neutrals}}$ that of the neutral gas) must be much greater than 1 to
Fig. 9. One component of the magnetic field of the shear Alfven wave received at three different axial positions \(z \parallel B_0\) from a disk exciter. The exciter radius is four \(R_{ci}\) (He). A phase point may be tracked and the wave phase velocity approximated as shown.

Observe strong ionization. The effect is weak when \(V_A/V_{neutral} \approx 1\) and does not occur when the ratio is less than 1.

Successes in this area have not been duplicated in space. A place to look for CIV is the chemical release experiments. After the canisters, which are traveling at the satellite orbital velocity, are detonated one would expect a period in which the neutral velocity is high with respect to that of the background ions. CIV should occur within 5 km from the release.\(^{27}\) There are competing processes such as photoionization so these experiments are best done in the earth's shadow, below the solar UV terminator. The highest CIV ionization (28%) was seen in the Porcupine experiment.\(^{28}\) This was followed by the Star of Lima experiment.\(^{29}\) The star of Lima which was supposed to be favorable for CIV turned out with a lower yield (less than 1%). Two more releases (CRIT I and CRIT II) which were done in nearly identical circumstances had mixed results. The critical ionization yield was small in the former and comparable to Porcupine in the latter. It is believed that both high yield experiments had a larger background electron density at injection. Finally two recent experiments which were part of the CRESS mission released Ba.\(^{30}\) The first produced a 0.14%, the second 0.4%. These experiments were well diagnosed but the reasons for "shot to shot" variations are not apparent.
Spacecraft experiments are hard to interpret because of the complex situation in which they were conducted. Aside from CIV there are other processes which can result in ionization. They are charge exchange, stripping (or associate ionization), dissociation by solar UV, collisions with atmospheric neutrals and thermal ionization from the initial release. Furthermore the physics of how CIV occurs is not understood. Hot electrons were observed in the cases in which CIV was enhanced (such as in the second CRESS release). Do the hot electrons come from the CIV process or another instability? Are wave particle interactions necessary for CIV to occur? How is momentum exchanged in the process, and so on. This might be an area where more laboratory experiments could come into play. Some of the physics issues could be explored with Laser Induced Fluorescence and Optical Tagging.\textsuperscript{31} This powerful, non perturbative diagnostic can trace ions and neutrals and measure particle distribution functions.

5. Alfvén Waves Studies

A series of preliminary experiments and a theoretical investigation of Alfvén waves have been initiated in the LAPD (LArge Plasma Device) at UCLA.\textsuperscript{32} The LAPD machine\textsuperscript{33} is a flexible and low maintenance device for studying a variety of waves and nonlinear effects in fully magnetized plasmas. The plasma column is 50 cm in diameter and 10 meters in length. The magnetic field is controlled by seven independent supplies which allow tailoring the axial magnetic profiles to be a uniform, converging, bumpy or mirror geometry. The maximum DC axial field is 2.5 kG which makes for 500 R\textsubscript{ci} across the column in He.

The plasma is produced by a DC discharge driven by an oxide coated cathode. This type of plasma has proven to be quiescent ($\delta n/n \approx 5\%$), and oxide coated cathode sources are stable for long periods of time ($\approx 8$ weeks) giving plasma discharges which are very reproducible from shot to shot. The plasma (H, He, Ar, Xe, Kr, Ne or any mixture) can be moderately high in density ($n \leq 5 \times 10^{12}$/cm$^3$). Highly ionized Helium plasmas (percentage of ionization $\approx 99\%$)\textsuperscript{34} have been achieved. The discharge is pulsed at 1 Hz to allow for efficient signal averaging and data processing. The plasma is diagnosed using a completely internal probe drive capable of moving, under computer control, an assemblage of magnetic and electric field sensors to any position within the plasma volume.\textsuperscript{35}

Alfvén waves are of fundamental interest in space plasmas since they are responsible for communicating information about changes in magnetic fields and current systems in magnetized plasmas. Bounded Alfvén modes have been studied in fusion related and basic physics experiments.\textsuperscript{36} Recent studies of both the shear and compressional mode were done in a narrow, partially ionized column.\textsuperscript{37} Wave propagation and polarization were measured but damping by neutral particles greatly changes the dispersion from the fully ionized case. Experiments related to
these since they used localized sources, but done at much higher neutral collision frequencies have been done in linear\textsuperscript{38} and toroidal\textsuperscript{39} machines.

In the LAPD device the waves were launched with a small (4R_{ci} \leq a \leq 8R_{ci}) disk of transparent wire. Figure 9 is raw data of a 3 cycle tone burst (f/f_{ci} = 0.63) received at three spatial locations from the exciter. The wave phase velocity is measured by tracking a phase front as shown. For the shear wave the measured phase velocity, V_{M}, is related to the Alfvén velocity by

\[ V_{M} = V_{A} \sqrt{1 - \frac{f^2}{f_{ci}^2}} \quad (6) \]

By varying the frequency and measuring the wave fields as a function of axial position a dispersion relation for the shear wave may be generated. This is shown in Figure 10.

Of fundamental interest is how the waves are excited. Antennas used in heating experiments, for fusion, generally surrounded the plasma and column modes were produced. An important issue for space plasmas is how does a local fluctuation in current, or magnetic field generate a wave? An equivalent question is: What is the Green’s function plasma response? The small disk exciter of radius a, produces a
Fig. 11. (a) Model for the generation of Alfvén cones. The disk exciter radiates waves which propagate outward in cones. There is a null in wave activity in the center ($r = 0$), an interference pattern between waves originating on opposite edges of the disc and a $1/r$ dependence of $B$ past the edge of the Alfvén wave current channel (b) Measured radial dependence, in $r/a$ where $a$ is the disc radius, of the wave magnetic field. The dotted line is theory which includes Landau damping and collisions with neutrals. for $T_e = 4.0$ e.V. and density $1.0 \times 10^{12}$ cm$^{-3}$, $p = a/\delta$ and an electron neutral collision frequency of 350 kHz. The waves are low amplitude with $\delta B/B \approx 2 \times 10^{-3}$. 
field aligned rf current, which in turn radiates the waves. Theory for this process predicts the Alfvén waves radiation pattern to be conical as shown schematically in Figure 11a. The Alfvén wave current lies within radius \( r_c \) given by:

\[
    r_c = \frac{z k_A}{k_s} + a; \quad k_s = \frac{\omega_{pe}}{c}, \quad k_A = \frac{2\pi}{\lambda}
\]  

(7)

The inverse skin depth is a consequence of kinetic theory and sets the scale size of the cones. For this experiment \( c/\omega_{pe} = 3.8 \text{ mm} \). A comparison with theory is shown in Figure 11b which is the rms. value of \( B_{\text{wave}} \) as a function of radial position \( (r = 0 \text{ is the center of the disk}) \). The wave amplitude is zero at \( r = 0 \) and maximizes at \( r > a \). The pattern then drops off as \( 1/r \), as if the wave current is contained in a wire whose radius increases with \( z \). The dotted curve is the theoretical prediction for which both Landau damping (the wave under these conditions has a parallel electric field) and the effects of collisions with neutral particles. The measured wave polarization beyond the current channel edge is observed to be azimuthal. The phenomena of current channel spreading along Alfvén wave cones could have important consequences in several areas of plasma physics. One of these is in the
Fig. 13. Geometry of two merging spheromaks. Shown are cases in which the currents and toroidal magnetic fields within both merging plasma tori are parallel (cohelicity case) and antiparallel (counterhelicity case) before (13b) and after (13c) reconnection. Note that when view end on (13a) both cases appear the same and look like the standard neutral sheet merging model.

auroral ionosphere where the skin depth ranges from 100 m at several hundred kilometers to over a kilometer at altitudes above 5000 km. Current channels of this skin depth size are commonly observed in the auroral regions. If these currents fluctuate at frequencies below fci, the Alfvén waves they radiate will move across the ambient magnetic field. The origin and nature of magnetic fields detected by rockets could be misinterpreted.

Equation 7 indicates that as a → ∞, the pattern will become a plane wave and the waves go over into an MHD picture. This in fact may not be the case. Data from a line source indicated that the wave breaks up into a filamentary pattern as shown in Figure 12. Each filament shown moves through the plasma at the Alfvén speed and is associated with a wavelength which satisfies the shear mode dispersion relationship. This complex pattern may be in part caused by nonuniformities in the plasma or reflections from the end of the device. It is also possible that an extended source behaves as a collection of smaller sources each of which radiate a pattern such as shown in Figure 11b. These effects are under active investigation. If these waves are subject to filamentation in the linear regime one must rethink the behavior of Alfvén waves in space plasmas.
3D Reconnection
Yamada et al.  Phys Fluids 1991

poloidal flux contours

$t = 30 \mu sec$
$t = 35 \mu sec$
$t = 40 \mu sec$
$t = 45 \mu sec$
$t = 50 \mu sec$

Co-Helicity Merging  Counter-Helicity Merging

Fig. 14. Evolution of poloidal flux contours derived from magnetic probe data for cohelicity and counterhelicity merging. The plasma parameters are kept identical for the two cases.
Fig. 15. The measured reconnection rate as a function of approach velocity for merging spheromaks. Cases for two methods of spheromak production z−q (electrical breakdown) and gun injection are shown.

6. Magnetic Field Line Reconnection

One topic which has been of great interest to space plasma physicists for decades is magnetic field line reconnection. First invoked by Giovanelli\(^1\)\(^4\) and Hoyle\(^2\)\(^2\) to explain the origin of fast particles responsible for solar flares, it is now thought to be of considerable importance not only close to the sun but also in the Earth's magnetotail, the bow shock and in substorms. There is a body of laboratory experiments on this subject. Some early work with fast pinches\(^3\) were collision dominated and difficult to diagnose but nevertheless intriguing. A series of experiments in a well diagnosed experiment at UCLA\(^4\)\(^4\) explored many features of magnetic field line reconnection in a plasma in which the electrons were magnetized and the ions were not. This is the LLR regime discussed in the particle release experiments. A novel set of ongoing experiments are exploring reconnection in the regime where the ions are fully magnetized. To this end a spheromak,\(^4\)\(^5\) built to study new confinement ideas for Fusion, was modified to study basic physics. The spheromak density and magnetic fields are far higher than in space (\(n \approx 5 \times 10^{14} \text{cm}^{-3}, B_t = 1 \text{ kG}, Te\)
- 5–15 eV, β ≤ 20%). The magnetic Reynolds number is of order 300. Without dwelling on the mechanics of plasma production, the group produced two toroidal plasmas, one above the other (Figure 13), and with external field coils forced them to merge. Each spheromak (plasma torus) has both toroidal and poloidal current and magnetic field. When viewed in cross section (Figure 13a) the antiparallel (poloidal) field lines assume the classical X point topology. The spheromak plasmas can be constructed such that the toroidal component of the current is parallel or antiparallel to the toroidal field. The two spheromaks can thus have the same or opposite magnetic helicity, K, before merging.

\[ K = \int A \cdot B dV = \pm c \varphi_s \psi_s \]  \hspace{1cm} (8)

Where A is the vector potential, c is a profile factor, \( \varphi_s \) is the toroidal flux and \( \psi_s \) the poloidal flux. The experiment is diagnosed with an array of 35 magnetic probes used to map one r-z plane of the device. Azimuthal symmetry is assumed. Figure 14 shows a time history of the magnetic field lines, \(^{47}\) generated from the probe data, for the case where the helicities are parallel (\( I_1 \parallel B_1 \)) for both spheromaks the merging is not as efficient as the counter helicity case where the plasmas completely merge. The counterhelicity plasmas merge violently and large amplitude oscillations were observed. The collision velocity, \( V_i \), of the two spheromaks was controllable in these experiments. Figure 15 displays the reconnection rate, \( \gamma \), as a function of \( V_i \). Clearly \( \gamma \) is linearly dependent on \( V_i \) which underscores the importance of driven reconnection. Finally the reconnection rate was observed to depend upon the merging angle of the field lines being most effective at 180°.

7. Magnetized Double Layers

Double layers are transitions in the plasma potential which are many Debye lengths across. They are usually not attached to boundaries although they may be profoundly influenced by them. They are one explanation for the generation of fast electrons on Auroral field lines. \(^{48}\) These structures have been well established in the laboratory where initial detailed work was done in unmagnetized plasmas. \(^{49}\) Subsequently there have been a number of interesting studies in magnetized plasmas. \(^{50}\) A recent work \(^{51}\) involves a two dimensional mapping of the plasma potential in magnetized double layer experiment. The work was executed in a triple plasma device (Ar, \( T_i < 0.1 \text{ eV}, T_e \approx 3 \text{ eV}, n = 2 \times 10^8/\text{cm}^3 \)) with an axial magnetic field strong enough to confine the argon ions (20 Larmor radii across at \( B = 360 \text{ G} \)). A schematic of the device is shown in Figure 16. RF sources produce plasmas at either end which are separated by double grids. With no axial magnetic field, and the grids biased to produce counterstreaming ions and electrons a single double layer is produced in the center as in the work by Leung. \(^{496}\) When the field is raised to 200 G the potential structure, as measured with an emissive probe, exhibits multiple double layers.
DOLI II Triple Plasma Device

Fig. 16. Schematic of device used to study magnetized double layers. The end chambers contain rf produced plasmas. These can be injected into the central target chamber with the use of grids. The target chamber is surrounded by coils which produce an axial magnetic field.

Axial symmetry begins to disappear as shown in Figure 17. Features observed here are the formation of multiple double layers along a given field line. The potential drop along each is less than $\kappa T_e$. By varying the axial magnetic field it was found that the perpendicular scale length of the double layers was proportional to the ion gyroradius, but the parallel scale lengths were not. The radial ($\perp B$) electric fields were measured to be stronger than the parallel ones which implies that the structures are probably fully three dimensional. It is not clear what was responsible for their shape; there was no obvious counter structures on the ends or walls of the device. It will take careful experimentation to discover these subtle influences. A consequence of this work is that the potential structures in the Aurora could be fully three dimensional as well.

8. Laboratory Simulations of a Tethered Satellite

A fundamental consequence of Maxwell's equations is that a potential difference is developed along a wire if it is perpendicular to and moves at right angles to a magnetic field. This has been proposed as a mechanism for generating electricity on space craft which orbit the Earth. An insulated wire is tethered to the shuttle and a small conducting satellite at the other end serves as one arm of a homopolar
Fig. 17. Plasma potential data in a plane obtained with a movable emissive probe. Ovals drawn indicate the position of double layers. The potential on each contour is in Volts. The lower insert is a surface plot of the above with perspective contours.
generator. The significant difference between the physics textbook problem of a conductor sliding along parallel rails threaded by a magnetic field and this is that the plasma must carry the current, and somehow the current must close. A simple model is that the current flows along the Earth’s field lines and closes in the collisional ionosphere. This leaves out the contribution of plasma waves, current closure across a magnetic field and nonlinear effects. A moving electrode is very difficult to build. To investigate this a series of laboratory experiments utilizing pulsed currents to electrodes which are not on the same magnetic field lines have been performed at UCLA.52

The experimental configuration is shown in Figure 18. The plasma source is a one meter diameter oxide coated cathode53 which produces a uniform plasma in a constant background magnetic field of 20G. The experiment is performed in the quiescent, current free, afterglow plasma which occurs when the ionizing electron beam from the cathode is switched off. A small, 1 cm diameter, cathode is positioned near \( L_{\text{ether}} = 12 \text{ cm across } B_0 \) a collector which are electrically connected to each other but floating with respect to the plasma chamber and source. Data is collected by three orthogonal magnetic field loops which may be moved anywhere within the interaction volume. The signals are collected by digitizers and volumetric data is stored on a minicomputer.

Since the source density is much higher than that in space the plasma diameter corresponds to 2.5 km and the probe separation to \( \approx 300 \text{ m} \). The electrodes are many electron Larmor radii apart \( (R_e \approx 2 \text{ mm}) \); the ion Larmor radius is large compared to \( L \), and the currents are carried by the electrons. This is the Hall MHD (or LLR)
regime where magnetic disturbances are carried by low frequency whistler rather than Alfvén waves.

It is observed that the currents close, across B, fairly close to the tethered electrodes. Figure 19 shows the three dimensional current 0.4 $\mu$s after the current system is pulsed on. The lines calculated from $J = 1/\mu_0 (\nabla \times B)$ have been color coded to aid the eye. The current flows along nested right hand polarized helices which join via cross field Hall currents. The structure moves along the magnetic field at the whistler speed. The insulated tether is also observed to induce plasma eddy currents when pulsed on. A moving tether, therefore, would generate a "whistler wedge". These experiments indicate that in the proposed tether experiments in space the current can close several tether lengths from the contactors. The enclosed flux, and induced voltage, would be much smaller than if closure occurred in the remote ionosphere ("phantom loop"). Modulation of the short current loop would not be very effective for exciting VLF waves.
9. Summary and Conclusions

We have reviewed several active experiments and a number of laboratory efforts directly related to phenomena which occur in space. What is evident here is that controlled experiments have a great deal to offer to the space physics community.

When a phenomena has been identified by a spacecraft and the basic physics of it is not well understood, the laboratory is the ideal place to study it. The problems encountered in space observations of single point measurements and nonrepeatability are overcome in the lab. A well planned experiment can be carefully tailored so that it is repetitive in space and time. Plasma laboratory technology has advanced to the point that many experiments pertinent to space plasma phenomena can be performed. In wave studies, for example, waves can be made linear or nonlinear by the turn of an amplifier knob. These waves can be launched from one or more antennas and their fields mapped in the near and far zone. Beams can be introduced from localized sources, density non-uniformities can be repeatably be produced, impurities added in known amounts at a given location, and plasma drifts created. Furthermore, measurements at thousands of (three dimensional) spatial positions and thousands of timesteps during the interaction can be acquired. This is all impossible in space.

Laboratory experiments can address both local and global physics issues (the latter is often determined by boundaries). In some cases, one can comprehensively analyze physical phenomena simultaneously from both global and local points of view. Finally, experimental devices may be rapidly configured to perform new experiments as ideas are developed. This can happen on the time scale of days or weeks, as contrasted with many years for satellites and several years for rockets. Laboratory hardware is reusable and flexible. Many different experiments can be performed on the same machine. What is called for is a dialogue between space plasma physicists and their laboratory counterparts. This would only serve to enrich the entire field.

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Notes


44. (Titles have been left on these references to illustrate the topics explored):


Parameters:

\( V_0 \approx 1 \text{ km/s} \)
\( \rho_i \approx 230 \text{ km} \)
\( R_b \approx 230 \text{ km} \)
\( \lambda_i \approx 40 \text{ km} \)

Plasma Regime:

Large Larmor radius
\( (\rho_i \gg L_n \sim \lambda) \)
Sub-Alfvénic
\( (M_A \approx 10^{-2}) \)
By $t = 44.00 \, \text{us}$

Fig. 12, p. 473.

$J(r)$ lines

$t = 100 \, \text{ns}$

Fig. 19, p. 481.