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CONTINUUM RADIATION AND ELECTRON PLASMA OSCILLATIONS IN THE DISTANT GEOMAGNETIC TAIL

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Abstract. ISEE-3 electric field measurements are used to examine the properties of electromagnetic continuum radiation in the distant geomagnetic tail. Continuum is observed in all the tail's plasma regions and in the magnetosheath. The power spectrum at 210 R_E is nearly identical to that at 40 R_E, indicating that the tail cavity forms a reasonably loss-free waveguide. The angular distribution exhibits both anisotropy, which is similar to that observed nearer the earth, and isotropy for high frequencies (f > 31.6 kHz) in the magnetosheath and for low frequencies (f $\leq$ 17.8 kHz) in the tail lobes and boundary layer. Isotropic radiation suggests that, in addition to the near earth source, continuum is also generated over a large spatial region in the tail. Electrostatic electron plasma oscillations are also detected in the in the distant tail, and these could represent the local source of the continuum.

Introduction

The near earth magnetospheric cavity is filled with low amplitude, spectrally continuous electromagnetic radiation which propagates above the local electron plasma frequency (Brown, 1973; Gurnett and Shaw, 1973). From an extensive study using IMP-6 and IMP-8 at r < 40 R_E, Gurnett (1975) divided this continuum radiation into two classes: (1) trapped continuum characterized by frequencies in the range 5 kHz < f_c < 20 kHz (or $f_c < f_p$ in the solar wind); and (2) escaping continuum with 20 kHz < f_c < 100 kHz (or f below the range for auroral kilometric radiation) (Gurnett, 1975; Kurth et al., 1981; Barbosa, 1982). Escaping continuum exhibits discrete frequency structure, significant spatial and temporal variability, and a strong anisotropy modulation, m = 0.8, in the angular distribution of intensity; here $m = 1-E^2(\min)/E^2(\max)$ where E(min), E(max) are the minimum and maximum electric field amplitude detected during a 360° scan. Trapped continuum has a generally featureless spectrum, a weak radial variation in intensity, and a low anisotropy m = 0.2. Analysis of propagation directions for the escaping continuum indicates that the wave source region is located just outside the dawnside plasmapause (Gurnett, 1975; Kurth et al., 1981). The lower anisotropy and smoother frequency spectrum of the trapped continuum suggest that the waves undergo multiple reflections from the magnetosheath plasma, and thus quasi-uniformly fill the magnetospheric cavity. Finally, in the near earth tail, Gurnett et al. (1976) noted that the low frequency cut-off of the continuum was approximately constant and independent of satellite location. They concluded that the cut-off frequency must be determined by the plasma frequency at the continuum source.

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In this letter we use plasma wave observations from ISEE-3 to investigate the properties of continuum radiation in the distant geomagnetic tail. We have chosen a 6 hour interval (0000 UT to 0600 UT) on January 24, 1983 when ISEE-3 at r ≈ 210 R_E passed from the magnetosheath into the tail boundary layer and subsequently into the tail lobe and plasma sheet (see Bame et al., 1983); hence we can study continuum in all the different tail plasma regions. In close association with the continuum we also observe electron plasma oscillations (Langmuir waves).

Continuum Radiation Observations

Figure 1 displays the electric field amplitudes for the top 8 frequency channels from 1.78 kHz to 100 kHz. The dark curve denotes the local electron plasma (or upper hybrid) frequency which is calculated from the electron density measurements, and the bar code, at the bottom, indicates the tail plasma regions (Bame et al., 1983). We concentrate our analysis on plasma waves detected near and above f_p.

From 0000 UT to 0115 UT ISEE-3 was in the magnetosheath with local $f_p \sim 25$ kHz. The 31.6 kHz E-field channel detected large amplitude, impulsive (high peak-to-average ratio) signals which we identify as electrostatic electron plasma oscillations (Scarf et al., 1971). Between 0011 UT and 0030 UT the high intensity peaks disappear, and a low and constant amplitude persistent emission is evident, which is characteristic of electromagnetic waves. Electromagnetic plasma waves propagate over much larger distances than do Langmuir waves, and therefore usually exhibit smooth amplitude profiles since a large source region is sampled by the wave detector. (Note the smooth profile of the Type III solar radio burst near 0300 UT.) After a short burst of plasma oscillations (0030 UT to 0040 UT), the electromagnetic waves persist throughout the remainder of the time interval. Figures 2a, b, c show the angular distributions of the 31.6 kHz electric field amplitudes at 0012, 0018, and 0127 UT. Each angular distribution is formed from 360 successive electric field measurements made 0.5 second apart. The E-field antenna is oriented in the ecliptic, perpendicular to the spin axis; the ISEE-3 spin frequency is about 1/3 Hz so that successive E-field measurements are plotted about 60° apart. In the 0012 UT angular distribution, the high amplitude, scattered points are interpreted as the impulsive electron plasma oscillations. A comparison of Figure 2a with the 0018 UT angular distribution, when only the electromagnetic waves are detected,

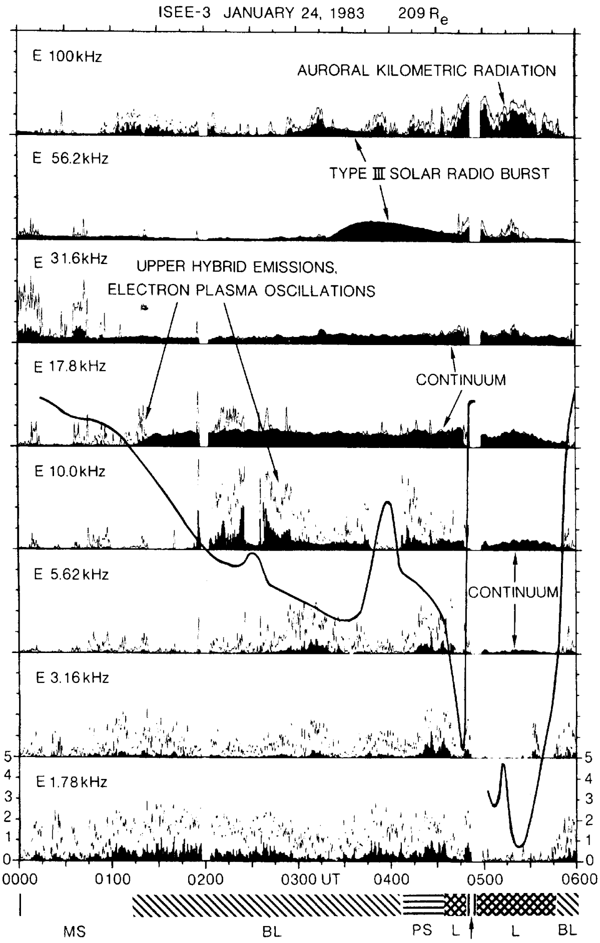

Fig. 1. Electric field wave measurements from 1.78 kHz to 100 kHz obtained by ISEE-3 on January 24, 1983. The filled-in curve denotes the 128-second average amplitude during the averaging interval. The solid curve denotes the local value of the electron plasma frequency. The bar graph at the bottom indicates the spatial region as determined by Bame et al., 1983; MS = magnetosheath, BL = boundary layer, PS = plasma sheath, L = lobe. Impulsive signals (high peak-to-average ratio) with $f \geq f_p$ are interpreted as electron plasma oscillations. Signals with $f \geq f_p$, smooth amplitude variations, and low peak-to-average ratios are interpreted as electromagnetic plasma waves.

demonstrates that the isotropic, low amplitude "ring" in the 0012 UT plot is due to the electromagnetic signal.

Near 0115 UT ISEE-3 entered the magnetotail boundary layer. The plasma density decreased smoothly from ~ 8 cm^{-3} (f_p = 25 kHz) in the magnetosheath to a local plateau of 1.8 cm^{-3} (f_p = 12 kHz) by 0127 UT; the flow speed decreased sharply from 330 km/sec to 250 km/sec at 0127 UT. Although the 31.6 kHz wave amplitude increased very slightly upon entering the boundary layer, the angular distribution changed from isotropic at 0121 UT to anisotropic (m = 0.37) at 0127 UT (Figure 2c), and remained anisotropic thereafter. The anisotropy results from the increased amplitude of waves with k-vectors directed away from (or toward) the earth. The amplitude of waves with k-vectors orthogonal to the tail axis remained unchanged from the earlier magnetosheath value.

During the gradual density decrease ISEE-3 also detected impulsive electron plasma oscillations at 17.8 kHz which began with low amplitudes near 0045 UT and became very intense near 0120 UT when $f_p \approx 17.8$ kHz (Figure 1). As the plasma oscillations decayed, the 17.8 kHz average amplitude increased, becoming roughly constant after 0130 UT. Figure 2d and 2e exhibit the 17.8 kHz angular distributions at 0118 UT and 0124 UT. In Figure 2d the high amplitude electron plasma oscillation points surround a low amplitude isotropic ring. By 0124 UT the Langmuir waves are gone, and the higher amplitude isotropic distribution is due to the smooth electromagnetic continuum radiation.

As ISEE-3 penetrated deeper into the boundary layer, the plasma frequency decreased to $f_p < \sim 10$ kHz near 0200 UT. Once again ISEE-3 detected

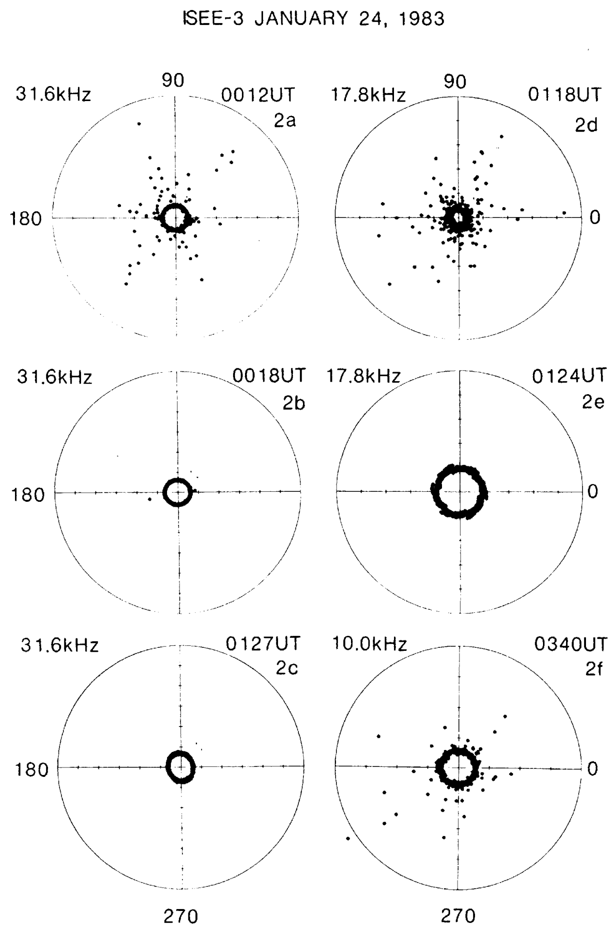

Fig. 2. Angular distributions of electric field amplitudes in the ecliptic plane; 0° is sunward and 90° is toward dusk. Each plot contains 360 successive points measured 0.5 seconds apart, or approximately 60° in rotation phase. The scattered high amplitude points are interpreted as Langmuir waves. The continuous, low amplitude rings are interpreted as electromagnetic radiation.

very strong electron plasma oscillations and an underlying lower amplitude continuum. The angular distributions at 0230 UT (not shown), during and interval in which Langmuir waves are absent, and at 0340 UT (Figure 2f) show that the angular distribution of the 10 kHz continuum is isotropic. The plasma oscillations remain active until 0345 UT when both they and the continuum are cut-off by a brief interval of higher density (f_p > 10 kHz) plasma. Both wave modes remained excited as ISEE-3 passed into the plasma sheet (0405 UT), then into the tail lobe (0435 UT), and briefly into the magnetosheath (0448 UT). During the interval 0200 to 0448 UT, the angular distribution at 31.6 kHz was anisotropic with m varying between 0.3 and 0.4, while the 17.8 kHz and 10.0 kHz distributions were isotropic.

After 0500 UT ISEE-3 entered the tail lobe, and the electron density fell to values near 0.03 - 0.04 cm^{-3} ($f_p \approx 1.6 - 2.0$ kHz). Figure 1 shows that although continuum radiation was detected at 5.6 kHz, no signal was measured at 3.16 kHz. In Figure 3 we have plotted the E-field amplitude spectrum at 0519 UT. The continuum has a broad peak between 5.6 kHz and 31.6 kHz, while the amplitude of the 3.16 kHz and 1.78 kHz channels are at the detector threshold. We have also plotted the E-field spectrum obtained by Gurnett (1975) on IMP-8 at 41 R_E in the midnight sector of the tail. With the exception of the Auroral Kilometric Radiation (AKR) enhancement at 100 kHz, the ISEE-3 and IMP-8 continuum spectra are nearly identical.

Figure 4 displays the angular distributions from 5.6 kHz to 100 kHz measured at 0519 UT. The 5.6 and 10 kHz distributions are isotropic (m = 0). At higher frequencies, the angular distributions are clearly anisotropic with m = 0.37 for 17.8 and 31.6 kHz m = 0.67 for 56.2 kHz, and m = 0.96 for 100 kHz. The three high frequency angular distributions also exhibit a definite asymmetry with respect to the earth-sun line. The 100 kHz waves are almost certainly auroral kilometric radiation; the source of the 56.2 and 31.6 kHz radiation is less certain (see below), but presumably a substantial fraction also originates near the earth. For an earthward source the orientation of the asymmetry implies that the highest amplitude waves arrive at ISEE-3 from a direction which is dusk-ward of the earth-sun line.

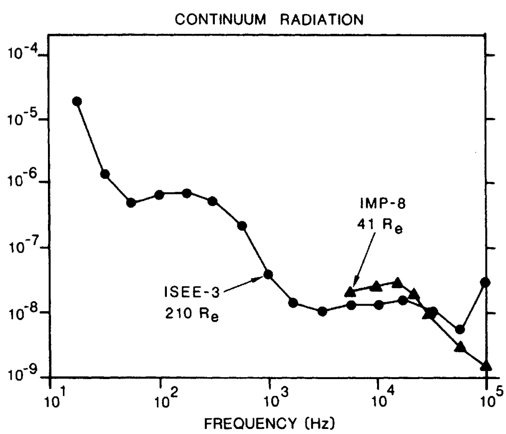

Fig. 3. Electric field amplitude spectrum in volts/meter -$(Hz)^{1/2}$. The solid dots are the ISEE-3 measurements obtained at a distance of 210 R_E in the tail lobes; the solid triangles were obtained by Gurnett (1975) on IMP-8 at 41 R_E.

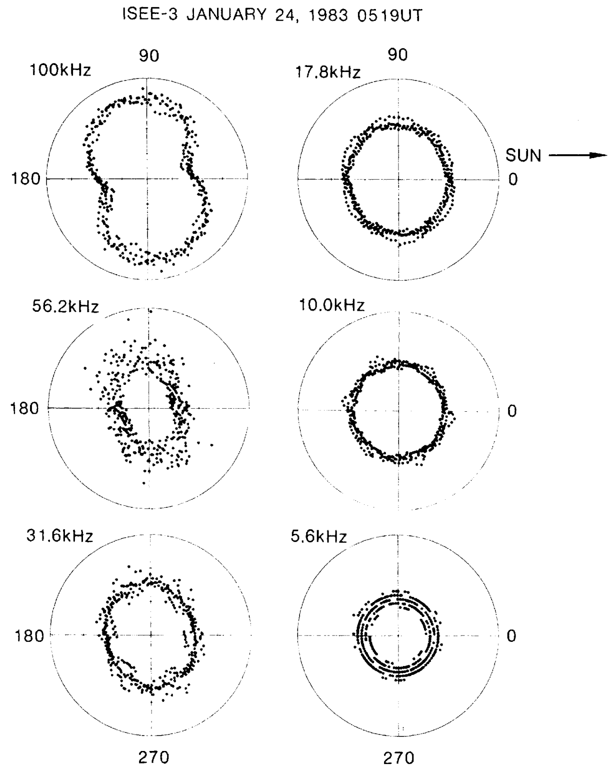

Fig. 4. Angular distribution of the electric field amplitude measured at 0519 UT when ISEE-3 was located in the tail lobes. The local electron plasma frequency was ∿ 1.8 kHz. The continuum is isotropic at 5.0 and 10.0 kHz, and becomes progressively more anisotropic at higher frequencies.

Discussion

The continuum radiation in the distant geomagnetic tail exhibits some properties which are familiar from studies conducted nearer the earth, and others which are new. The amplitude spectrum measured by ISEE-3 at 210 R_E is virtually identical to the IMP-8 spectrum observed at 41 R_E. The similarity between the 41 R_E and 210 R_E spectra indicates that the tail forms a relatively constant cross-section wave guide, and that little wave energy is lost by leakage out the sides of the tail cavity. The low frequency, 5.6 kHz cutoff of the continuum is consistent with the IMP-8 observations of Gurnett et al. (1976). Either the continuum is generated in regions where the plasma density exceeds about 0.3 cm^{-3}, or, if the continuum is generated in the lower density tail lobes (~ 0.01 - 0.03 cm^{-3}), its amplitude is quite weak. Within the tail, the density exceeds 0.3 cm^{-3} in the plasma sheet, the tail boundary layer, and the magnetosheath; hence, as originally suggested by Gurnett (1975), these regions may be sites of continumm generation.

The angular anisotropy of the 56 kHz and 100 kHz continuum and AKR observed at 210 R_E is similar to the IMP-8 measurements, indicating that the high frequency radiation propagates to ISEE-3 from the earth. At 50 - 100 kHz, the wave frequency exceeds the electron plasma frequency in the magnetosheath (at least on January 24, 1983), so that, naively, this radiation might be expected to escape from the tail cavity; this implies that these waves would arrive at ISEE-3 with a reduced (about 1/5) amplitude relative to those observed by IMP-8. However, electromagnetic plasma waves reflect when $f = f_p \sec \theta$ where θ is the angle of incidence measured from the local normal to the density gradient. Hence 100 kHz (56 kHz) waves reflect off the magnetosheath when θ exceeds 75° ($\sim$60°); this condition is easily met well within 210 R_E for a large fraction of the rays which propagate away from the earth in the anti-solar direction. Thus the tail cavity should also constitute a good wave guide for high, as well as low, frequency waves.

The angular anisotropy of the intermediate frequency (17.8 and 31.6 kHz) continuum exhibited a mixed character. In the tail lobes, both frequencies had $m = 0.3 - 0.4$ which is consistent with propagation to ISEE-3 from a near earth source. In the tail boundary layer, the 31.6 kHz anisotropy was also $m = 0.3$, but the 17.8 kHz waves were isotropic. Isotropic 31.6 kHz continuum was detected in the magnetosheath, and became anisotropic when ISEE-3 entered the boundary layer. The low frequency continuum (5.6 and 10.0 kHz) was isotropic both in the boundary layer (10 kHz) and tail lobe. Many other ISEE-3 continuum radiation events in the distant tail exhibit both isotropic and anisotropic angular distributions of a similar character.

If the only source of the intermediate and low frequency continuum is located near the earth, an isotropic angular distribution would imply that the tailward propagating waves experience many reflections and/or scatterings before reaching ISEE-3. However, the change from isotropic in the magnetosheath to anisotropic in the boundary layer of the 31.6 kHz continuum appears inconsistent with strong scattering of the 31.6 kHz radiation within the tail cavity. An alternative explanation for the observed isotropy is that there are two sources of intermediate and low frequency continuum--one localized near the earth and one which is more spatially distributed in the magnetosheath and tail boundary layer; the latter possibly was first suggested by Gurnett (1975). A possible continuum source is the strong electron plasma oscillations which were detected in the magnetosheath and boundary layer. Electron plasma oscillations are known to generate Type III radio bursts by either wave-wave scattering to produce 2 f_p electromagnetic radiation or by the scattering of Langmuir waves from low frequency density fluctuations (or gradients) to produce electromagnetic radiation at f_p (Hafizi et al., 1982). The simultaneous observation of impulsive, large amplitude Langmuir waves and an isotropic core of lower amplitude continuum is certainly suggestive of the direct local conversion of Langmuir to electromagnetic radiation.

In their report on the January 24, 1983 plasma observations, Bame et al. (1983) showed that the 0.5 - 1.0 keV electrons had a bi-directional streaming distribution in both the magnetosheath and boundary layer, and commented that bi-directionality was commonly observed in these regions. Streaming electron distributions are very likely to generate electron plasma oscillations by the conventional bump-on-tail Landau instability. Hence we suggest that the tail boundary layer and surrounding magnetosheath may also be a source of continuum radiation whenever Langmuir unstable electron distributions occur. Since streaming electrons travel great distances along the magnetic field, continuum will be generated over a large region of the magnetosheath and boundary layer, and thus the angular distribution of tail-generated continuum should be isotropic.

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