

Cerenkov emissions of ion acoustic-like waves generated by electron beams emitted during TSS 1R

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Abstract. During the Tethered Satellite System reflight the Spacecraft Particle Correlation Experiment detected fluxes of energetic electrons and ions that were simultaneously modulated at low frequencies during firings of both the fast pulsed electron gun (FPEG) and the electron generator assembly (EGA). The modulations have been interpreted as signatures of large-amplitude, ion acoustic-like waves excited in Cerenkov interactions between electron beams and ambient plasmas as the shuttle moved at supersonic speeds across the ionospheric magnetic field. We present examples of particle modulations observed during steady beam emissions. Measurements show that (1) most electron modulations were at frequencies of several hundred Hertz and (2) ions modulated at similar frequencies appeared at spectral energy peaks during shuttle negative charging events. Detection of modulated ion fluxes confirms the Cerenkov emission hypothesis. Observed frequency variations indicate that the EGA beam underwent more spatial spreading than the FPEG beam.

Introduction

The first TSS flight (TSS 1) offered an opportunity to demonstrate a new technique for detecting low (<10 kHz) frequency (LF) modulations of energetic (>10 eV) electrons and ions [Gough *et al.*, 1997]. The observed modulations resulted from bunching of resonant ($v_{\parallel} \approx \omega/k_{\parallel}$) electrons by large amplitude electrostatic waves. Beam-plasma interaction studies were conducted with the deployable satellite stowed in the

shuttle payload bay and the fast pulsed electron gun (FPEG) emitting 1 keV electrons at 100 mA. Observational results were that: (1) LF modulations with average frequency of ~ 1.4 kHz correspond to no natural plasma oscillation, (2) distribution functions at the energies of the modulated electrons were stable, (3) modulation events were more common on the night than the day side, (4) modulation frequencies depended weakly on beam pitch angles and ambient plasma densities.

During electron beam emissions of the Spacelab 2 mission Feng *et al.* [1992] detected electrostatic waves in the low kilohertz band downstream of the shuttle. The directions of beam propagation were nearly perpendicular to the magnetic field ($k_{\perp}/k_{\parallel} \gg 1$). Linear dispersive characteristics indicated that they were either ion acoustic or high harmonic ion cyclotron waves. TSS 1 observations were interpreted by Gough *et al.*, [1997] as direct effects of ion acoustic-like waves driven by a Cerenkov beam-plasma interaction. They conjectured that electron beams emitted from the shuttle resemble field-aligned columns of dilute negative space charge moving across the ionosphere at orbital speed. This hypothesis requires that ions in the immediate vicinity of the beam be modulated at the same frequencies as the resonant electrons. During TSS 1, no significant shuttle charging occurred.

Beam-plasma interaction experiments were also conducted during the reflight of the Tethered Satellite System (TSS 1R) in 1996 with two critical differences. First, the tethered satellite was deployed and second, two different electron beam emission devices were employed. The beams heated ambient electrons, some fraction of which returned to conducting surfaces of the shuttle, occasionally charging it to < -10 V [Burke *et al.*, 1998a, b]. Fluxes of ambient ions accelerated across the sheath were monitored by the Shuttle Potential and Return Electron Experiment (SPREE) in the payload bay. Modulation characteristics of incoming fluxes were measured by the Spacecraft Particle Correlator Experiment (SPACE) which processed particle measurements made by the SPREE [Gough *et al.*, 1997].

The purpose of this observational paper is to demonstrate that the beam emissions of TSS 1R led to the detection of LF modulations of both electron and ion fluxes, consistent with the Cerenkov-generation hypothesis. We first briefly describe relevant TSS instruments, then present examples of modulated electron/ion fluxes

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detected during the TSS 1R deployment and compare these modulations with those observed on TSS 1. The Cerenkov hypothesis suggests that different frequency responses, measured with the two emission devices operating resulted from different degrees of beam spreading as electrons emerged into the ambient plasma.

Instrumentation

The full complement of TSS instrumentation, including SPREE/SPACE [Oberhardt *et al.*, 1994], FPEG [Agüero *et al.*, 1994] and electron generator assembly (EGA) [Bonifazi *et al.*, 1994] is described in *Il Nuovo Cimento* [1994]. The SPREE consisted of two triquadrangular electrostatic analyzers (ESAs) mounted on rotary tables. Fluxes of electrons and ions were measured in 32 logarithmically spaced energy channels ranging from 9.8 eV to 10 keV. The ten angular zones span a latitudinal range of $\sim 100^\circ$ from shuttle horizontal to shuttle zenith. SPACE consisted of a set of microprocessors which analyzed the particle detection pulses made by the SPREE ESAs. The LF units accumulated autocorrelation functions (ACFs) for 3 s intervals. Sampling occurred in three frequency ranges: 0 - 1.25 kHz, 0 - 5 kHz, and 0 - 10 kHz which were switched every 90 s. A 32-point ACF of intervals ("lags") was generated for each energy channel for each zone. From this a fast Fourier transform (FFT) can be generated to show the frequencies of modulations in the particle fluxes. The time corresponding to one lag is given by $\Delta t = 1/2f_{\max}$, where f_{\max} is the maximum frequency in the range being measured (1.25, 5, or 10 kHz). A detailed description of the instrument and this technique is given by Gough *et al.* [1997] and references therein.

The EGA consisted of two diodes, each of $\sim 6.4\mu\text{P}$ perveance, with the cathodes attached to the shuttle end of the tether and anodes connected to shuttle ground [Bonifazi *et al.*, 1994]. Only one EGA operated at a time and fired toward shuttle zenith. The FPEG can generate 100 mA in dc or pulsed modes. Beam elec-

trons were emitted 23° above the shuttle's right wing at an energy of 1 keV. FPEG could be fired with the tether isolated from shuttle ground or connected to it by one of four resistors, ranging from 15 Ω to 2.5 M Ω [Agüero *et al.*, 1994].

Observations

The observations presented here were made when the tether was deployed between 6 and 16 km and either FPEG or the EGA was firing in dc mode. Table 1 summarizes conditions at the times of significant LF modulations. From left to right the columns list event number, universal time of the observation on days 56 and 57, particle species which exhibited modulations, energies, E, in electron-volts and frequencies, F, in Hertz of detected modulations, energies, E_B , of beam electrons in electron-volts, tether current, I_T , in milliamps, shuttle potential, Φ_S , in volts, magnetic field in nanoTesla, beam pitch angle, α_B , and beam-electron gyroradius, ρ_B , in meters. Events 9, 10 and 12 were FPEG firings, the rest were by the EGA.

Ion modulations were observed in six TSS 1R events. An example (event 12) is shown in Figure 1a. This event occurred on day 57 at 0043:26 UT with FPEG firing. Plate 1B of Burke *et al.* [1998b] shows that the 25 k Ω resistor was in the circuit and that the shuttle charged to -55 V. Figure 1a includes the FFT of the signal received in zone 6 (left plot) and the corresponding ACF (center) which shows a coherent signal corresponding to a single modulation frequency of 1.25 kHz. The energy of the modulated ions was 55 eV, corresponding to the shuttle potential. The SPREE ion spectrum (right plot) exhibits a sharp peak at this energy. No electron modulations were observed at this time. An example of an electron flux modulation (event 10) is shown in Figure 1b in the same format as Figure 1a. The FFT and ACF are plotted for the lowest energy channel in zone 6 on day 57 at 0007:27 UT, again while FPEG was firing but with the shuttle uncharged. The ACF

Table 1. TSS 1R parameters during LF modulations

Event	Day/UT	Species	E	F	E_B	I_T	Φ_S	B	α_B	ρ_B
1	56/2317:06	i^+	86	469	671	129	-86	34867	84°	2.0
2	56/2348:07	e^-	18	1250	835	180		36393	138°	2.1
3	56/2349:51	e^-	28	312	872	192		35377	139°	2.0
4	57/0000:08	e^-	527	391	875	193		24700	131°	2.9
5	57/0001:30	e^-	69	4690	835	180		23482	128°	2.9
6	57/0002:00	e^-	213	469	772	160	-10	22639	125°	2.9
7	57/0003:10	i^+	28	469	623	116	-28	21641	121°	2.8
8	57/0003:16	i^+	28	312	623	116	-28	21401	120°	2.8
9	57/0006:26	e^-	14	625	1000	2		18958	32°	4.0
10	57/0007:27	e^-	9	938	1000	2		18666	23°	4.0
11a	57/0042:24	i^+	14	625	627	117	-14	35343	49°	1.7
11b	57/0042:24	e^-	69	625	627	117	-14	35343	49°	1.7
12	57/0043:26	i^+	55	1250	1000	98	-55	36649	9°	2.0
13	57/0051:18	i^+	55	781	1429	403	-55	34630	92°	2.6

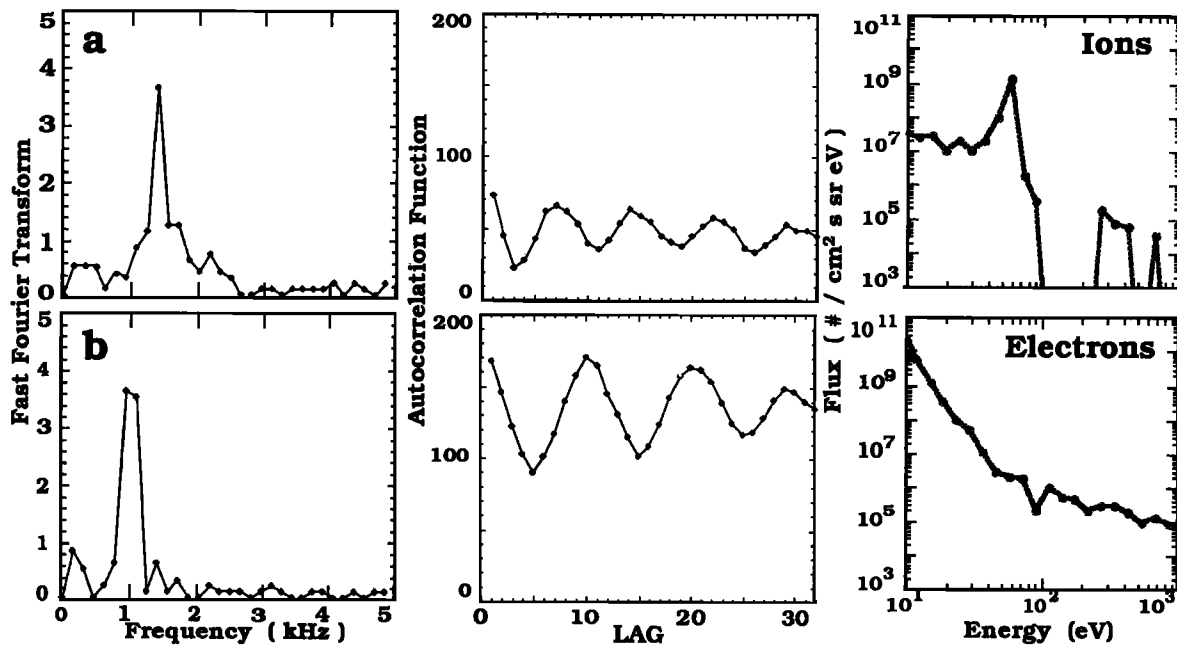


Figure 1. a. Fast Fourier transform (FFT), auto correlation function (ACF), and energy distribution for modulated ions observed during event 12 of Table 1. b. FFT, ACF, and energy distribution for modulated electrons observed during event 10 of Table 1.

shows a clear signature whose FFT peaks at 938 Hz. Only electrons in the energy channel centered at 9.8 eV were strongly modulated. The SPREE spectrum appears stable, which is consistent with TSS 1 LF results [Gough *et al.*, 1997]. Note from Table 1 that the tether current is small, 2 mA. This is similar to TSS 1 results when electron modulations were observed while FPEG was decoupled from the tether part of the circuit.

Event 11 shows that electrons and ions can be modulated simultaneously at the same frequency but different energies. The modulations and spectra are similar to those in Figure 1. While the ion spectrum peaks at 14 eV, corresponding to the magnitude of the shuttle potential, modulated electrons are seen at energies ≤ 69 eV. Simultaneously modulated ions and electrons are rare, mainly because observations of modulated ions require that the shuttle be charged to < -10 V.

Discussion

The relevant facts that must be accommodated in any theoretical explanation of the SPACE data presented here are: (1) LF modulations in both ion and electron fluxes are observed simultaneously and independently. (2) Observed frequencies of 1.28 ± 0.50 and 0.65 ± 0.23 kHz for electrons and ions respectively correspond to no naturally driven plasma oscillation. (3) At the modulation energies electron distribution functions are stable, *i. e.* $\partial f / \partial v < 0$. (4) The energies of modulated ions always correspond to the shuttle potential. Ambient ions could only be detected by SPREE when the shuttle was charged negatively.

Cai *et al.* [1987] suggested that oscillations in the shuttle potential could modulate particle fluxes. However, this should cause fluxes at all energies to be modulated. Our observations show that electrons are modulated in limited energy ranges. Feng *et al.* [1992] detected ion acoustic-like waves in the shuttle wake during FPEG emissions with frequencies between 0.2 and 0.4 kHz in the rest frame of the plasma. They proposed that electrons returning to the shuttle constitute a current which drives ion acoustic or high harmonic ion cyclotron waves [Kindel and Kennel, 1971]. Our simultaneous detection of modulated ions and electrons in the payload bay makes this explanation appear unlikely. Further, the shuttle's orbital speed does not allow for growth of ion acoustic waves to large amplitudes.

Gough *et al.* [1997] suggested that charge neutrality within electron beams is not fully achieved. To the ambient plasma the beam appears to be a field-aligned column of dilute negative space charge attached to and moving with the shuttle across the magnetic field. Since the shuttle moves faster than the ion acoustic speed, the beam column interacts with the ambient plasma to emit Cerenkov radiation in either ion acoustic or high harmonic ion cyclotron mode [Krall and Trivelpiece, 1973]. An estimate of the frequencies emitted by the moving beam can be obtained from the time, T_c , required for the beam width moving at the shuttle speed of ~ 7.7 km/s to cross a point in space. The excited frequency f_c would then be $\frac{1}{T_c}$.

Figure 2 compares observed modulation frequencies for both species relative to the beam-crossing frequency, f_c , for the events in this and TSS 1 studies. Open circles

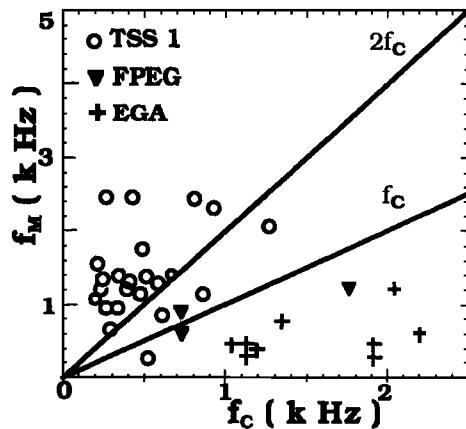


Figure 2. Scatter plot of modulation frequencies versus those estimated from beam crossing times.

represent TSS 1 data from Figure 11 of [Gough *et al.*, 1997]; filled triangles and "+" signs represent measurements during FPEG and EGA emissions listed in Table 1. TSS 1 data for FPEG firings generally lie above the $f_M = f_C$ line. Gough *et al.* [1997] suggested that higher frequencies are excited as ambient ions respond to space charge irregularities caused by electron drift waves on the beam's edges [Neubert *et al.*, 1986]. Most EGA events lie below the $f_M = f_C$ line. The difference between EGA and FPEG results may lie in the beam characteristics, in particular the degree to which the beam spreads. We estimate the beam diameter as twice the electron gyroradius (typically ~ 1 m), assuming no spreading. Computer simulations show rapid divergence of the electron beam immediately upon emission [Okuda and Ashour-Abdalla, 1990]. While we have no way to estimate the true spreading of the beams emitted during flight we infer that the EGA beam spreads to a greater extent than does the FPEG beam. While imperfect, the Cerenkov emission mechanism does meet the requirements for generating ion acoustic-like waves in the vicinity of the shuttle. Detailed calculations that take into account the characteristics of both beams and external plasmas require computer simulations that are well beyond the scope of this observational report.

Acknowledgments. This work was supported by the U. S. Air Force Office of Scientific Research task 2311PL014, Air Force contract F19628-96-K-0030 with Boston College, and the Particle Physics and Astronomy Research Council of the UK. The authors thank N. Bonito, C. Roth, and E. Courtney of RADEX, Inc., who designed and maintained the SPREE software.

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(Received September 24, 1997; revised November 21, 1997; accepted January 19, 1998.)