ELF Noise Bands Associated with Auroral Electron Precipitation

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Observations of a new type of ELF noise band that is closely associated with low-energy auroral electron precipitation are reported. These observations have been made at relatively low altitudes (<3000 km) with the polar-orbiting satellite Injun 5. The noise bands typically have a center frequency of 100–300 Hz and often appear to consist of many nearly monochromatic bursts, typically of a few seconds' duration, superimposed to produce the observed noise band. These ELF noise bands are observed only in a relatively narrow range of latitudes (a few degrees) in the auroral zone and are almost always associated with intense fluxes, 10^9 el cm^{-2} sec^{-1} $ster^{-1}$, of precipitating electrons with energies from a few hundred electron volts to several kiloelectron volts. On the dayside of the magnetosphere the region where the ELF noise bands and the associated low-energy electron precipitation are observed has been identified as the polar cusp. In considering the possible explanations of these ELF noise bands it is noted that the spectral characteristics of this noise are very similar to a type of narrow-band electromagnetic noise called 'lion's roar,' which has been observed at much higher altitudes in the magnetosheath with the satellite Ogo 5. It is suggested that the ELF noise bands observed at low altitudes with Injun 5 are caused by lion's roar emissions that have propagated down 'open' magnetic-field lines to low altitudes from the magnetosheath region.

CHARACTERISTICS OF ELF NOISE BANDS

Intense bands of extremely low frequency (ELF) electromagnetic noise are frequently observed with the low-altitude polar-orbiting satellite Injun 5 in association with low-energy auroral electron precipitation and VLF auroral hiss events. (See *Gurnett et al.* [1969] for a description of the VLF instrumentation on Injun 5.) A frequency-time spectrogram illustrating the spectral characteristics of this type of ELF noise is shown in Figure 1. Here the ELF noise band has a center frequency that varies from about 150 to 200 Hz and extends over about 2° invariant latitude (INV) with a maximum broad-band magnetic-field strength of about 60 mγ. This event occurred during the local evening at about 2130 magnetic local time (MLT).

The ELF noise bands of the type illustrated in Figure 1 usually have a band width of 100 Hz or less and a center frequency, which is remarkably similar from event to event, seldom greater than 300 Hz or less than 100 Hz. The frequency-time spectra of these emissions often appear to consist of many nearly monochromatic bursts, typically of a few seconds' duration, superimposed to give the appearance of a nearly continuous noise band. The individual nearly monochromatic bursts are evident in the frequency-time spectrum of the noise band shown in Figure 1. The duration of these ELF noise bands varies considerably from event to event, from a few seconds to several tens of seconds. ELF noise bands of this type are observed only in a narrow latitudinal region a few degrees wide in the auroral zone, typically at about 70° to 80° invariant latitude. The noise bands are observed with essentially identical spectral characteristics for both the electric and the magnetic antennas, and thereby the electromagnetic character of the noise is established. Typical broad-band electric- and magnetic-field strengths for these events are about 3–10 mv m^{-1} and 10–30 mγ, respectively.

These ELF noise bands are clearly distinguishable from chorus and ELF hiss, because of their distinctly different frequency spectra and region of occurrence. To our knowledge these ELF noise bands do not correspond to any of the well-known categories of magnetospheric ELF or VLF emissions [*Helliwell*, 1965] and represent an entirely new phenomenon insofar as low-altitude observations are concerned.

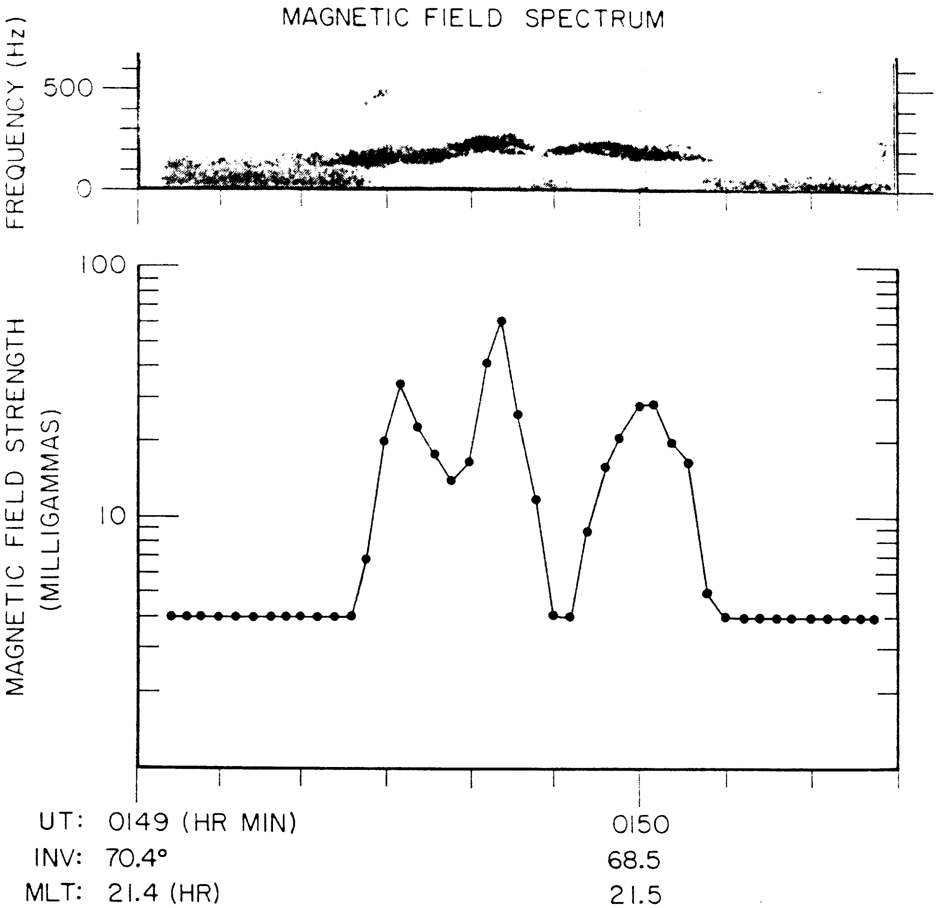

Fig. 1. Frequency-time spectrogram and magnetic-field strength of a typical auroral-zone ELF noise band observed during the local evening of December 9, 1968, with Injun 5 (resolution 1487).

Association with Low-Energy Electron Precipitation

ELF noise bands of the type shown in Figure 1 are found to be closely associated with inverted 'V' electron precipitation events of the type described by *Frank and Ackerson* [1971]. This association is illustrated by Plate 1, which shows the energy-time spectrogram of the precipitated electron flux observed simultaneously with the ELF noise band shown in Figure 1. (See *Frank and Ackerson* [1971] for a description of the charged-particle instrumentation on Injun 5.) The inverted 'V' energy-time structure evident from 01h 49m 30s to 01h 50m 10s UT in Plate 1 corresponds almost exactly with the location of the ELF noise band shown in Figure 1. As was discussed by *Frank and Ackerson* [1971, 1972], the characteristic inverted 'V' energy-time variation is primarily a spatial variation due to the latitudinal motion of the spacecraft as it passes through the precipitation region. Inverted 'V' electron precipitation events have been associated directly with visible auroral arcs on the same geomagnetic-field line [*Ackerson and Frank*, 1972]. From a detailed comparison of the events in Figure 1 and Plate 1 it is evident that the maximum field strength of the ELF noise band occurs near the boundaries of the inverted 'V' structure at times when the average electron energy is of the order of several hundred electron volts. The maximum precipitated electron flux in this event is about 10^9 el cm^{-2} sec^{-1} $ster^{-1}$.

The inverted 'V' events centered at 01h 48m 10s and 01h 48m 40s UT in Plate 1 are also associated with ELF noise bands similar to the event shown in Figure 1. All the inverted 'V' events and associated ELF noise bands on this pass are located poleward of the trapping boundary, at about 01h 50m 10s UT ± 10 sec, for electrons of $E > 45$ kev. Since the trapping boundary of the $E > 45$ kev electrons is believed to correspond to the boundary between open and closed geomagnetic-field lines, it is concluded that the ELF noise bands observed on this pass are on open field lines poleward of the trapping boundary.

Similar ELF noise bands and associated inverted 'V' electron precipitation events have been observed over a wide variety of local times. The events shown in Figure 2 and Plate 2 for a high-latitude pass through the afternoon local-time region provide another striking illustration of the association between these ELF noise bands and the low-energy electron precipitation. On the high-latitude part of this pass, from about 0455 to 0501 UT, the orbit is such that the spacecraft is moving along a trajectory of nearly constant latitude and increasing local time. During this part of the pass, which extends over almost 3 hours of magnetic local time, the spacecraft is also fortuitously following the longitudinal extension of an auroral arc and is repeatedly passing in and out of the region of intense low-energy electron precipitation. The times during which the spacecraft is in the auroral electron precipitation region are evident in Plate 2 from the intense fluxes (red) of electrons with energies up to several kiloelectron volts. This electron precipitation event is also of the general inverted 'V' form: however, since the spacecraft is moving longitudinally along the precipitation region, the usual latitudinal inverted 'V' energy variation is not so evident. This low-energy electron precipitation region is identified as the low-altitude extension of the dayside polar-cusp region, similar to previous observations by *Frank and Ackerson* [1971]. This identification is supported by the similarity of the electron energy spectrum to previous polar-cusp observations, the location

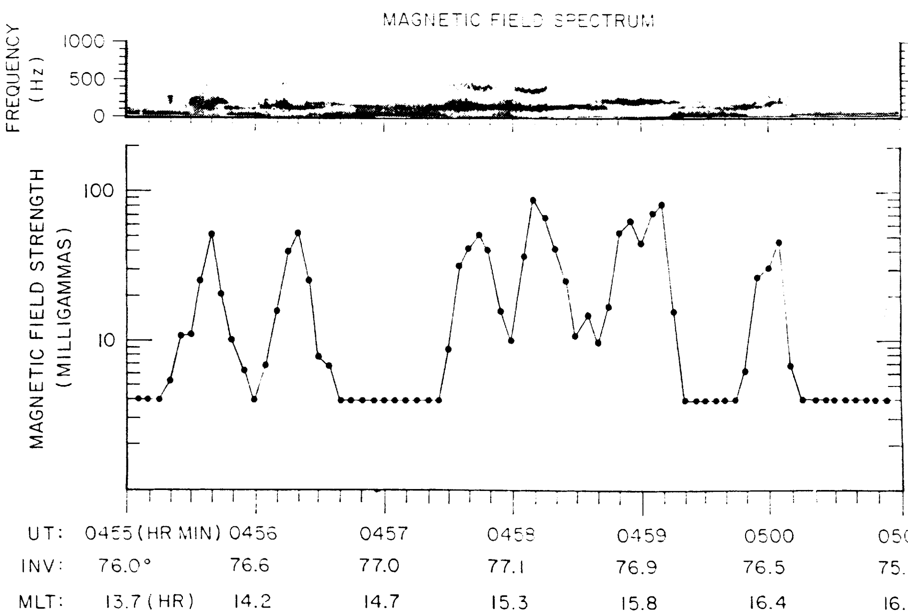

Fig. 2. Frequency-time spectrogram and magnetic-field strength of ELF noise bands observed during the high-latitude part of a pass over the northern polar region (December 17, 1968, revolution 1586). Note that the invariant latitude (INV) during this period is nearly constant, whereas the magnetic local time (MLT) changes by more than 3 hours.

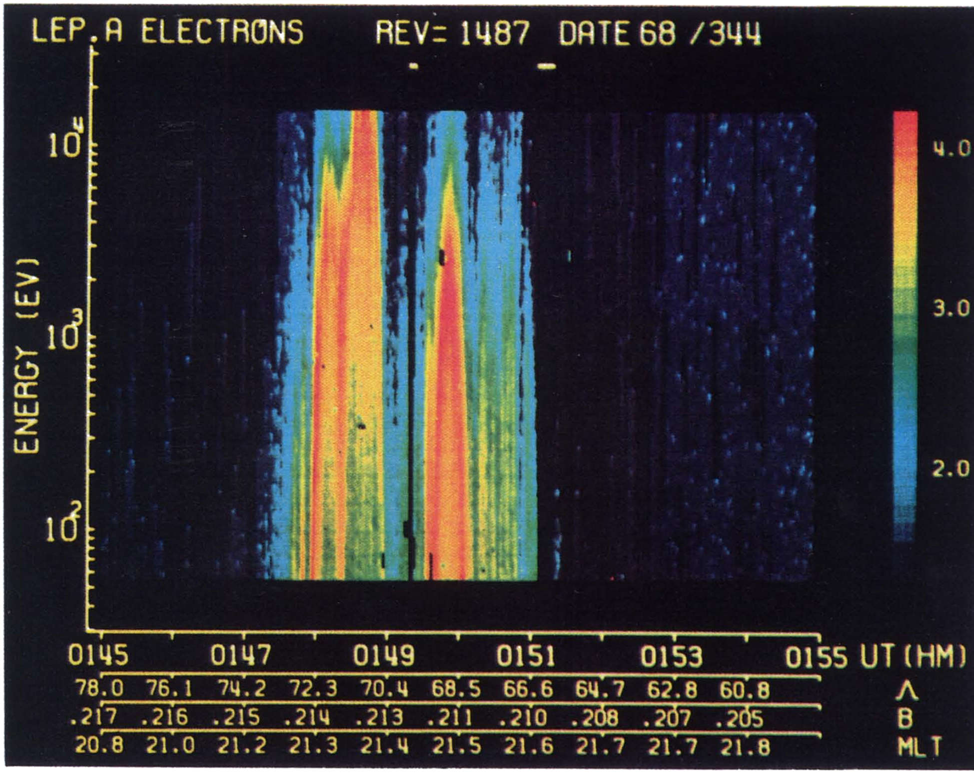

Plate 1.

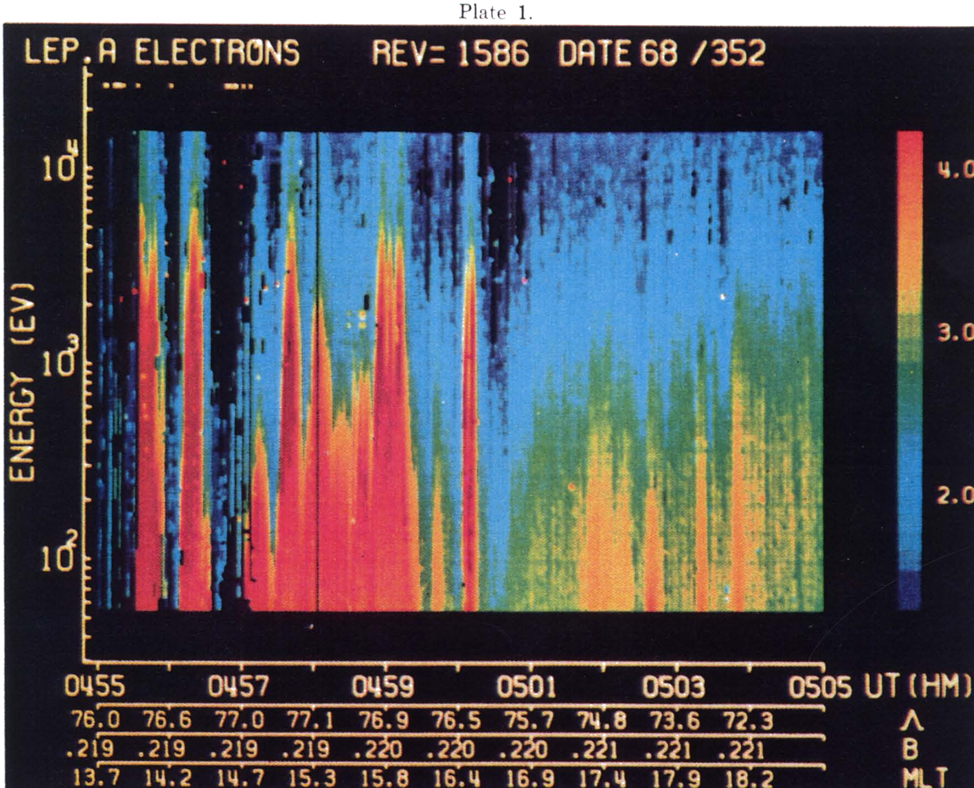

Plate 2.

poleward of the $E > 45$ kev electron trapping boundary (at 05h 03m 55s UT ± 10 sec on this pass) on the dayside of the magnetosphere, and the simultaneous occurrence of intense VLF hiss of the type known to be generated in the polar-cusp region [*Gurnett and Frank*, 1972]. By comparing the precipitated electron fluxes shown in Plate 2 with the intensity of the ELF noise bands shown in Figure 2, it is evident that, when the spacecraft is in the region of intense electron precipitation, an ELF noise band is observed and, when the spacecraft is outside the precipitation region, the ELF noise band is absent. These observations strongly indicate that the ELF noise bands are closely associated with the dayside polar-cusp region and its longitudinal extension into the nightside of the magnetosphere.

Although ELF noise bands of the type illustrated in Figures 1 and 2 are very frequently observed in association with inverted 'V' electron precipitation events, cases have been found of inverted 'V' events for which no detectable ELF noise band is present. However, in every case investigated having an ELF noise band, a corresponding inverted 'V' electron precipitation event was observed.

Discussion

In comparing these observations with data from other satellites, it is evident that the ELF noise bands observed at low altitudes with Injun 5 have certain spectral characteristics similar to those of the narrow-band magnetic emissions observed by *Smith et al.* [1969] in the magnetosheath with the eccentric orbiting Ogo satellites. These magnetosheath emissions consist of tonelike bursts with frequencies typically between 50 and 200 Hz, last from 1 to 10 sec, and are referred to as 'lion's roar.' A frequency-time spectrogram of lion's roar observed in the magnetosheath with Ogo 5 is shown in the top panel of Figure 3 [from *Smith et al.*, 1969]. Note the difference in the time scales of Figures 1 and 3. By comparing the spectral characteristics of lion's roar with the ELF noise bands observed with Injun 5, the following relationships are noted: (1) the typical center frequencies and relative bandwidth for the two phenomena are very similar; (2) both phenomena are made up of nearly monochromatic bursts with durations of a few seconds; (3) the period between the individual bursts is usually shorter for the ELF noise bands observed by Injun 5 than for the lion's roar; sometimes the period is so short that the individual bursts in the ELF noise band are essentially unresolvable.

Because of the similarity of the spectral characteristics of these two phenomena, the question of whether the ELF noise bands observed with Injun 5 are in fact lion's roar emissions that have propagated downward from the magnetosheath region to the Injun 5 altitude naturally arises. This possibility is even more suggestive in view of the recent evidence by *Frank and Gurnett* [1971] that the inverted 'V' electron precipitation events, which occur in the same region as the ELF noise bands, occur on 'open' magnetic-field lines that extend into the magnetosheath region. This geometry is illustrated in Figure 7 of *Frank and Gurnett* [1971], which shows open magnetic-field lines (for example, B-B) extending from the magnetosheath, through the magnetopause, and down to low altitudes in the auroral zone. Since the ELF noise bands are observed only over a narrow range of latitudes, it appears that the lion's roar emissions must be guided very nearly along the magnetic field from the magnetosheath to low altitudes. As was discussed by *Smith et al.* [1969], the lion's roar emissions are believed to be propagating in the right-hand polarized whistler mode. Although whistler mode waves do not necessarily follow the magnetic-field lines because of magnetoionic guiding alone, it is well known from terrestrial whistler observations that, when suitable field-aligned density gradients are present, whistler mode waves are guided (ducted) almost exactly along the static magnetic field [*Helliwell*, 1965]. Therefore, if the ELF noise bands observed by Injun 5 are due to lion's roar emissions from

Plate 1. (Opposite) Energy-time spectrogram of precipitated electrons observed simultaneously with the ELF radio noise data shown in Figure 1. Note that the inverted 'V' energy-time structure from 01h 40m 30s to 01h 50m 10s UT corresponds to the ELF noise band in Figure 1.

Plate 2. (Opposite) Energy-time spectrogram of precipitated electrons observed simultaneously with the ELF radio noise data shown in Figure 2. Note the repeated occurrence of intense fluxes of low-energy electrons as the spacecraft passes longitudinally through the dayside polar-cusp region.

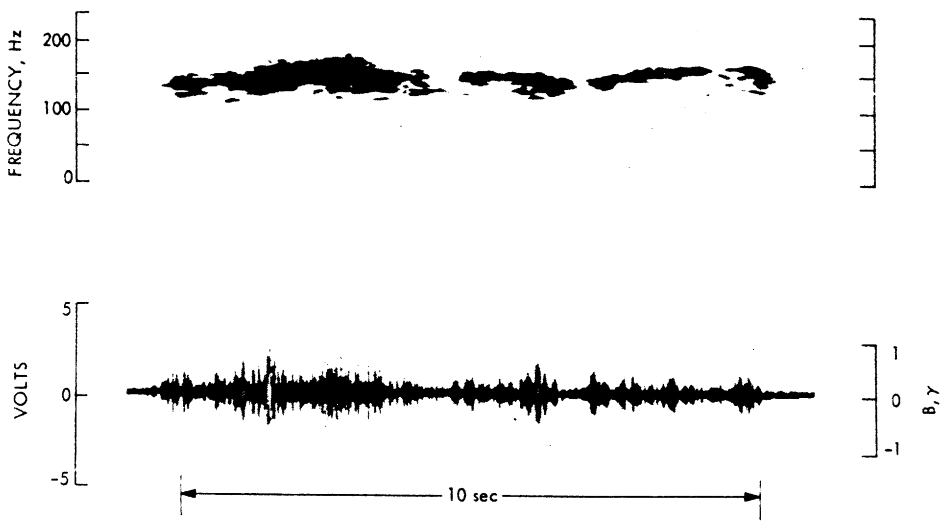

Fig. 3. Frequency-time spectrogram and wave-form signature of lion's roar observed in the magnetosheath with Ogo 5 on March 12, 1968, 17h 14m 31s GMT [from *Smith et al.*, 1969].

the magnetosheath, the field-aligned density gradients must play an essential role in guiding these waves down to the Injun 5 altitudes. Since density variations of only a few per cent are required to produce whistler mode ducting, it is virtually certain that the required density variations are present on these auroral-zone field lines [*Lund et al.*, 1967]. Even if whistler mode ducting is ineffective over part of the path, the magnetoionic guiding effect for whistler mode propagation will assure that, if the wave is initially propagating along the static magnetic field toward the earth, it must continue to propagate toward the earth until the lower hybrid resonance frequency exceeds the wave frequency as can only occur at relatively low altitudes ($<2 R_E$). Since the wave frequency is less than the electron gyrofrequency at all points along the path, there is no propagation cutoff or resonance that could prevent whistler mode propagation over this path. A possible exception is the $L = 0$ cutoff at low altitudes ($<$3000 km) discussed by *Gurnett and Burns* [1968]. However, if the waves are being ducted along the static magnetic field, the wave normal directions will be aligned nearly parallel to the static magnetic field, and mode coupling will prevent the $L = 0$ cutoff from being effective, much as mode coupling prevents the effectiveness of this cutoff for proton whistlers at high latitudes [see *Rodriguez and Gurnett,* 1971; *Wang,* 1971]. The shorter period between individual bursts and the tendency in some cases for the individual bursts to merge into a nearly continuous noise band at the Injun 5 altitude, mentioned earlier, can be accounted for by the 'funneling' of lion's roar emissions from a relatively large region of the magnetosheath into a small latitudinal region at the Injun 5 altitude, due to the convergence of the magnetic-field lines. The direction of propagation for the individual bursts in the ELF noise bands observed by Injun 5 has been determined by using the Poynting flux sensing techniques described by *Gurnett et al.* [1971]. Both downgoing and upgoing bursts are observed. The upgoing bursts are believed to be caused by the reflection of downgoing bursts below the satellite.

Since lion's roar emissions are believed to be nearly always present in the magnetosheath region, the question of why the corresponding ELF noise bands are not always observed when an inverted 'V' electron precipitation event occurs arises. At this time the answer to this question is not clearly understood although two possibilities occur. First, since the ducting of the lion's roar emissions down to low altitudes depends critically on the presence of field-aligned density gradients, it is possible that in some cases the necessary gradients have not been established from the magnetosheath down to low altitudes. Second, the occurrence of lion's roar has not yet been thoroughly studied, particularly at high latitudes; it may be that there are periods or regions within the magnetosheath for which few or no lion's roar emissions occur.

These considerations make it entirely plausible that the ELF noise bands observed at low altitudes with Injun 5 do originate from the high-altitude magnetosheath region. Despite this considerable body of supporting evidence it must be pointed out that without observations at intermediate altitudes in the polar magnetosphere this explanation cannot yet be regarded as totally conclusive, since it is always possible that some instability mechanism associated with the inverted 'V' electron precipitation events may also be able to account for all the observed characteristics. However, at the present time the interpretation of these ELF noise bands as having originated from the magnetosheath is considered the simplest and most likely explanation of this new phenomenon.

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