Laboratory Investigation of Near-Earth Space Plasma Processes

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Introduction: Energetic particles and plasma dynamics in the near-Earth space environment can significantly impact operation of both military and civilian systems. The underlying physical mechanisms relevant to two important space plasma issues, radiation belt dynamics and auroral ionospheric space weather, are under investigation in the NRL Space Physics Simulation Chamber (SPSC). Plasma conditions within this large laboratory device can be scaled to match key dimensionless parameters representative of ionospheric or magnetospheric regions of interest. Under scaled radiation belt conditions, Space Chamber experiments are addressing linear and nonlinear whistler wave propagation characteristics and wave-particle interactions. Under scaled auroral ionospheric conditions, the generation of electromagnetic ion cyclotron waves by sheared plasma flows and their impact on the dynamics and morphology of the geospace environment are being investigated. Additionally, Space Chamber research is directed at development of innovative diagnostic techniques for space and laboratory use.

Background: Both the military and civilian populations are increasingly dependent on space-based assets for uninterrupted operation of critical systems. The reliable operation of space-based assets, in turn, depends on many different physical aspects of the space plasma environment. For example, the operational lifetime of a satellite can be limited by the accumulated dose of high-energy electrons that form the Earth's highly dynamic radiation belts. In the natural environment, populations of high-energy electrons trapped and accelerated in the Earth's dipolar magnetic field can remain in stable, long-lived orbits. Such particles bounce back and forth between the poles, mirroring at altitudes above the Earth's neutral atmosphere. For those particles whose mirror point is at lower altitudes where the density of the neutral atmosphere is sufficiently high, collisions between neutrals and the electrons harmlessly precipitate the energetic particles.

The trapped high-energy electron populations are controlled to some degree by the interactions between naturally generated electromagnetic plasma waves and the energetic electrons. Such interactions scatter the energetic electrons from their stable orbits, which can lower their mirror point, leading to their precipitation into the atmosphere. In addition to natural waves, these particles can also be scattered by waves produced by Navy very low frequency (VLF) transmitters. Field experimental work on such wave-particle interactions has uncovered a wealth of interesting, unexplained phenomena. Among the most interesting are the nonlinear amplification of waves and triggered wave emissions at frequencies different from that of the transmitter. At present, these phenomena are not well understood, but appear to result from nonlinear interactions with the trapped radiation belt population itself.

At lower altitudes, in the auroral zones, ion cyclotron waves triggered by localized plasma flows can have significant impact on the dynamics and morphology of high-latitude ionospheric and magnetospheric plasmas. Broadband extremely low frequency waves are routinely observed by sounding rockets and satellites. These waves are often observed in conjunction with ion energization perpendicular to the magnetic field. The same force that causes mirroring of the energetic radiation belt electrons causes these heated ions to move to higher altitudes, allowing heavy, otherwise gravitationally bound ionospheric ions to become a major constituent of magnetospheric plasma. This chain of events resulting in a redistribution of the mass, energy, and momentum of ionospheric and magnetospheric plasma can affect near-Earth space weather processes. In addition, electromagnetic ion cyclotron waves created in this process can propagate to the magnetosphere, where they are an important secondary source of energetic radiation belt electron scattering and precipitation.

Current Research: The natural phenomena described above share some common space physics themes, namely, the transition from electrostatic to electromagnetic character of waves and the interaction of waves with plasma particles. These themes are being investigated in the SPSC, shown in Fig. 1. The SPSC is a state-of-the-art, large-scale laboratory plasma device dedicated to the study of near-Earth space plasma phenomena. Under conditions scaled to the inner radiation belt, electromagnetic whistler wave propagation and nonlinear wave-particle interactions are being investigated. Under conditions scaled to the auroral ionosphere, ion cyclotron wave generation and particle heating are being investigated. Both investigations are being coordinated with NRL theoretical and computational studies.

To simulate wave propagation in the radiation belt environment, various styles of whistler wave antennas have been developed and tested in order to efficiently produce a narrowband electromagnetic

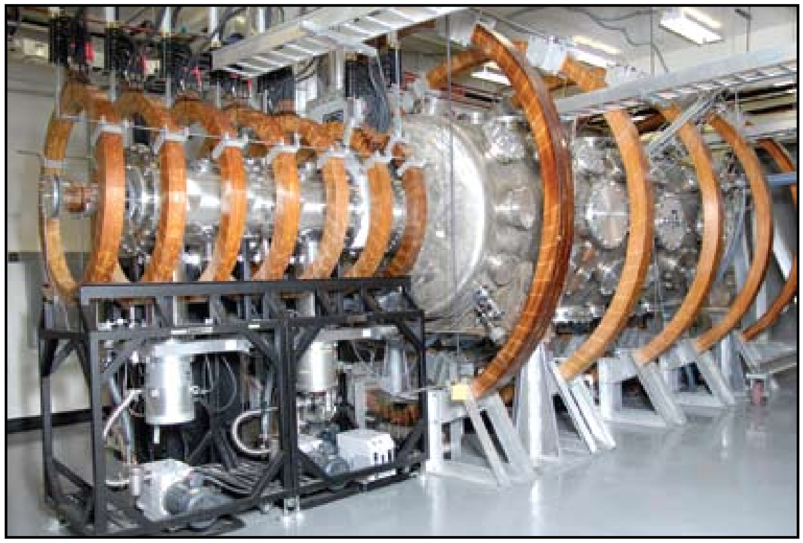

FIGURE 1
NRL Space Physics Simulation Chamber.

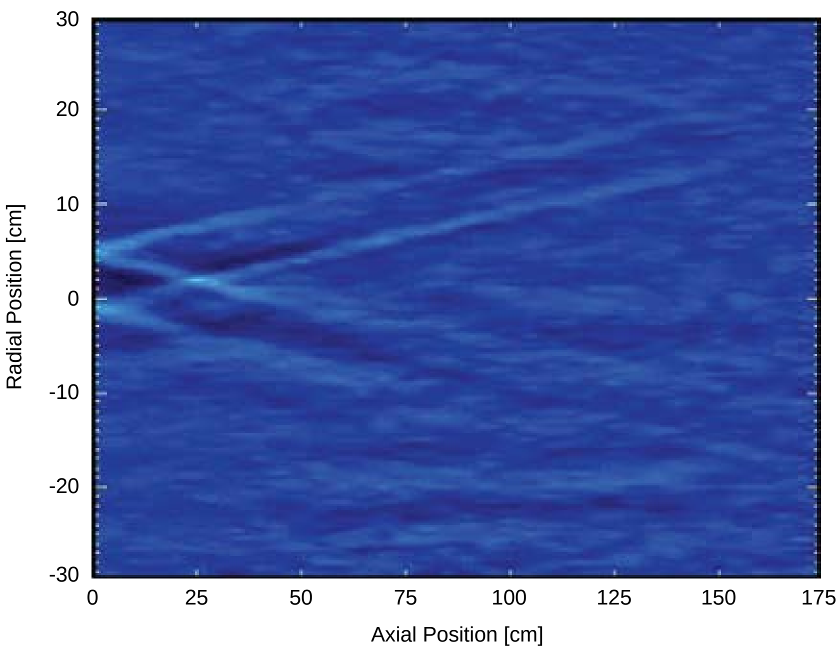

FIGURE 2
Whistler wave propagation in the Space Chamber plasma. A snapshot in time of a planar cut of electric field amplitude of a whistler wave launched from an antenna located at the left of the figure.

whistler wave spectrum, as shown in Fig. 2.[1,2] With the ability to control frequency and wave vector, the linear and nonlinear propagation characteristics have been investigated and compared to the cold-plasma dispersion relation. Transitions between the predominantly electrostatic lower hybrid wave and the predominantly electromagnetic whistler mode have been observed. A nonlinear transition from linear dispersive propagation to nonlinear self-ducted wave propagation, where the wave travels the length of the plasma column without loss, has also been observed. Current research is directed at the development of energetic electron sources and diagnostics. The characteristic residence time of the energetic electrons in a magnetic mirror configuration similar to the Earth's with and without whistler waves will be investigated, followed by studies of nonlinear interactions of the waves with the trapped electrons.

For studies of ionospheric space weather, the generation of electromagnetic ion cyclotron waves by structured quasistatic electric fields that form in the auroral zone are currently under investigation. NRL has led the theoretical and experimental study of ion cyclotron wave destabilization by such fields and has shown that they can lead to plasma energization and transport. In the laboratory, our goal is to investigate the transition from electrostatic to electromagnetic wave propagation, to determine the characteristics of the electromagnetic ion cyclotron waves, to document transverse ion heating and transport produced by such waves, and to investigate any potential radiation belt electron scattering by these waves.

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