THE EARTH AS A RADIO SOURCE

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Abstract. Satellite low frequency radio measurements have revealed that the Earth is a very intense and interesting radio source with characteristics similar to other astronomical radio sources such as Jupiter, Saturn and the Sun. In this paper we summarize the primary characteristics of radio emissions from the Earth's magnetosphere, consider the origin of these emissions, and discuss the similarities to other astronomical radio sources.

1. Introduction

The Earth is usually not thought of as an intense radio source. However, in the past few years low frequency radio measurements by satellites have revealed that the Earth's magnetosphere is a very intense radio emitter, with characteristics similar to other astronomical radio sources such as Jupiter, Saturn and the Sun. In this paper we consider only radio emissions which can propagate freely away from the Earth at frequencies above the local electron plasma frequency. We do not discuss the many other types of whistler-mode waves and plasma instabilities which are present at frequencies below the electron plasma frequency.

The first clear evidence of intense radio emissions from the Earth's magnetosphere was obtained from satellite measurements by Benediktov *et al.* (1965, 1968) in which radio emissions at 725 kHz and 2.3 MHz were detected in association with geomagnetic storms. Later Dunckel *et al.* (1970) reported similar observations of intense radio emissions, also associated with magnetic disturbances, at frequencies below 100 kHz. Only recently, however, with radio and plasma wave instruments on the IMP-6 and IMP-8 satellites, have measurements been made over a sufficiently broad frequency range and with adequate sensitivity, dynamic range and directional resolution to provide a comprehensive picture of radio emissions from the terrestrial magnetosphere (Stone, 1973; Brown, 1973; Frankel, 1973; Gurnett, 1974, 1975).

As currently understood two principal types of radio emissions can be identified coming from the terrestrial magnetosphere. We refer to these radio emissions as auroral kilometric radiation and continuum radiation. The characteristic spectrums of these two types of radio emissions are illustrated in Fig. 1. In addition to these two principal types of radiation several other types of radio emissions of lower intensity and/or infrequent occurrence are known to occur which have not yet been studied in much detail. The purpose of this paper is to summarize the present state of knowledge concerning these radio emissions and discuss their origin and relationship to other astronomical radio sources.

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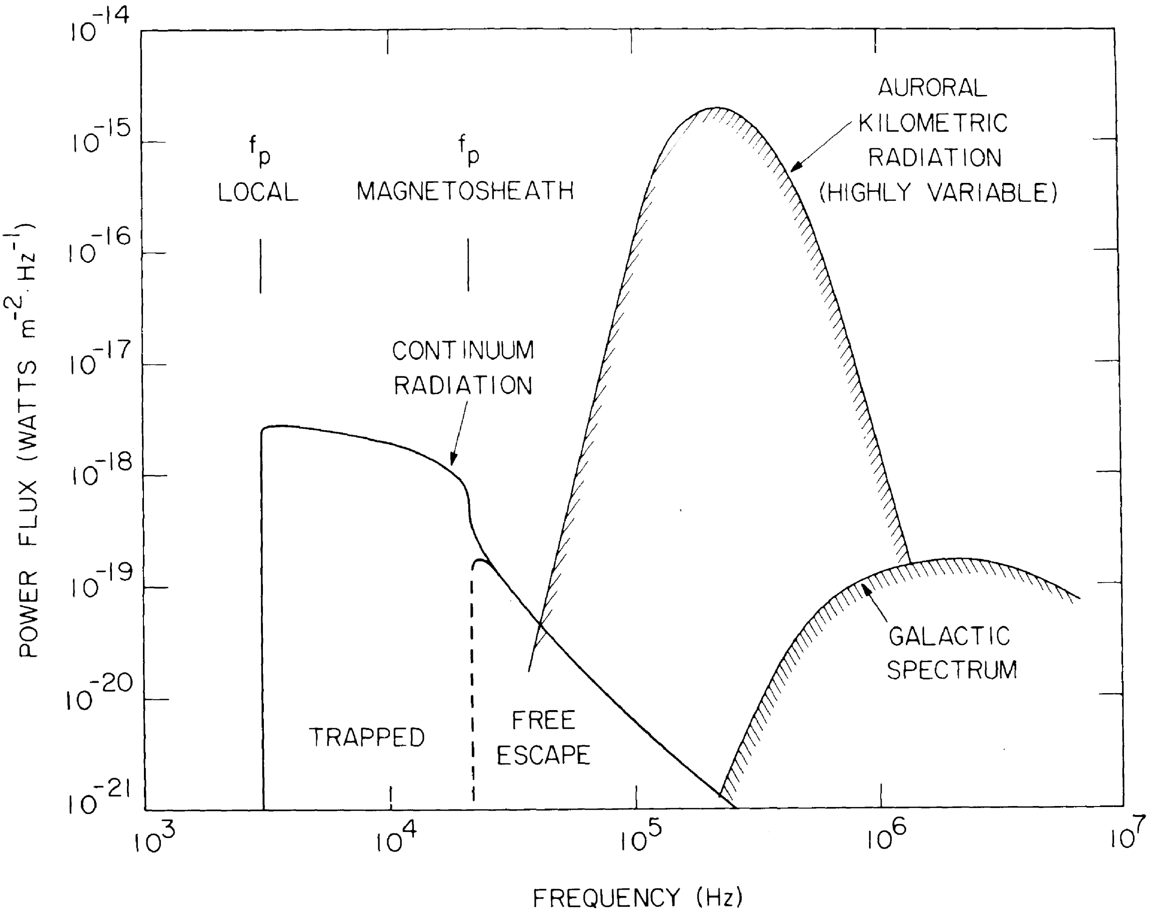

Fig. 1. The spectrums of the galactic background, the auroral kilometric radiation and the non-thermal continuum radiation as would be observed by a satellite $30 R_E$ from the Earth.

2. Auroral Kilometric Radiation

As shown in Figure 1 auroral kilometric radiation is characterized by a very intense peak in the frequency spectrum at about 100 to 300 kHz. The intensity of this radiation is highly variable. Sometimes the radiation intensity is below the galactic background and completely undetectable, while at other times the intensity is six to seven orders of magnitude above the galactic background at $30 R_E$ from the Earth. At peak intensity the total power radiated by the Earth exceeds 10^9 W (Gurnett, 1974). The Earth is therefore a very intense planetary radio source with a total power output comparable to the decametric radio emission from Jupiter. For comparison the total power of the decametric radiation from Jupiter has been estimated by Warwick (1963) to be about 2×10^7 W. More recent measurements indicate, however, that the power radiated by Jupiter may be somewhat larger than given by Warwick.

Auroral kilometric radiation has been previously called 'high-pass' noise by Dunckel *et al.* (1970) and 'midfrequency' noise by Brown (1973). Because of the close association of this radiation with the occurrence of auroral arcs (Gurnett, 1974) and the kilometer wavelength of the radiation we chose to refer to the radiation as auroral kilometric radiation. The close association of this radiation with the occurrence of auroral arcs is

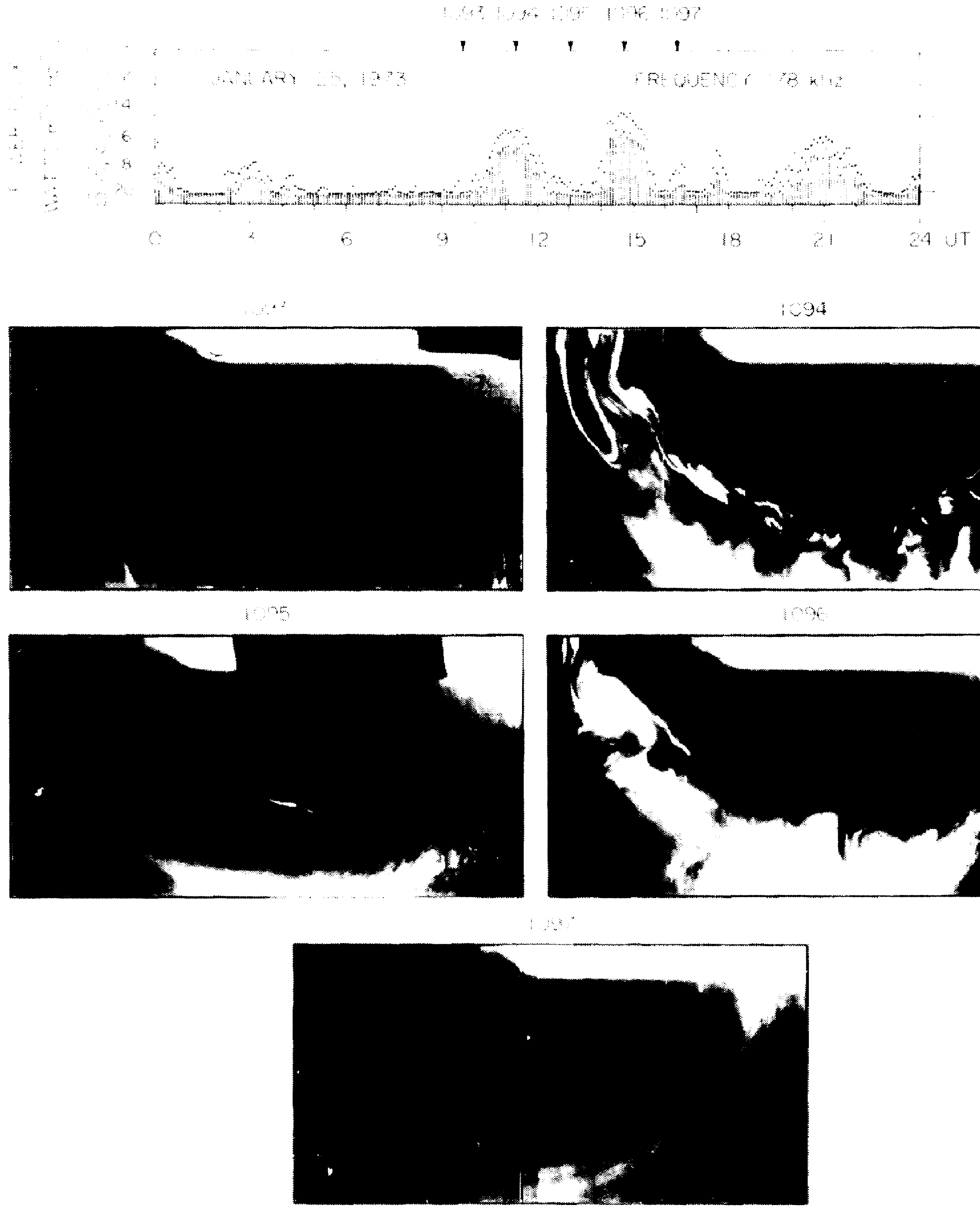

Fig. 2. The intensity of auroral kilometric radiation at 178 kHz and a sequence of photographs of the aurora over the northern polar region taken by the DAPP satellite. The intense bursts of auroral kilometric radiation are seen to be closely correlated with the occurrence of auroral arcs.

illustrated in Figure 2. The top panel of this illustration shows the radio noise intensity at 178 kHz for a 24 h period while the spacecraft (IMP-6) is about $30 R_E$ from the Earth. The bottom panels show a series of auroral photographs obtained during the same 24 h period by the low altitude polar-orbiting DAPP spacecraft as it passes over the northern polar region. Three intense bursts of auroral kilometric radiation occurred during this day, centred on approximately 1120, 1450, and 2100 UT. Each intense burst of auroral kilometric radiation is seen to be closely associated with the occurrence of bright discrete

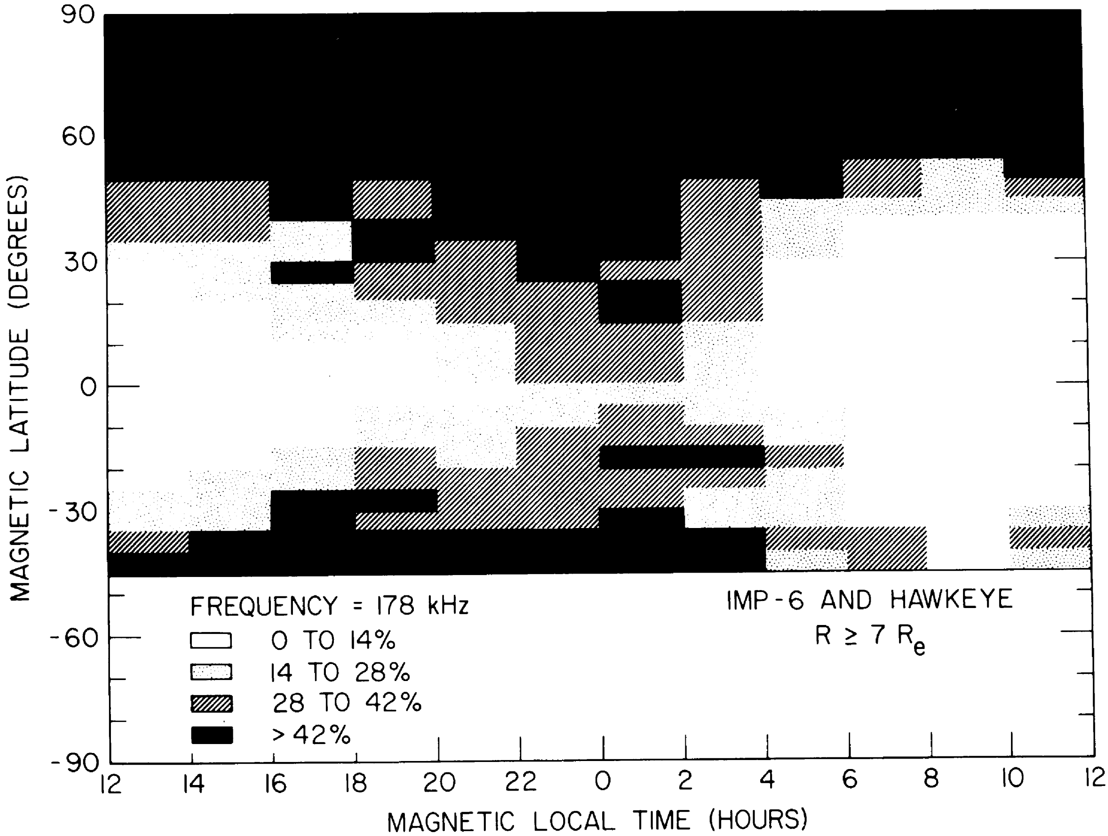

Fig. 3. The angular distribution of auroral kilometric radiation in magnetic coordinates.

auroral arcs in the DAPP photographs (one photograph for each orbit). Direction-finding measurements by Kurth and Gurnett (1975) show that the apparent center of the source of the auroral kilometric radiation is in the nighttime auroral region at a distance of about 0.75 R_E from the polar axis of the Earth. The association of this radiation with auroral arcs and the location of the source in the high latitude auroral regions strongly suggest that this radiation is produced by the same low energy electrons which produce the auroral light emissions. The association of the radio emissions with discrete auroral arcs rather than the diffuse aurora specifically implies that the noise is associated with intense 'inverted V' electron precipitation bands of the type discussed by Frank and Ackerson (1971) and Ackerson and Frank (1972).

Further information on the generation and propagation of the auroral kilometric radiation can be provided by measurements of the angular distribution of the radiation escaping from the Earth. Figure 3 shows the angular distribution of auroral kilometric radiation at a frequency of 178 kHz as obtained from the IMP-6 and Hawkeye-1 satellites. IMP-6 provides measurements at magnetic latitudes below 55° and Hawkeye-1 provides measurements over the northern polar region. The contours in Figure 3 give the frequency of occurrence of events with a power flux exceeding a preset threshold which varies as R^{-2} to correct for the expected radial variation in the power flux. These measurements show that most of the radiation is observed poleward of a cone-shaped boundary which extends from latitudes near the magnetic equator in the local evening to

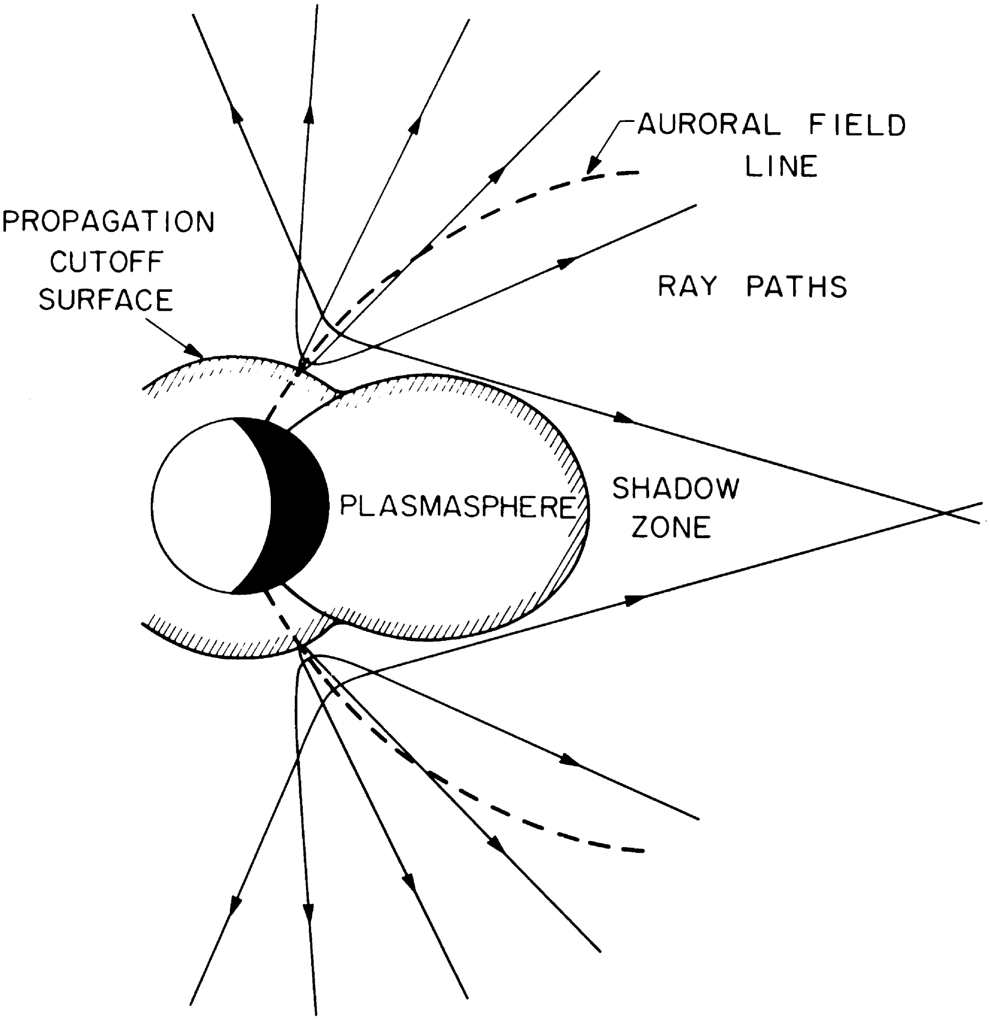

Fig. 4. A qualitative sketch of the ray paths and source region of auroral kilometric radiation. Note the distinct equatorial shadow zone caused by the plasmasphere.

latitudes of approximately 50° on the dayside of the Earth. Further studies (Green *et al.*, 1976) show that this cone-shaped boundary is frequency-dependent and rapidly shrinks poleward with decreasing frequency. This 'beaming' of the radiation is thought to be caused by the refraction of the radiation away from the ionosphere as illustrated in Figure 4. Since the index of refraction goes to zero at the propagation cutoff surface, which for these frequencies must occur at an altitude of about 1 to $1.5 R_E$ at 178 kHz, the ray path tends to be refracted upward away from the ionosphere. The frequency dependence of the cone-shaped boundary is qualitatively consistent with an essentially fixed source altitude at all frequencies, with the cone angle determined by the (frequency dependent) altitude of the propagation cutoff surface. A cone-shaped boundary, similar to that found for the auroral kilometric radiation, is observed for the Io related radio bursts from Jupiter and a similar beaming effect is a well known feature of radio emissions from pulsars.

Probably the most difficult feature of the auroral kilometric radiation which must be explained by any satisfactory theory is the very high efficiency with which this radiation is produced. The maximum power dissipated by the aurora during an auroral substorm is about 10^{11} W (Akasofu, 1968). If the corresponding maximum power of the auroral kilometric radiation is 10^{9} W, then the efficiency for generating this radiation must be at least 1%. From all present knowledge of magnetospheric radio emissions the generation of auroral kilometric radiation represents a very efficient conversion of charged-particle energy into radio waves. Interestingly, this efficiency is comparable to the efficiency by which a pulsar converts its rotational energy into radio emissions. Such high efficiencies cannot be obtained from an incoherent process, but must result from a coherent plasma instability. The location of the source, at an altitude of about 1 to $1.5 R_E$ along an auroral field line, coincides with the region where the auroral electron acceleration, anomalous resistivity and parallel electric fields are thought to occur (Mozer, 1976). Another type of intense whistler-mode radio emission called VLF auroral hiss is also thought to be generated in this same region (Gurnett and Frank, 1972).

Several theories have been developed which attempt to explain the principal features of the auroral kilometric radiation (Benson, 1975; Palmadesso *et al.*, 1976); Melrose, 1976). Most of these theories rely on the intermediate generation of electrostatic waves and the subsequent coupling of these waves to electromagnetic radiation to explain the observed intensities. At the present time no electric field measurements have been made in the source region which can confirm the existence of these electrostatic waves. Also, the polarization, which is a basic parameter that could help discriminate between the various theories, has not yet been determined.

3. Continuum Radiation

Brown (1973), using radio measurements from the IMP-6 satellite, has identified a weak continuum radiation coming from the Earth's magnetosphere in the frequency range from about 30 to 110 kHz. The intensity of this continuum decreases rapidly with increasing frequency, varying approximately as $f^{-2.8}$ (f is frequency). At about the same time Gurnett and Shaw (1973) identified another somewhat more intense continuum at even lower frequencies, from about 5 to 20 kHz. This radiation occurs at frequencies below the solar wind plasma frequency and is permanently trapped within the low density regions of the magnetospheric cavity. It now appears that these two types of radiation are simply different portions of a single non-thermal continuum spectrum which extends from frequencies as low as 500 Hz to greater than 100 kHz (Gurnett, 1975). This radiation, as implied by the term continuum, has a smooth monotonic frequency spectrum and a nearly constant intensity, seldom varying by more than 10 to 20 dB.

To illustrate the general features of the continuum radiation spectrum, Figure 5 shows five spectrums obtained from IMP-8 at various local times around the Earth and at a nearly constant radial distance of from 28.2 to $40.4 R_E$. Four of these spectrums were obtained in the solar wind and one (the center panel) was obtained in the low density region of the distant magnetotail. The spectrums in the solar wind all show the same basic characteristics, consisting of a monotonically decreasing intensity with increasing frequency and a sharp cutoff near the solar wind plasma frequency at about 20 to 30 kHz.

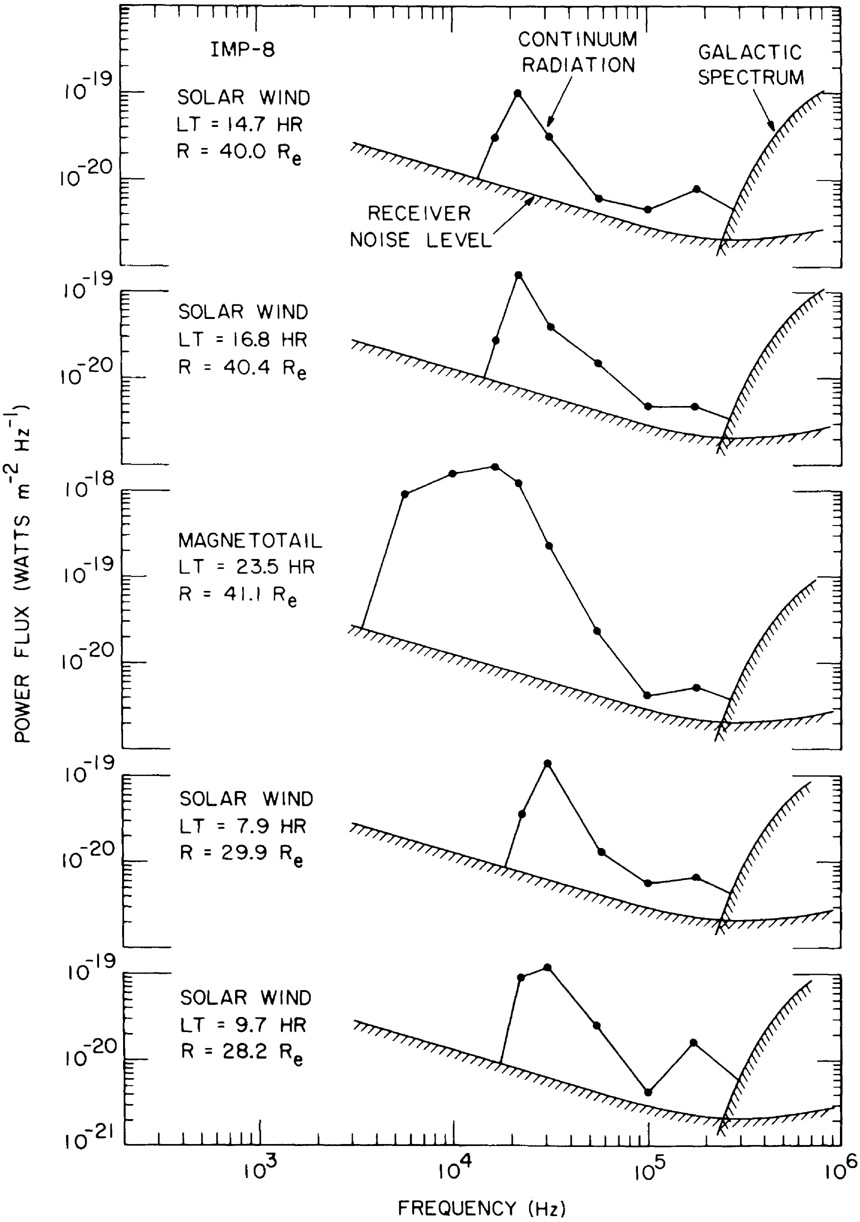

Fig. 5. Selected spectrum of continuum radiation observed by IMP-8 at various local times. The sharp cutoff in the solar wind spectrums occur near the solar wind plasma frequency.

The low frequency cutoff is almost certainly caused by the propagation cutoff at the solar wind plasma frequency. The spectrum in the magnetotail, however, extends down to frequencies well below the solar wind plasma frequency. The continuity of the magnetotail spectrum with the spectrums in the solar wind indicate that the radiation observed in both regions comes from the same source and that the spectrum observed in the solar wind represents that portion of the radiation which can escape into the solar wind above either the magnetosheath or solar wind plasma frequency, whichever is greater. The continuum radiation spectrum can therefore be divided into a trapped component and a freely escaping component as shown in Figure 1. At frequencies above the magnetosheath plasma frequency radiation from near the Earth can propagate directly to a distant

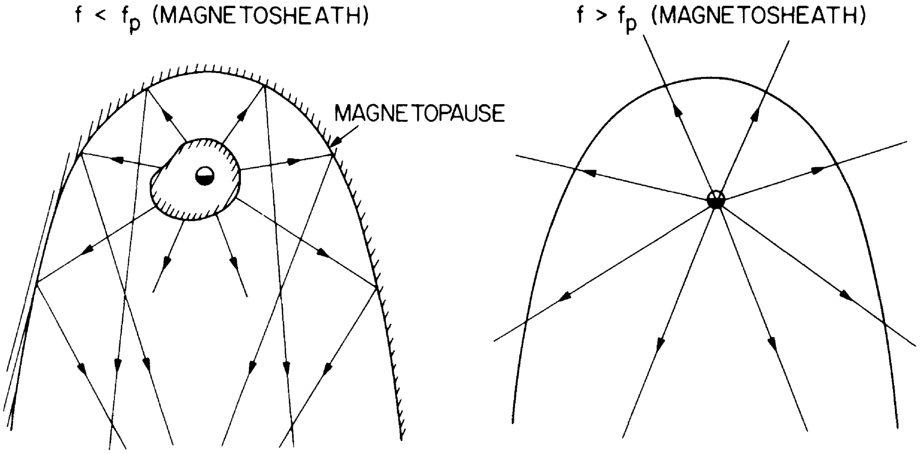

Fig. 6. A qualitative sketch of the ray paths from a source near the Earth at frequencies above and below the plasma frequency in the magnetosheath.

observer, whereas at frequencies below the magnetosheath plasma frequency the radiation is reflected into, and trapped in, the distant magnetotail as shown in Figure 6. Direction finding measurements (Gurnett, 1975) clearly show the transition from the free escape to the trapped regions and detailed ray path calculations exhibiting these effects have been performed by Jones and Grard (1975). Because the magnetosheath plasma frequency is largest near the nose of the magnetospheric cavity and decreases to approximately the solar wind value in the downstream region, the transition from the free escape to the trapped regions is not abrupt. Evidence showing the scattering of the escaping continuum radiation as it passes through the magnetosheath has been presented by Vesecky and Frankel (1975). Since only a slight, factor of 2, increase in the intensity occurs as the frequency varies from the free escape to the trapped region it can be concluded that the Q of the magnetospheric cavity is very low for this trapped radiation. Evidently a substantial portion of the radiation is reabsorbed in the distant downstream tail region.

Because of the complicated reflections which take place at frequencies below the magnetosheath plasma frequency it is nearly impossible to make a reliable determination of the source region from measurements of the trapped component. At frequencies well above the magnetosheath plasma frequency the source position can be determined directly from direction finding measurements. Gurnett (1975) using direction-finding measurements from the IMP-8 spacecraft has shown that the apparent center of the continuum radiation source is located on the morning side of the Earth at a radial distance, projected into the ecliptic plane, of about 2 to $3 R_E$ from the center of the Earth. From studies of individual passes it is also evident that the radiation extends all the way to the propagation cutoff at the plasmapause, even near the equatorial plane, with no evidence of an equatorial shadow zone as observed for the auroral kilometric radiation (see Figure 4). It is therefore concluded that at least some of the continuum radiation is generated near the equatorial plane and that this radiation is not a high latitude auroral zone emission. On the basis of these data a qualitative model of the

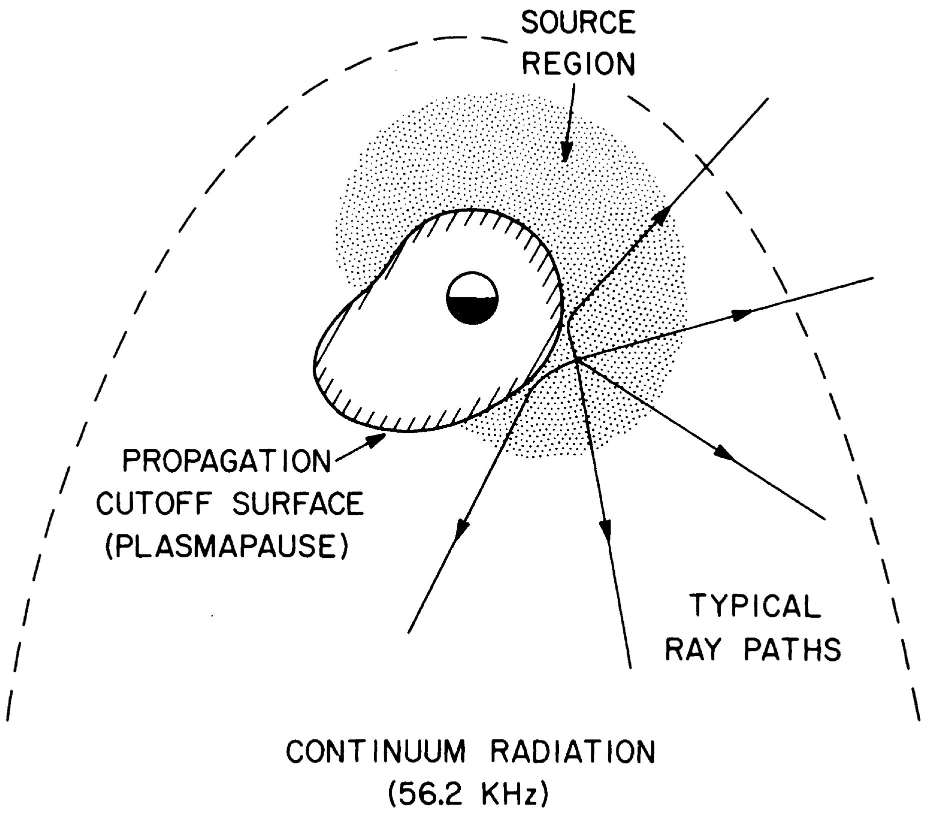

Fig. 7. A qualitative sketch of the source region of the continuum radiation as indicated by the direction-finding measurements in Figure 7.

source region of the continuum radiation is shown in Figure 7. This model is for a frequency of 56.2 kHz. At lower frequencies the propagation cutoff surface must extend to progressively larger radial distances into the outer magnetosphere.

At the present time the only comprehensive theory which attempts to explain the origin of the continuum radiation is by Frankel (1973), who proposed that the radiation is caused by gyro-synchrotron radiation from mildly relativistic, $E \simeq 100$ to 500 keV, electrons injected into the outer radiation zone during magnetic storms. In many respects the observed characteristics are in reasonably good agreement with Frankel's calculations. The frequency spectrum of the escaping continuum radiation, the radial location of the source, and the local time asymmetry are all in tolerable agreement with the gyro-synchrotron model. However, the gyro-synchrotron model also has several difficulties which remain to be explained. First, the power flux calculated from the gyro-synchrotron model is about a factor of 5 to 15 too small. Second, although the gyro-synchrotron model does account for the high frequency, ~100 kHz, portion of the spectrum which is generated deep within the magnetosphere at $L \sim 3$, it is difficult to see how this mechanism can account for the much more intense low frequency, ~10 kHz, portion of the spectrum which must be generated far out in the magnetosphere at $L > 6$, where the energetic electron intensities are much lower. Third, as shown by an event recently analyzed by Gurnett and Frank (1976), the continuum radiation is closely correlated with the injection of electrons with energies of 1 keV to 10 keV into the magnetosphere.

These energies are much too small to produce significant levels of gyro-synchrotron radiation. Also, in a related observation by Gurnett and Frank the intensity of the continuum radiation is observed to increase within an hour following the onset of a magnetic storm, much too quick to be accounted for by variations of the energetic, ~500 keV, electron intensities, which usually do not increase until several days after the onset of a magnetic storm (Owens and Frank, 1968).

3. Other Magnetospheric Radio Emissions

Several other types of magnetospheric radio emissions are known to occur at frequencies above the local plasma frequency, but which have not yet been studied in as much detail as the auroral kilometric radiation and continuum radiation. The characteristics of these radio emissions are summarized below.

3.1. DAYSIDE KILOMETRIC RADIATION

Kaiser and Stone (1975) have reported a weak quasi-continuous radiation with a sharply defined peak in the spectrum at about 200 kHz which is thought to be generated at high latitudes on the dayside of the Earth. The distinct peak at 178 kHz in the selected continuum radiation spectrums of Figure 5 is probably from this source. Because of the similarity in the shape of the spectrum to the nightside auroral kilometric radiation it is thought that this dayside radiation may be basically of the same origin as the nightside auroral kilometric radiation except that it is produced by the much less energetic, ~100 eV, polar cusp electrons.

3.2. RADIATION FROM UPSTREAM OF THE BOW SHOCK

From direction finding measurements with IMP-8 it is virtually certain that some radiation is detected from the region near the bow shock (Gurnett, 1975). At least one component of this radiation appears to be a narrow band emission, first detected by Dunkel (1973), at the harmonic, $2f_p$, of the solar wind plasma frequency. Radiation is also sometimes observed at the fundamental, f_p.

The radiation at $2f_p$ is thought to be generated by non-linear interactions of the electron plasma oscillations upstream of the bow shock (Scarf *et al.*, 1971) which are generated by electrons from the bow shock. Although this radiation is very weak it is of considerable interest because of the possible similarity to the generation of type II and type III solar radio bursts by electron plasma oscillations (Ginzburg and Zheleznyakov, 1958).

3.3. DISCRETE BURSTS

Very narrow bandwidth radio bursts, with bandwidths of less than 100 Hz and durations from a few tenth of a second to several seconds, are sometimes observed at frequencies above the local plasma frequency (Gurnett and Shaw, 1973). The center frequency of a given burst tends to decrease rapidly after the onset of the burst, similar to the so-called 'S bursts' from Jupiter at frequencies in the 10 MHz range (Warwick, 1967). The occurrence of narrowband emissions of this type is clear evidence of a resonant plasma instability operative at frequencies above the local plasma frequency, possibly comparable to the resonant whistler-mode instability which produces chorus and other discrete VLF emissions.

4. Discussion

It is evident that the Earth's magnetosphere produces a variety of complex and very interesting radio emissions at frequencies above the local plasma frequency. Since these waves can escape from the Earth's magnetosphere these radio emissions can be expected to have close similarities to radio emissions produced by other astronomical radio sources. Already certain close similarities are evident. The auroral kilometric radiation has features very similar to the Io-related decametric radiation from Jupiter and the recently discovered decametric radiation from Saturn (Brown, 1975). The radiation at f_p and $2f_p$ upstream of the bow shock appears to be generated by the same mechanism as type II and type III solar radio bursts. The beaming of the auroral kilometric radiation into a cone-shaped region over the polar cap has some similarity to the angular distribution of radiation from Io and to the beaming of radio emissions from pulsars.

At the present time the mechanisms by which most of these radio emissions are generated are rather poorly understood and the proper explanation of these radio emissions represents a significant challenge to the theorists. It should however be possible to arrive at a reasonably clear understanding of how these radio emissions are generated since a great deal is known about the charged particle distributions and processes which occur in the Earth's magnetosphere. Because a comparable detailed knowledge of the charge particle distribution will probably never be known for most other radio sources in the universe the study of these terrestrial radio emissions provides a unique opportunity to extend our understanding of radio emissions from other planets and astronomical objects.

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