NATURAL PRECEDENTS
TO ACTIVE MAGNETOSPHERIC EXPERIMENTS

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Many proposed active experiments in the magnetosphere have naturally occurring analogues. Energetic charged particle injections occur during substorms. Lightning-induced whistlers provide wave injections. The "detachment" of plasma from the plasmapause is equivalent to light ion seeding in the outer magnetosphere. Understanding the behavior of these phenomena is essential for proper planning of the associated active experiments. Furthermore, these phenomena provide a range of conditions unlikely to be duplicated in active experimentation and hence complement these experiments.

An examination of wave generation in detached plasma regions, the analogue of proposed plasma seeding experiments, reveals the generation of ELF electromagnetic noise when the energetic electron exceeds the stably trapped limit, but also indicates that a critical dimension for the seeded volume exists transverse to the geomagnetic field.

1. Introduction

Most active magnetospheric experiments now being performed or planned attempt to modify the magnetospheric plasma by injecting charged particles or waves. In this approach the experimenter can to some extent control the parameters under which the experiment is taking place, and hence these experiments approach the situation in the laboratory. There are three general classes of injection: cold (or thermal) plasma; energetic particles, usually in the form of a beam; and waves of various frequencies. Each of these types of injection has a naturally occurring counterpart which duplicates at least some of the physical conditions occurring in the artificial injection region. The advantage of these naturally occurring analogues over the artificial experiments is that they require no large experimental apparatus to be developed, and thus are less expensive and are available now.

In this paper we survey these natural precedents to active experiments, discussing their relative advantages and disadvantages. After this general overview we concentrate on one of these precedents showing what can be learned in an in-depth study.
2. Active Experiments and their Precedents

2.1. Heavy Ion Clouds

The most frequently performed active experiment in the last decade was the release of clouds of heavy ions, usually barium, into the magnetosphere. These releases have been made principally in the ionosphere but have also included an injection from a rocket at $5R_e$ (earth radii) [1] and a release from a satellite, HEOS-1, at $12.5 \ R_e$ [2]. The primary purpose of these experiments is to measure electric fields by observing the drift of the ionized cloud across field lines. There is no close natural analogue to barium injection in the magnetosphere. However, there are injections of light ions into the magnetosphere, either as a consequence of the “detachment” of plasma from the plasmasphere [3], or of the energization of plasma as the result of substorm processes [4]. These newly injected plasma clouds then drift around the earth under the combined action of the magnetospheric electric and magnetic fields and their distribution has been used to infer electric field patterns [5].

2.2. Acceleration of Heavy Ions

More recently, shaped-Ba charges have been used to generate plasma jets with velocities of several km s$^{-1}$, permitting field lines to be traced for up to altitudes of $3 \ R_e$ [6]. This “painting” of field lines, in addition to providing a measure of the electric field over a wide range of altitudes, can also be used to study point conjugate studies at low latitudes [7, 8]. Although no strict natural analogue of the shaped-charge injection has been observed, the discovery of large fluxes of energetic O$^+$ ions [9] suggests the possibility of the existence of O$^+$ ion beams accelerated from the ionosphere in parallel electric fields associated with auroral arcs.

2.3. Acceleration of Light Ions

Two of the principal instruments being studied for inclusion in the Space Shuttle AMPS (Atmosphere, Magnetosphere and Plasmas in Space) payload are a plasma gun and an ion accelerator [10]. The plasma gun would generate a plasma with an energy of 10—1000 eV. It will be used to heat the ionosphere and produce artificial aurorae. The natural analogue of this experiment occurs in the polar cusp region. The ion accelerator will generate ions up to 10 keV and will be used to generate magnetosonic and Alfvén waves. Sharply field-aligned ion fluxes with a maximum flux in the normal “loss cone” have been detected at synchronous orbit [11]. Studies of these beams could provide information on the stability of the proposed ion accelerator beam.

2.4. Acceleration of Electrons

Accelerated beams of electrons have been used to measure magnetospheric electric fields, to trace field lines, and to study magnetospheric wave-particle interactions. The two principal rocket-launched experiments were the artificial aurora experiment [12, 13] and the electron echo experiment [14]. The main
magnetospheric analogue of these experiments is the "inverted V" event seen over the auroral oval [15]. Another analogue is the energetic electron cloud accelerated during substorms and observed to drift around the earth [16]. We note that energetic electrons have historically been used as indicators of the boundary between the closed magnetosphere and the open polar cap. However, only when a solar electron event is in progress and when the loss cone can be resolved can this identification be made truly unambiguous.

2.5. Injection of Waves

Wave injection has been used to prime (in the sense that one primes a water pump) the magnetospheric plasma for the generation of VLF waves [17]. In a recent test it appears that VLF transmission also primes the magnetosphere for ULF wave generation [18]. We note that proposals for direct ULF wave injection [19, 20] have not been carried out. At medium and high frequencies wave injection has been used to produce parametric plasma instabilities [21].

Wave injection experiments have many natural analogues, for the magnetosphere is permeated by waves of a variety of frequencies. One of the best known is the lightning-generated whistler. The amplification of whistlers by the magnetospheric plasma is evident from the long duration (multiple hops) of many whistlers. The priming of the plasma is evident from whistler triggered emissions [22]. A more recent discovery is the ULF sideband instability in which a signal primes the plasma for the generation of daughter and then granddaughter, etc., emissions [23].

2.6. Injection of Cold Plasma

Brice has proposed that the magnetospheric plasma be "seeded" with cold plasma to enhance wave-particle interactions [24—27]. These suggestions have been further explored by Cornwall [28] and Cornwall and Schulz [29]. Fig. 1 illustrates how seeding enhances wave-particle interactions [30]. The three curves of the left-hand panel show the parallel resonant energy of protons unstable to wave generation at the equator for three cold plasma densities of 1, 10 and 100 cm⁻³ in a dipolar magnetic field given a pitch angle anisotropy of 0.2. If the density of the plasma is 1 cm⁻³, 20 keV protons are unstable beyond 11.7 $R_e$, and stable within that distance. If the density is 10 cm⁻³, the 20 keV protons are unstable beyond 7.9 $R_e$, and if the density is 100 cm⁻³, they are unstable beyond 5.3 $R_e$. Thus, if the plasma density at 5.3 $R_e$ is raised in a plasma seeding experiment to above 100 cm⁻³, the originally stable 20 keV protons would become unstable, causing plasma wave growth and pitch-angle diffusion, leading ultimately to particle precipitation when the proton enters the atmospheric loss cone. A similar story holds for electrons as is sketched in the right-hand panel for 40 keV electrons.

The naturally occurring counterpart to this process is the detachment of plasma from the main body of the plasmasphere [3]. The resulting "detached" plasma regions convect through the outer magnetosphere, markedly altering the conditions for wave-particle instability for the particles drifting through these regions. The advantages of these regions for studying the effects of plasma seeding is that they have a variety of sizes, require no extra payload on a satellite to carry the injection plasma and they occur frequently. On the other hand, their
occurrence is limited primarily to the afternoon sector, and only the dimension along the orbit track of the spacecraft can be measured. With an artificial injection all universal and local times can be examined, the regions have known dimensions and the ionic species can be varied. However, the injections are limited in size and number.

3. A Pilot Study of Detached Plasma Regions

The OGO 5 spacecraft carried a comprehensive set of plasma and plasma wave diagnostic instruments including an ion mass spectrometer furnished by Lockheed, a search coil magnetometer furnished by JPL/UCLA, a VLF electric field experiment from TRW, and an energetic electron spectrometer and a fluxgate magnetometer from UCLA. The search coil, electric field and ion mass spectrometer observations on a typical pass through the outer magnetosphere are shown in Fig. 2 [30]. Initially, the satellite is outside the plasmasphere in a plasma with an ion density of 2—4 cm⁻³. The search coil is observing high latitude dayside hiss in the upper frequency channels [31]. The first “spike” of high density plasma (shaded), presumably detached from the plasmasphere is observed at 0234 UT. The high frequency hiss drops in amplitude and then recovers as the satellite leaves this region. At 0236 another larger region of detached plasma is encountered.
Again, the high frequency hiss disappears, but this time a new emission occurs at lower frequencies. This behavior is repeated for several more encounters with regions of enhanced density until 0245 UT. After that time the occurrence of plasma enhancements is not correlated with ELF electromagnetic noise. The

![Graph showing correlated ELF-hiss and plasma density enhancements observed by OGO 5 on 13 September 1968.](image)

Fig. 2. Correlated ELF-hiss and plasma density enhancements observed by OGO 5 on 13 September 1968. Bottom panel, measurements of the Lockheed Light Ion Mass Spectrometer; middle panel, amplitude of the 200 Hz channel of the TRW Electric Field Experiment; upper panels, rms magnetic noise measured along the spacecraft z axis by the UCLA/JPL Search Coil Magnetometer at seven frequencies from 10 to 999 Hz. The intervals during which the plasma density exceeded 4 cm\(^{-3}\) have been shaded in the 100 Hz channel and in the ion density plots to emphasize the strong correlation. The noise in the 467 and 999 Hz channels was at saturation prior to 0236 UT except for a brief interval and was initially anticorrelated with the density enhancements.

The electric field noise follows a similar but subtly different pattern (for more detail see [30]).

There are two possible explanations for the lack of correlation of noise with plasma enhancements in the first and last two plasma "spikes". First, the density enhancements may be too narrow to duct the signal if generated or to confine the signal in the amplification process. Second, the particle fluxes may be below the stably trapped limit and hence not permit wave growth at this time.

Fig. 3 allows us to examine this question. Here the flux of electrons with energies greater than 50 keV are plotted against time. The lower panel shows the ion data. The minimum resonant energy has been calculated for three intervals
and the stable trapping limit \( j^* \) calculated [32]. The observed integral flux above the minimum resonant energy \( j \) is also given in the first two cases. We see that the fluxes of electrons should indeed be unstable in the detached plasma spikes as they are observed to be. In the third case the resonant energy has dropped below the energy range of the energetic electron spectrometer, so we do not know whether the electron flux exceeded the stably trapped limit here. On the other hand, the first two of the spikes for which no emission was observed should

![Graph showing electron flux and ion mass spectrometer data.](image)

Fig. 3. Hydrogen ion density measured by the Lockheed Light Ion Mass Spectrometer and integral direction flux of >50 keV locally mirroring electrons measured by the UCLA energetic electron spectrometer on 13 September 1968. The minimum resonant energies have been determined for the density peaks just to the right of the vertical dashed lines at 0236.5, 0243 and 0256 UT, and estimates of the theoretical maximum stably trapped flux and the measured flux above these energies are shown. Although the observed energetic electrons satisfy the instability conditions, their distribution has not been visibly affected.

have been unstable. Hence, we must ascribe the lack of emission in these two cases to the narrowness of the enhancement.

We note that there are no large reductions of the electron fluxes corresponding to the plasma enhancements. While the plasma instabilities in these enhancements certainly caused a marked change in the amplitudes of the plasma waves and presumably in the electron precipitation rates, these rates, when multiplied by the drift time through the enhancement, give that a precipitated flux is a very small fraction of the pre-existing flux.
4. Summary and Conclusions

From the present vantage point, the 1980’s will bring a decade of intensive active magnetospheric experimentation. The beginnings of this era are already upon us. In preparation for these active experiments and to complement them, we should also pursue their naturally occurring analogues. Many sets of data already exist on these natural analogues and these can be exploited now. The study of one such set of data on the physics of “detached” plasma regions indicates that plasma seeding studies will generate plasma instabilities, if the seeded plasma is dense enough or equivalently if there are sufficient resonant particles; it also indicates that there may be a critical dimension of the seeding plasma for instability, perpendicular to the geomagnetic field.

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