Observation of Large-Scale Density Cavities and Parametric-Decay Instabilities in the High-Altitude Discrete Auroral Ionosphere under Pulsed Electromagnetic Radiation

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A large density cavity that measured 2000 km across and 500 km in height was observed by DEMETER and Formosat/COSMIC satellites in temporal and spatial relation to a new mode of propagation of electromagnetic (em) pulses between discrete magnetic field-aligned auroral plasmas to high altitudes. Recorded positive plasma potential from satellite probes is consistent with the expulsion of electrons in the creation of density cavities. High-frequency decay spectra support the concept of parametric instabilities fed by free energy sources.

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Introduction.—The polar region with electrons and ions precipitating along the magnetic field lines and anisotropic electron distributions such as the loss-cone distributions (consequence of the converging magnetic field) is a region of free energy sources, feeding the growth of instabilities. One of them, the auroral kilometric radiation (AKR) of power in the range of 0.1–1 GW, has been observed by a number of satellites [1,2] and explained theoretically as driven by an upward-going electron loss-cone distribution [3–5].

Furthermore, the triggering of AKR by solar type III bursts has also been advanced statistically [6,7]. It is noteworthy that the field strength of a type III solar burst is a rather weak field in the range of $\mu\mathrm{V/mHz}^{1/2}$ while a ground-based transmitting facility can routinely generate fields of $\mathrm{mV/mHz}^{1/2}$. These fields can reach the upper ionosphere under certain ambient conditions such as discrete auroral conditions or artificially generated striations such as observed during high power electromagnetic irradiation of the ionosphere. The understanding and application of AKR might be enhanced if it is triggerable and followed in its temporal development.

Another type of triggerable instabilities is the electromagnetic and electrostatic ion cyclotron unstable waves driven by electron currents along the magnetic field lines [8–10]. Such ion cyclotron waves have been invoked to explain the ion upflows in the polar region. If the frequency of these ion cyclotron waves can be controlled it might lead to determining the species of upflowing ions.

Laboratory and field experiments [11,12] have shown that three-wave parametric excitations have lower thresholds when one of the two daughter waves is marginally stable with negligible damping rates. This finding is consistent with the ease of triggerability of the AKR emission and the low-frequency waves such as ion cyclotron waves. If the AKR and ion cyclotron waves are near the instability threshold their damping rates would be negligible and the parametric excitation will have correspondingly low thresholds.

During discrete auroral conditions in the Arctic ionosphere em waves excited by ground-based transmitters can propagate upward following the earth's magnetic field lines to a height of at least 700 km, much above the normal ionospheric layer. In this mode of propagation the em electric field vector is perpendicular to the earth's magnetic field and can therefore interact with various collective plasma resonances in the radial profile of discrete auroral plasmas. This configuration has been shown in laboratory plasma experiments to yield efficient coupling between modulated high-frequency em waves at the upper hybrid resonance and low-frequency ion cyclotron waves [13]. The discrete plasma configuration might also allow excited low-frequency em ion cyclotron waves to propagate up and down the earth's magnetic field.

Since the precipitation of electrons is seldom uniform in space, it should be expected that the density profile of plasmas produced by these electrons in the auroral region is equally nonuniform across the magnetic field. Additionally, horizontal nonuniformities could arise from instabilities perpendicular to the earth's magnetic field. In the auroral region, a distribution of discrete plasma columns known as striations is more common than a uniform horizontal layer, thus allowing high-frequency waves to propagate to high altitudes where free energy sources reside. A number of observers [14] have noted that AKR emissions commonly occur during discrete auroral conditions which favor the propagation of upward propagating em waves.

Observations by DEMETER and COSMIC satellites.—The HIPAS facility (64.873° latitude and −146.837° longitude, [15]) was utilized to radiate em pulses during conditions which are favorable to natural AKR emission and the propagation of em pulses to high altitudes (700 km) where the DEMETER satellite passes over the field lines connecting with the HIPAS transmitting facility. There are observed electron precipitations and associated discrete plasma tubes along the earth's magnetic field lines. This discrete spatial distribution of plasmas is very different from the diffusive distribution which occupies a large horizontal extent that would have blocked the propagation of em waves upward to the height of DEMETER. These plasma tubes, spaced kilometers apart, allow the passage of HF waves (wavelengths of 100's of meters) and yet provide resonant plasma interactions with the electric field of these waves during their upward propagation.

HIPAS transmits cycles of 20 seconds on and 20 seconds off. During each on period short pulses at a pulse rate equal to a particular ion cyclotron frequency are sent; for example, in order to generate a wave at the proton cyclotron resonance HF pulses of 100 μs are repeated at the rate of 808 Hz ,which is equal to the proton cyclotron resonance at a height of 200 km. The low-duty cycle of 8% avoids heating the lower atmosphere and self-absorption, which would have attenuated the upward propagation of the HF pulse emitted from HIPAS. Also relatively low average power ($\sim$100 kW) is transmitted in order to demonstrate that a small amount of energy can direct a large amount of free energy to an efficient excitation of waves of a selective frequency. In our experiments another modulation frequency such as 28.6 Hz corresponding to N_2^+ is used in order to gauge the dependence on the ion cyclotron frequency.

DEMETER, [16] a polar orbiting satellite, is capable of monitoring em signals in both the high- and low-frequency range (0–3.5 MHz) by means of electric dipoles and magnetic loop sensors. Its Langmuir probe records the ambient plasma density while its ion energy analyzer registers both the density and energy of ions. The HIPAS on-off sequence was clearly observed during all evening passes of DEMETER.

The experiments were performed in the evenings of January 21 and 27, February 3, and 9, and March 12, 2008 when DEMETER was executing a polar orbit from south to north. The HIPAS transmitter was turned on when DEMETER was within 10 minutes to the south of its overhead position. HIPAS was maintained on for 20 minutes. As shown in Fig. 1(a), the electron density recorded by DEMETER on January 21, 2008 at 06:44:04 UT started to decrease at the turn-on of the HIPAS pulse sequence. The electron density continued to decrease from 10^4 cm^{-3} to below 10^3 cm^{-3} as it reached the position directly over HIPAS. When the electron density fell below 10^3 cm^{-3} the Langmuir probe on board the satellite could not display the density and temperature of electrons. However, the ion density taken by the ion energy analyzer was able to show a similar downward trend by 2 orders of magnitude to 10^2 cm^{-3}. From the speed of DEMETER, one can estimate the horizontal extent of the density cavity to be 2000 km. This new observation of the density cavity at 700 km complements the previous satellite observations of density cavities from naturally excited AKR at heights greater than $1R_E$ (earth radius).

A constellation of six satellites, the Formosat/Cosmic, was used to independently measure the electron density profile during the HIPAS-DEMETER experimental period. Each satellite measures the total electron content (TEC) along a chord intersecting the density profile above HIPAS by comparing the phase information from two GPS satellites. The density profiles averaged over 5 days before and after the experiment on January 21 2008 were compared against the profile taken during the HIPAS on period. As

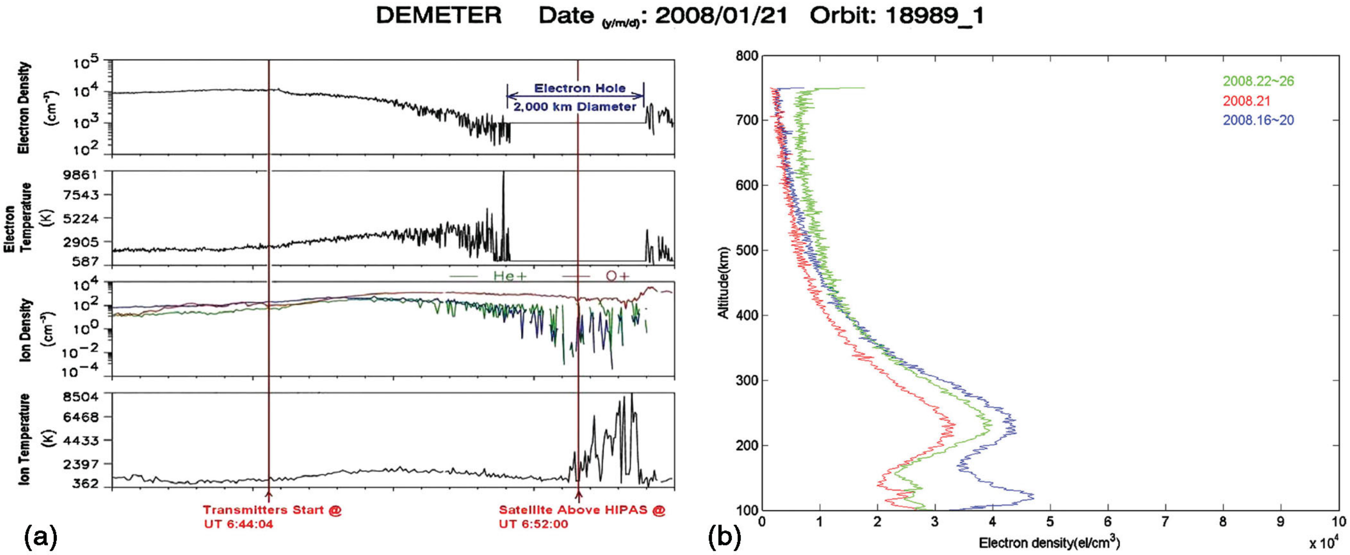

FIG. 1 (color). (a) Density Cavity observed by DEMETER satellite. (b) The averages profiles observed during a 5-day period of time before and after and on January 21, 2008. The blue, green and red denote before, after, and on the observation day between 6:00–7:45 UT. FORMOSAT/COSMIC data by T. Liu and L. Lee [17].

noted in Fig. 1(b) the profile taken on January 21 displays the lowest density. The maximum density change occurs at the height of 245 km where the 2.85 MHz excitation frequency matches $2f_c$, the second harmonic of the electron cyclotron frequency at that height. Airglows and nonlinear coupling from high to low frequencies have been observed in past experiments at HIPAS [18] when the em frequency matches both the local plasma frequency and $2f_c$ at this height of "double resonance".

These above measured changes in density profiles by Formosat/COSMIC revealed that the density cavity extends from a lower height of 200 km to 700 km, the height of the DEMETER satellite. This independent measurement of density cavities by a completely different set of satellites complements our observation using DEMETER and also shows the height extent of the density cavity.

In order to understand the creation of this large density cavity we have analyzed the high-frequency spectral response recorded by DEMETER (Fig. 2). The primary upward-going HF wave at 2.85 MHz, the pump, decays into a lower sideband 2.75 MHz and a low-frequency idler of 100 KHz, which is in the range of typical auroral kilometric radiation (AKR). It is important to note that the power in the high-frequency sideband 2.75 MHz is an order of magnitude higher than the pump power, a consequence of energy flow from the pump at 2.85 MHz to the high-frequency sideband at 2.75 MHz. This energy flow is explained by the inclusion of pump depletion in the parametric decay process [11,19]. The low-frequency idler of 100 KHz in this parametric process is approximately equal to the plasma frequency of the depleted density at the bottom of the cavity. The parametric process is especially enhanced during the portion when the HF is modulated at the proton ion cyclotron frequency 808 Hz. This low-frequency idler persists even during the off time of the pump because it is marginally stable in the presence of free energy sources. A similar phenomenon has been observed in the excitation of drift waves which persists as a result of its low damping rate [20].

The observed large density cavity in vertical and horizontal extents can be explained by the local resonantly enhanced electric fields generated by the upward propagating em waves. These fields energized electrons at the resonant locations and the resulting electron pressure gradient moves neighboring electrons along the earth's magnetic field lines. Furthermore, the HF fields pulsed at the proton ion cyclotron resonance impart perpendicular energy to protons in a resonant manner. The increased magnetic moment of protons in a divergent earth's magnetic field propels ions upward, thereby contributing to the density depletion.

The observed change in potential towards positive values with the on-off sequence of the em wave is a consequence of this depletion process (Fig. 2) in which electrons with lighter mass are accelerated first. Such large-scale density perturbations are not observed when there is a uniform plasma layer in the E and F region which would have reflected the upgoing em wave. This is confirmed during a daytime operation when there is a uniform horizontal plasma layer produced by solar UV ionization. Electromagnetic pulses were not registered by DEMETER and density depletion was not observed.

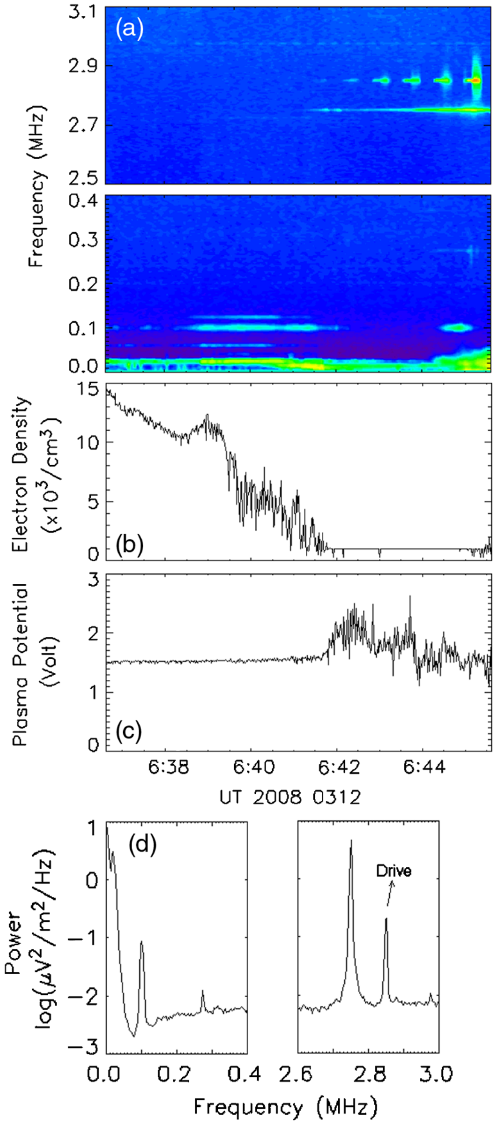

FIG. 2 (color online). (a) HF spectra received by DEMETER during period 6:37–6:45 UT. (b) Electron density taken by DEMETER Langmuir probe. (c) Plasma potential. (d) Power spectrum at UT 6:45, March 12, 2008.

An event of triggered emission of AKR was observed on March 12, 2008 (Fig. 3) when both the second harmonic at the local electron cyclotron frequency, $2\omega_c$, at the height of DEMETER (700 km) and a range of AKR frequencies between 100 KHz and 500 KHz were observed. The onset of the $2\omega_c$ emission and AKR appears to correlate with the on time of the HIPAS HF pulses received by DEMETER.

According to theories by Wu and Lee [4] and by Lee, Kan and Wu [3,21], density depletion plays an important

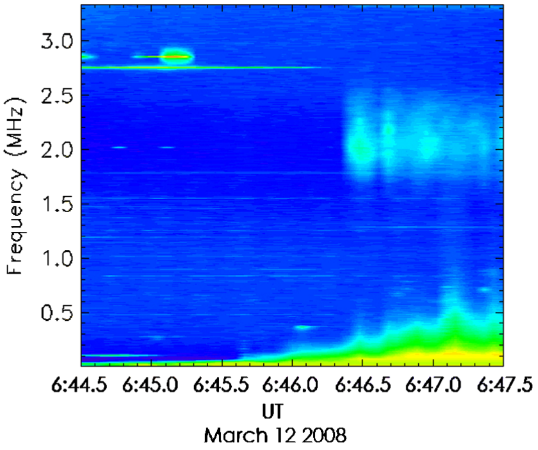

FIG. 3 (color online). Triggered emission.

part in determining whether the first harmonic or second harmonic of the electron cyclotron frequency has a higher growth rate. For $\omega_{pe}/\omega_{ce} > 0.3$ the growth rate at the second harmonics is higher than that at the fundamental harmonics. This might explain the observed emission at 2–2.2 MHz, twice the local electron cyclotron frequency at 700 km. Their theories also predict that for $\omega_{pe}/\omega_{ce} < 0.2$, a condition likely to prevail at heights greater than the 700 km, AKR should appear at the fundamentals of electron cyclotron resonance frequencies at those heights. The observations of frequencies in the range from 100–600 KHz could be a result of such conditions. The presence of discrete auroras [14] opens up the possibility of waves communicating between different heights. AKR made unstable at greater heights can propagate to lower heights to resonate with electron plasma resonances at lower heights.

In summary we have shown that the density in a large region of space can be depleted when irradiated by em pulses, especially when these waves are modulated at a frequency near an ion cyclotron resonance. These space experiments correlate with laboratory experiments where ion cyclotron waves can be excited by modulated em waves and the expulsion of plasma ions was observed [22].

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