REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
01-05-2005

2. REPORT TYPE
REPRINT

3. DATES COVERED *(From - To)*

4. TITLE AND SUBTITLE
Ionospheric Modification at Twice the Electron Cyclotron Frequency

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

5d. PROJECT NUMBER
2311 1010

5e. TASK NUMBER
SD HR

5f. WORK UNIT NUMBER
A4 A1

6. AUTHOR(S)
F.T. Djuth*, T.R. Pedersen, E.A. Gerken**, P.A. Bernhardt+, C.A. Selcher++, W.A. Bristow@, and M.J. Kosch#

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Air Force Research Laboratory/VSBXI
29 Randolph Road
Hanscom AFB, MA 01731-3010

8. PERFORMING ORGANIZATION REPORT NUMBER
AFRL-VS-HA-TR-2005-1070

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSOR/MONITOR'S ACRONYM(S)
AFRL/VSBXI

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited.

13. SUPPLEMENTARY NOTES
REPRINTED FROM: Physical Review Letters, Vol. 94, 2005 DOI: 10.1103/PhysRevLett.94.125001, Copyright 2005, The American Physical Society. (continued over)

14. ABSTRACT
In 2004, a new transmission band was added to the HAARP high-frequency ionospheric modification facility that encompasses the second electron cyclotron harmonic at altitudes between ~220 and 330 km. Initial observations indicate taht greatly enhanced airglow occurs whenever the transmission frequency approximately matches the second electron cyclotron harmonic at the height of the upper hybrid resonance. This is the reverse of what ahppens at higher electron cyclotron harmonics. The measured optical emissions confirm the presence of accelerated electrons in the plasma.

15. SUBJECT TERMS
Airglow
Ionospheric disturbances
Plasma radiofrequency heating

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
UNCL	UNCL	UNCL	UNL		Todd R. Pedersen
					19b. TELEPHONE NUMBER *(Include area code)* (781) 377-2845

Block 13 (Cont.)

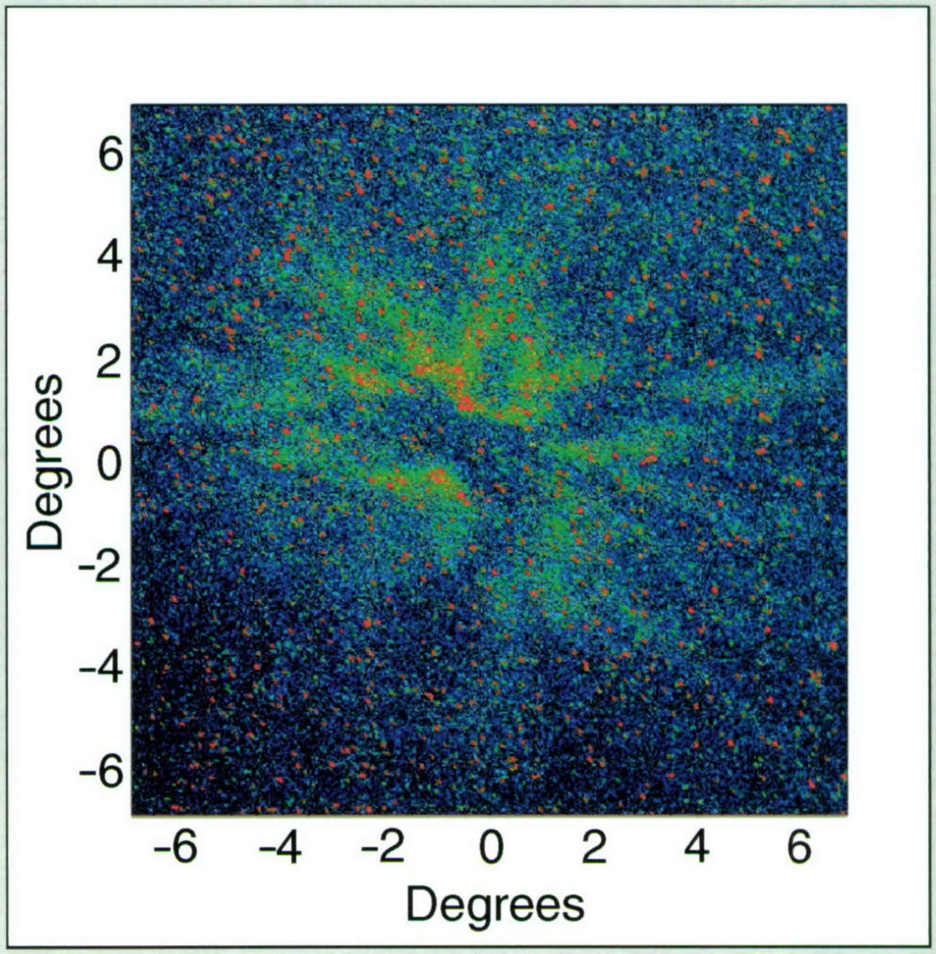
*Geospace Research Inc., El Segundo, CA
**Electrical and Computer Engineering Department, Cornell University, Ithaca, NY
+Plasma Physics Division, Naval Research Laboratory, Washington, DC
++Information Technology Division, Naval Research Laboratory, Washington, DC
@Geophysical Institute, University of Alaska at Fairbanks, Fairbanks, AK
#Communications Systems, Lancaster University, Lancaster LA1 4YR, United Kingdom

AFRL-VS-HA-TR-2005-1070

PHYSICAL REVIEW LETTERS

Articles published week ending
01 APRIL 2005

Volume 94, Number 12



APS Published by The American Physical Society

Ionospheric Modification at Twice the Electron Cyclotron Frequency

F. T. Djuth,[1] T. R. Pedersen,[2] E. A. Gerken,[3] P. A. Bernhardt,[4] C. A. Selcher,[5] W. A. Bristow,[6] and M. J. Kosch[7]

[1]*Geospace Research, Inc., El Segundo, California 90245, USA*
[2]*Air Force Research Laboratory, Hanscom Air Force Base, Massachusetts 01731, USA*
[3]*Electrical and Computer Engineering Department, Cornell University, Ithaca, New York 14853, USA*
[4]*Plasma Physics Division, Naval Research Laboratory, Washington, D.C. 20375, USA*
[5]*Information Technology Division, Naval Research Laboratory, Washington, D.C. 20375, USA*
[6]*Geophysical Institute, UAF, Fairbanks, Alaska 99775, USA*
[7]*Communications Systems, Lancaster University, Lancaster LA1 4YR, United Kingdom*
(Received 22 November 2004; published 31 March 2005)

In 2004, a new transmission band was added to the HAARP high-frequency ionospheric modification facility that encompasses the second electron cyclotron harmonic at altitudes between ~220 and 330 km. Initial observations indicate that greatly enhanced airglow occurs whenever the transmission frequency approximately matches the second electron cyclotron harmonic at the height of the upper hybrid resonance. This is the reverse of what happens at higher electron cyclotron harmonics. The measured optical emissions confirm the presence of accelerated electrons in the plasma.

DOI: 10.1103/PhysRevLett.94.125001 PACS numbers: 94.20.Vv, 52.35.Qz, 94.20.Bb, 94.20.Ji

Recent ionospheric modification experiments performed with high-power, high-frequency (HF) facilities at polar latitudes have yielded prodigious amounts of HF-induced airglow (hundreds of Rayleighs) [e.g., [1–3]]. The most intense airglow occurs when the HF beam is pointed at the geomagnetic zenith (i.e., parallel to the geomagnetic field **B**). The airglow is accompanied by strongly enhanced electron heating of the plasma [4]. These experiments are performed in the F region ionosphere at altitudes between ~200 and 400 km. Similar airglow experiments have been conducted using HF frequencies that are harmonics of the electron cyclotron frequency f_{ce}. Past measurements have employed frequencies near the third electron cyclotron harmonic and higher, that is, $n \geq 3$, where n is an integer multiple of f_{ce} [5]. The resonance of interest occurs near the height at which the frequency matching condition

$$f_{\mathrm{HF}} = n f_{ce} = f_{\mathrm{UH}} = [f_{pe}{}^2 + f_{ce}{}^2]^{1/2} \qquad (1)$$

is satisfied, where f_{UH} and f_{pe} are the frequency of the upper hybrid oscillations and the local plasma frequency, respectively. The results of [5] demonstrate that HF-enhanced 630.0 nm emissions from atmospheric $O(^1D)$ and 10-m backscatter from artificial geomagnetic field-aligned irregularities (AFAIs) reach a minimum when the HF frequency is stepped across $3f_{ce}$. However, experiments conducted at Platteville, CO in 1971 [6] showed an order of magnitude increase in 2–10 m AFAIs when HF transmissions were made slightly above the second cyclotron harmonic. These early Platteville experiments provided the first indication of an enhanced plasma response at $f_{\mathrm{HF}} = 2f_{ce}$.

In this Letter, we present polar airglow results obtained for the first time at $n = 2$. The observations were made with the High-Frequency Active Auroral Research Program (HAARP) facility (62.39 °N, 145.15 °W) in Gakona, AK. HAARP began operating in the $2f_{ce}$ band (2.720–2.850 MHz) in late February and March 2004; results from March 20, 2004 (UT) are reported here. During the experiment, the HAARP transmitter was tuned to 2.75 MHz, and the effective radiated power (ERP = power × antenna gain) was ~10 MW. O-mode polarization was used for all observations. The HF beam was directed toward the magnetic zenith (15° zenith angle, 204° azimuth); the half-power beamwidth was ~32° in the magnetic meridian plane and ~45° in the geomagnetic east-west direction. At HAARP, the magnetic zenith is well beyond the Spitze angle (~8.2° at 2.75 MHz), and therefore the radio wave reflects obliquely in the ionosphere. In

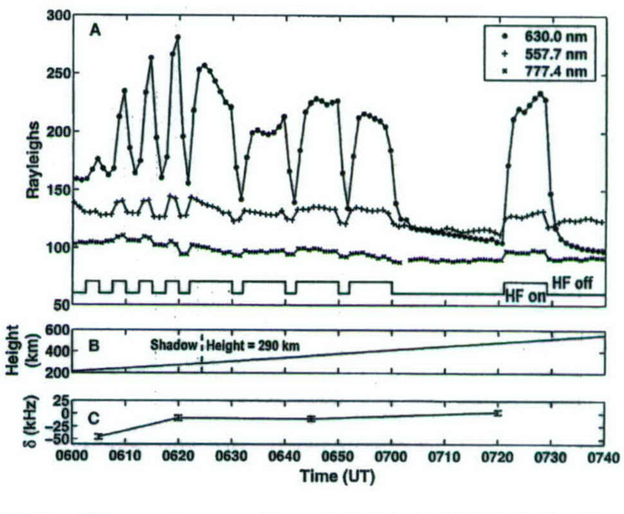


FIG. 1. Observations made on 20 March 2004 during ionospheric sunset. When the HF beam is switched on, optical emissions are enhanced above natural atmospheric levels (Panel A). The increase in the shadow height of the sun is plotted in Panel B; local time = UT − 9 h. Measured values of the frequency mismatch of the $2f_{ce}$ resonance are displayed in Panel C along with estimated random errors.

the current study, the peak plasma frequency in the F region was ~3 MHz. Ray tracing of the modifying HF beam was performed using true-height electron density profiles deduced from ionograms recorded during the experiment. The results indicate that the radio wave reflection occurred ~1 km below the critical layer at $f_{pe} = f_{\rm HF}$, or ~5 km above the location of the upper hybrid resonance, and therefore the frequency matching condition in (1) could be satisfied in the plasma.

Panel A of Fig. 1 summarizes the optical measurements of March 20, 2004. These data were acquired with a charge coupled device (CCD) imager, and emissions within a ±3.5° square centered on the magnetic zenith were averaged to produce the plotted values. Emissions from the forbidden transitions of atomic oxygen, $(^1S_0 \rightarrow {}^1D_2)$ at 557.7 nm and $(^1D_2 \rightarrow {}^3P_2)$ at 630.0 nm, are shown along with airglow from the permitted transition $(^5P \rightarrow {}^5S^0)$ at 777.4 nm. The lifetimes of the $^1S_0$ and ^5P states are 0.74 s and ~10 ns, respectively; the $^1D_2$ state is quenched by atmospheric/ionospheric collisions, which yields a decay constant of ~54 s for the current observations. As a result, the radiation at 630.0 nm, 557.7 nm, and 777.4 nm is emitted within ~40 km, ~2 km, and ~10 μm of the point of electron excitation, respectively. With the inclusion of electron energy loss processes in the F region (mainly caused by collisions with N_2); the minimum electron energy required to excite 630.0 nm and 557.7 nm emissions is ~3.1 eV and ~5.4 eV, respectively [7]. Emissions at 777.4 nm are excited by ~10.7 eV electrons. The fact that 777.4 nm airglow is detectable is indicative of the presence of HF-accelerated electrons in the plasma. Otherwise, unrealistically high electron thermal temperatures would be required to excite $O(^5P)$. As discussed below, suprathermal electrons also contribute to the excitation of 630.0 nm and 557.7 nm airglow.

The background ionospheric plasma modified by the HF beam was highly structured by natural auroral processes as reflected in ionograms obtained at HAARP and backscatter monitored from Kodiak, AK with the SuperDARN HF radar. This is a common occurrence at HAARP. Figure 2 shows an image of the 557.7 nm airglow centered on the geomagnetic zenith. The emission structure is similar to other CCD images at this wavelength and is caused by the trapping of the HF wave by large-scale (~1–5 km) F region irregularities. Because of the short lifetime of the 557.7 nm emissions (0.74 s), the altitude-dependent diffusion distance of the emitting $O(^1S_0)$ atoms is relatively small. Values of ~0.9–2.0 km are obtained at altitudes between 260 and 340 km with the diffusion model of [7,8]. Also note that the intensities of the 557.7 nm airglow inside ionospheric structures (65–75 R) are much greater than the spatially averaged enhancements shown in Fig. 1, panel A. This is consistent with models of airglow generated by electron heating and acceleration inside striations near the upper hybrid resonance [9,10].

Figure 3 shows a CCD image of the 630.0 nm emissions recorded beginning at 0617:36 UT, or 6 s after the start of an HF modification period. The data integration time is 7.5 s. In general, the emissions exhibit a very steep growth curve (~ 60 R above background in certain regions of the CCD image after ~6 s), which is generated by a burst of hot electrons at HF turn-on. These emissions occur so quickly that ionospheric structure is evident in the CCD image. Normally this is not the case because the long time constant of the $O(^1D)$ state permits the oxygen atom to diffuse a great distance before it emits a 630.0 nm photon. It is noteworthy that a faster than thermal rise of 630.0 nm emissions from Platteville, CO was found in the analyses

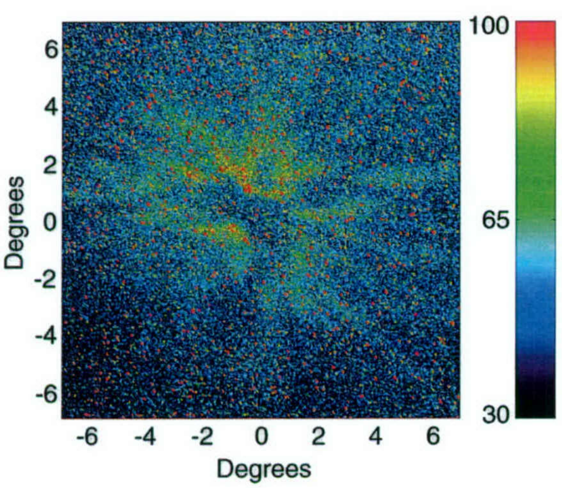


FIG. 2 (color). CCD image of 557.7 nm emissions acquired immediately after HF turn-on during the period 0617:30–0618:00 UT on 20 March 2004.

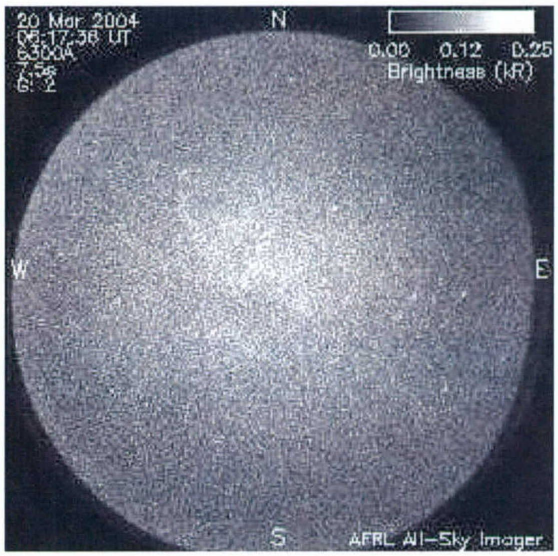


FIG. 3. CCD image of 630.0 nm emissions acquired during the period 0617:36.0–0617:43.5 UT on 20 March 2004. The full field of view is 16° centered on the geomagnetic zenith.

of Mantas and Carlson [11]. The model calculations of [11] ruled out a purely electron thermal source of the airglow, and they attributed their observations to the excitation of both suprathermal and thermal electrons in the plasma. The HAARP 630.0 nm measurements have a similar explanation. The -3-dB full width of the airglow spot in Fig. 3 is $\sim 8°$, and the structure in Fig. 2 extends about 9°. This is significantly less than the -3-dB full width of the HF beam ($\sim 32° \times \sim 45°$). Thus, HF wave propagation within $\sim 4°$ of **B** appears to define the spatial extent of the airglow. The preference for radio wave propagation parallel to **B** is seen in all high latitude airglow experiments.

A powerful O-mode wave reflecting in the ionosphere gives rise to weak spectral sidebands surrounding the HF frequency known as stimulated electromagnetic emissions (SEE) [12,13]. During the current experiment SEE was measured from a site ~ 13 km south of HAARP. A series of SEE spectral observations is presented in Fig. 4. At early times near 0600 UT when the optical emissions are weak, little if any SEE exists. However, with increasing time SEE features become evident at the downshifted maximum

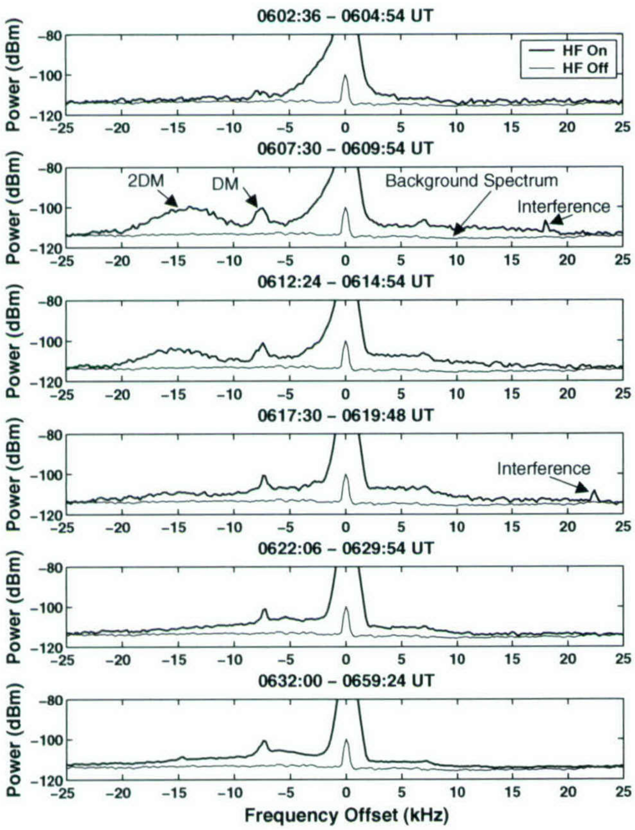


FIG. 4. SEE spectra monitored on March 20, 2004. Frequency is referenced to the modifying HF frequency, 2.75 MHz. The amplitude of the specularly reflected modifying wave has been truncated; its level is approximately -45 dBm. The small peak at zero frequency offset in the background spectrum is caused by leakage from the HAARP facility. SEE measurements are not available after 0700 UT.

(DM) and at twice the frequency offset of the DM (2DM). Physically, the SEE is the result of the pump electromagnetic wave (EW) being directly converted into an electrostatic wave within a FAI at the upper hybrid (UH) resonance. This UH wave subsequently decays into a second UH wave, UH2, and a lower hybrid (LH) wave. UH2 has a frequency near $f_{\rm HF} - f_{\rm LH}$, where $f_{\rm LH}$ is 7–8 kHz; it is transformed back to an EW by gradients within the FAI giving rise to the DM. The further decay of UH2 waves into an electromagnetic wave and a LH wave produces the 2DM [14,15]. Previous SEE studies indicate that the DM and 2DM disappear when the HF pump frequency is near a high f_{ce} harmonic ($n = 3$–7) [12–15]. In contrast, SEE emissions appear to be active at the upper hybrid resonance when the HF frequency is near $n = 2$.

In addition to the SEE diagnostic, we attempted to monitor 14-m AFAIs with the SuperDARN radar. During the time period 0600 UT–0615 UT natural 14-m irregularities were strongly present over HAARP, and AFAIs were difficult to detect. Most likely, the natural irregularities had reached saturation levels in the plasma. At HAARP the F region ionosphere often becomes heavily striated once the sun sets at E region (100–120 km) altitudes. After 0615 UT the natural 14-m echoes diminished in strength and disappeared completely at 0630 UT. This was caused by a weakening F region in the vicinity of HAARP, which led to a loss in aspect angle between the radar ray path and the geomagnetic field lines in the HF-modified volume.

Over the past three years, many airglow experiments have been performed at HAARP using transmissions in the low frequency (LF) band, 3.155–3.400 MHz, while pointing the beam at magnetic zenith. In this band the HAARP ERP is about twice that of the $2f_{ce}$ band (2.720–2.850 MHz). The LF band has yielded significant thermal enhancements at 630.0 nm (~ 40 R to ~ 280 R), but no detectable emissions at 557.7 nm or 777.4 nm. Thermally enhanced 630.0 nm emissions in the $2f_{ce}$ band range from ~ 30 R to ~ 280 R, but the amount of this type of data is very limited. The absolute level of the 630.0 nm emissions is strongly dependent on background atmosphere/ionosphere conditions.

Enhanced, nonthermal emissions at 557.7 nm, 777.4 nm, and 630.0 nm are observed only when the frequency matching conditions of (1) are approximately satisfied in the plasma. The CCD image in Fig. 2 shows evidence of 557.7 nm airglow emanating from inside large-scale (1–5 km) field-aligned irregularities. Within these irregularities the ratio of the 557.7 nm emissions to the 630.0 nm emissions is much larger than that calculated from the average values shown in Fig. 1. Effective values of the order of 0.3 are estimated in regions where the intensity of the 557.7 nm emissions is high (~ 60–70 R). Such ratios are indicative of electron acceleration in the plasma. Suprathermal electrons also contribute to the intensity of the 630.0 nm emissions as illustrated by the burst of hot electrons at HF turn-on (Fig. 3). HF-induced enhancements of the more energetic 777.4 nm emissions ($\sim$10.7 eV) confirm the presence of accelerated electrons in the plasma. Packets of short-scale (1–20 m) AFAIs formed near the height of the upper hybrid resonance are believed to be contained within the large-scale structures, e.g., [16]. Most likely, electron acceleration and electron thermal heating inside these striations [9,10] give rise to the observed 630.0 nm and 557.7 nm emissions.

For the observations presented here, estimates of resonance heights were made with the aid of an HF sounder (digisonde) located at HAARP. The ionograms were carefully refitted to obtain the true-height electron density profiles, and the interferometry capability of the digisonde was exploited as needed. At the beginning of the observations at 0600 UT, the upper hybrid resonance was located at $\sim$258 km altitude. Between 0605 UT and 0610 UT the resonance moved into a stable height range between 285 km and 292 km. Panel B in Fig. 1 shows the solar shadow height for visible wavelengths during the observations. The UV terminator for ionizing solar radiation resides $\sim$45 km above the heights plotted. A dashed line denotes the time at which the shadow moves above the 290 km resonance zone. These data are presented to demonstrate that possible optical pumping of O states in solar twilight did not impact the observations. The relative ratios of the three emissions in panel A were maintained throughout the data segment even though shadow passage took place near 0625 UT. Clearly the airglow recorded during the last HF pulse beginning at 0721 UT was generated in complete darkness. At this time the shadow height was $\sim$540 km.

The HAARP $2f_{ce}$ results of March 20, 2004 indicate that electron acceleration occurs in the plasma when the resonance condition shown in (1) is approximately satisfied. Our estimates of the frequency mismatch $\delta = f_{\text{HF}} - 2f_{ce}$ at the upper hybrid resonance are presented in panel C of Fig. 1. The display indicates that δ was negative during the observations except for the last heating pulse where it was slightly positive (+2.8 kHz). Notice that initially when δ is -46 kHz, only weak 630.0 nm and SEE emissions result, but when δ is within $\sim$10 kHz of the resonance the signals are much stronger.

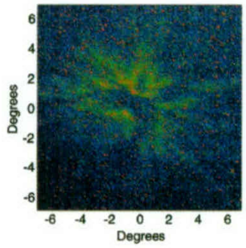
Because of complexities in incorporating Bernstein modes at low cyclotron harmonics into the AFAI formalism, theoretical predictions for the saturated plasma state at $2f_{ce}$ are lacking. However, the theory for wave-plasma interactions at $n = 3$ and higher is better developed. The approaches of Mjølhus [17] and Istomin and Leyser [18] are similar, and their predictions along with those of Gurevich *et al.* [16] are consistent with the presence of greater HF-induced plasma effects (e.g., anomalous absorption and electron acceleration [18]) at frequencies slightly above the resonance. A deep null is observed in wideband absorption, AFAIs, and HF-induced airglow when (1) is exactly met [5,12]. In addition, the SEE DM and 2DM are suppressed [12,13]. This occurs because the upper hybrid oscillations are heavily Landau damped, which constrains resonance phenomena. Moreover, the Bernstein modes at $n > 2$ are not trapped inside the striations and therefore cannot drive the AFAIs. In contrast, it is likely that at $2f_{ce}$ Bernstein modes become trapped in the AFAIs. This would produce results opposite to the observations at $3f_{ce}$ and consistent with the AFAI observations at Platteville, CO and the airglow and SEE measurements above.

Finally, we note the similarity between the current work and studies of natural auroral processes at $f_{\text{UH}} = 2f_{ce}$ [19]. The latter is a current-driven instability that has some of the features of the wave-driven processes discussed here. There is much to be gained by combining the common elements of theories used to describe these two phenomena.

The HAARP program is a Department of Defense project managed jointly by the U. S. Air Force and the U. S. Navy. Support from the Office of Naval Research (ONR) under Contract Nos. N00014-03-C-0482 (F. T. D.), N00014-03-1-0912 (W. A. B.), and N00014-03-1-0978 (E. A. G.) is gratefully acknowledged. The Naval Research Laboratory SEE instrumentation is sponsored by the HAARP program office and ONR. F. T. D. thanks A. V. Gurevich and E. Mjølhus for helpful comments concerning this work.

[1] M. J. Kosch *et al.*, Geophys. Res. Lett. **27**, 2817 (2000).
[2] B. Gustavsson *et al.*, J. Geophys. Res. **106**, 29 105 (2001).
[3] T. R. Pedersen *et al.*, Geophys. Res. Lett. **30**, 1169 (2003).
[4] M. T. Rietveld *et al.*, J. Geophys. Res. **108**, 1141 (2003).
[5] M. J. Kosch *et al.*, Geophys. Res. Lett. **29**, 2112 (2002).
[6] P. A. Fialer, Radio Sci. **9**, 923 (1974).
[7] P. A. Bernhardt, C. A. Tepley, and L. M. Duncan, J. Geophys. Res. **94**, 9071 (1989).
[8] P. A. Bernhardt *et al.*, J. Geophys. Res. **105**, 10 657 (2000).
[9] A. V. Gurevich and G. M. Milikh, J. Geophys. Res. **102**, 389 (1997).
[10] Y. S. Dimant, A. V. Gurevich, and K. P. Zybin, J. Atmos. Terr. Phys. **54**, 425 (1992).
[11] G. P. Mantas and H. C. Carlson, J. Geophys. Res. **101**, 195 (1996).
[12] P. Stubbe *et al.*, J. Geophys. Res. **99**, 6233 (1994).
[13] T. B. Leyser *et al.*, J. Geophys. Res. **99**, 19 555 (1994).
[14] P. A. Bernhardt *et al.*, Phys. Rev. Lett. **72**, 2879 (1994).
[15] A. V. Gurevich *et al.*, Phys. Lett. A **231**, 97 (1997).
[16] A. V. Gurevich, A. V. Lukyanov, and K. P. Zybin, Phys. Lett. A **211**, 363 (1996).
[17] E. Mjølhus, J. Atmos. Terr. Phys. **55**, 907 (1993).
[18] Ya. N. Istomin and T. B. Leyser, Phys. Plasmas **10**, 2962 (2003).
[19] M. Samara *et al.*, Geophys. Res. Lett. **31**, L22804 (2004).

NEWSPAPER



CCD image of induced airglow in the upper atmosphere from an ionospheric modification experiment by the High-Frequency Active Auroral Research Program (HAARP). The emissions are from forbidden transitions in atomic oxygen colliding with electrons accelerated by a high-frequency radio beam from the HAARP transmitter in Alaska. See article 125001.

PHYSICAL REVIEW LETTERS

Contents

Articles published 26 March–1 April 2005

VOLUME 94, NUMBER 12 — 1 April 2005

(Continued on Third Cover)

LITHO IN USA
CANTERBURY PRESS

0031-9007(20050401)94:12;1-5

94
PRL 94 (12), 120401–129604, 1 April 2005 (304 total pages)
12