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Review of Kilometric Continuum

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Abstract. Kilometric continuum radiation is a non-thermal magnetospheric radio emission. It is one of the fundamental electromagnetic emissions in all planetary magnetospheres [cf. the review by Kaiser, 27]. We review its observational properties in view of their agreement with theoretical models. Although this emission has been observed and studied for more than 35 years, there are still several unverified theories on how this emission is generated. It is by now quite certain that it is emitted from the plasmasphere, in particular from the plasmapause and from density notches and cavity gradients. Mode conversion at density gradients plays an important role. Observations show that the radiation consists of a magnetospherically trapped and an escaping component. It exhibits a narrow-band fine structure that is barely understood, but beaming models can be safely excluded based on the observations of the frequency-time structure of the radiation. We investigate its relation to geomagnetic activity and solar activity.

Key words: Magnetosphere, continuum radiation, non-thermal radiation, plasmapause source

2.1 Introduction

A magnetospheric electromagnetic emission that is associated with intense narrow-band electrostatic emissions in the vicinity of the plasmapause at the geomagnetic equator is the non-thermal continuum (NTC) radiation (see for example: [17, 29]). NTC is observed over a very broad frequency range from as low as 5 kHz [Gurnett, 15]. Its highest frequency was known to be 200 kHz [Kurth et al., 30] before the identification of “kilometric continuum” by Geotail [Hashimoto et al., 19]. The conventional lower frequency component of continuum has been called the “normal continuum” by a number of authors.
[eg., 19, 28] and as terrestrial myriametric radiation [Jones, 23] based on its wavelength range ($\lambda \sim 10$ km at $f \sim 30$ kHz). On the other hand, a new component, kilometric continuum, is its high-frequency extension with frequencies up to as high as 800 kHz.

The NTC is generated in the free space L-O mode above $f_p$, where $f_p$ is the local electron plasma frequency, from sources at or very near the plasmapause. The strong electrostatic bands occur at frequencies where the frequency of the electrostatic upper hybrid resonance ($f_{uhr}$) is equal to the frequency of the electrostatic $(n + \frac{1}{2})f_g$ resonance, where $f_g$ is the local electron cyclotron frequency [Kurth, 31]. The kilometric continuum is not merely a high frequency extension. It triggered new investigations since this frequency range is above the maximum plasma frequency of a few hundred kHz observed at the plasmapause. This is believed to be generated in events separate from the lower frequency non-thermal continuum. Recent NTC research has focused on improving our understanding of the source location, emission cone characteristics, propagation characteristics, and detailed spectral measurements primarily in the kilometric frequency range.

Much of what has emerged from these studies in terms of source location is summarized in Fig. 2.1 adapted from Green et al. [12]. The lower frequency trapped and escaping continuum is typically generated in the pre-noon sector and has been called the “normal continuum”, the continuum enhancement is generated in the morning sector [6, 13, 28], and the kilometric continuum

![Fig. 2.1. The observed source locations of the escaping after [5], trapped [16], kilometric [19] and continuum enhancement [28] emissions [12]](image-url)
is generated in deep plasmaspheric notch\(^1\) structures that corotate with the plasmasphere [10] and other density irregularities [20]. The purpose of this paper is to introduce NTC briefly and to review our current understanding of the kilometric continuum radiation.

### 2.2 Trapped and Escaping NTC

From its unique polar orbiting vantage point, the IMAGE/RPI instrument [Reinisch et al., 44] has observed NTC over its entire frequency range at many local times. Figure 2.2 shows a frequency time spectrogram from the RPI instrument during a pass of IMAGE through the magnetic equator. The NTC extends from about 29 kHz to about 500 kHz forming a Christmas tree pattern in the spectrogram nearly symmetric about the magnetic equator which is clearly delineated by the increased intensity of the \((n + \frac{1}{2})f_e\) electrostatic emission bands. The orbital position of the IMAGE during these observations is shown in the upper left panel of the spectrogram in Fig. 2.2. Due to the relatively weak nature of the emission, the NTC observations in

![Figure 2.2](image)

**Fig. 2.2.** An RPI frequency-time spectrogram taken during a passage through the magnetic equator on the dawn side (see orbit insert). The Christmas tree pattern of nonthermal continuum is clearly shown nearly centered about the magnetic equator delineated by the intense electrostatic emissions

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\(^1\)Notches were also called bite-outs [9].
Fig. 2.2 were made during quiet geomagnetic times on the dawn side of the magnetosphere. At frequencies less than the magnetopause plasma frequency (∼50 kHz in this example), the continuum radiation has been referred to as the “trapped” component by Gurnett and Shaw [14] since it is observed primarily in the magnetospheric density cavity between the plasmapause and the magnetopause. The trapped continuum spectrum is observed as a broadband emission with very little frequency structure. The broadband structure of the trapped continuum spectrum is believed to be produced from a series of narrow band emissions at slightly different frequencies from an extended source region at the plasmapause whose emission then mixes due to multiple reflections (with some Doppler broadening) in the magnetospheric density cavity. As shown in Fig. 2.2, the trapped continuum is observed first (the widest part of the Christmas tree pattern) since multiple reflections from the magnetopause broaden its angular distribution [9].

NTC at frequencies above the magnetopause plasma frequency has been referred to as the “escaping” component by Kurth et al. [30] since it propagates from the Earth’s plasmapause to well outside the magnetosphere. As shown in Fig. 2.2 the escaping component extends from above 50 kHz. A common characteristic of all the escaping continuum radiation is that it has narrow frequency bands of emissions showing that the name continuum is not entirely descriptive of the radiation in this frequency range. Although there are few published examples of normal continuum radiation extending above 100 kHz, Fig. 2.2 shows the high frequency portion of the NTC that is very weak and is beamed around the magnetic equator into emission cones of less than about ±15° in latitude. These two characteristics might account for it not being routinely observed and reported by equatorial orbiting spacecraft.

### 2.2.1 Continuum Enhancement

Another type of continuum is called continuum enhancement. The continuum enhancement is characterized by a strong variation in intensity and frequency and has been observed to last for only 1-2 hours [6, 13, 28]. The spectrum of continuum enhancement is distinct, with discrete emissions at almost uniform spacing as shown in the frequencies less than 100 kHz in the upper right of Fig. 2.1. The spacings of the discrete continuum enhancement are believed to be at the electron cyclotron frequency with the source being embedded in the plasmapause. This has allowed prediction of the radial location of the source, and if the wave direction can be determined, the location of the source in magnetic local time (MLT) can also be inferred. Direction findings indicate that these emissions originate at midnight and propagate dawnward. Gough [13] interpreted this to be due to the inward motion of the plasmapause due to enhanced convection, while Filbert and Kellogg [6] associated it with the dusk-to-dawn motions of injected electrons. Kasaba et al. [28] used the continuum enhancement to analyze the displacement of the plasmapause during substorms.
2.3 Generation Theories

There are three lines of theoretical models [see, 2, 32, 36, 46, for reviews] that try to explain continuum radiation in general:

- synchrotron radiation [7, 48],
- linear mode conversion models [21, 22, 23], and
- nonlinear mode conversion models [8, 38, 45].

The synchrotron radiation model is believed to be a factor of ten too weak at the nominal plasmapause location. The linear and nonlinear models assume that the sources of the freely propagating electromagnetic waves are electrostatic waves generated near the upper hybrid-resonance frequency. The sources of the electrostatic waves are most likely energetic electrons in the tens of keV energy range with highly anisotropic phase-space density distributions which become unstable when the resonant wave-particle interaction conditions are satisfied. Sharp boundaries like the plasmapause are good regions for instability to occur because the resonance conditions vary greatly when moving across that boundary.

In the linear model there is a narrow radio window through which the electrostatic waves can propagate and be converted into electromagnetic waves at the same frequency [Jones, 21, 22, 23]. Okuda et al. [42] performed calculation on O mode radiation from electric fluctuations. The electrostatic waves are in the Bernstein modes which are connected to the Z mode at smaller wavenumbers. The Z mode wave is mode-converted to the O mode where the local plasma frequency is equal to the wave frequency. A ray path to the mode conversion point at the local plasma frequency from the Bernstein mode was verified through ray tracing studies in a hot plasma [18, 49]. The linear model predicts that the angle between the equator and the wave normal direction of the O mode, the beaming angle, is defined as \( \alpha = \tan^{-1}(f_E/f_p) \) [22, 23]. Almost no conversion occurs in the equatorial direction according to full-wave, warm plasma computations [26].

In the nonlinear model of Melrose [38], density irregularities formed by low frequency waves coalesce with upper hybrid waves generating this radiation. In the nonlinear model of [8], an electrostatic wave propagating into a density gradient can nonlinearly interact with its reflected wave to generate an electromagnetic wave at twice the electrostatic wave frequency. Rönnmark [45] showed coalescence of upper hybrid waves with high-harmonic ion Bernstein waves to produce electromagnetic radiation. Both linear and nonlinear models predict that the electromagnetic waves will be beamed in magnetic latitude with the beaming becoming more perpendicular to the magnetic field as the ratio of the electron plasma to cyclotron frequency increases. At a sharp plasmapause, since the cyclotron frequency is almost constant, this means that the higher the wave frequency, the closer it is beamed to the magnetic equator.
2.4 Kilometric Continuum

Kilometric continuum (KC) is a major component of the escaping continuum radiation in the 100–800 kHz frequency range first identified by Hashimoto et al. [19] from the Sweep Frequency Analyzer (SFA) data of the Geotail Plasma Wave Instrument (PWI) [Matsumoto et al., 37]. Although the escaping continuum is not “continuum” as shown in the previous section, the new extension is named “kilometric continuum” to distinguish it from auroral kilometric radiation or AKR (which is in the same frequency range) and yet indicate that it is a high frequency extension of NTC.

KC intensities are similar to those of normal continuum and much weaker than those of AKR. A typical example observed by Geotail/PWI above 100 kHz is shown in Fig. 2.3. This emission is a collection of narrowband emissions and often lasts more than six hours. The spacings of the discrete narrowband emissions are often irregular. It is important to note that KC is typically observed without the accompanying lower frequency component.

KC has sparked considerable interest in further understanding of various aspects of this radiation that make it different from its lower frequency trapped and escaping (< 100 kHz) counterparts generated in the pre-noon sector as shown in Fig. 2.1. The frequency range for the kilometric continuum is approximately that of AKR but, as shown in the lower right hand panel of Fig. 2.1, there are significant differences that can be used to easily distinguish

Fig. 2.3. Kilometric Continuum Radiation [19] (Reprinted with permission of the American Geophysical Union)
between these two emissions. KC has a narrow band structure over a number of discrete frequencies while AKR is observed at a distance to be a much stronger broadband and sporadic emission and can be seen from 16:00-17:10 and from 21:30 to 24:00 UT in that spectrogram.

The kilometric continuum has been observed at all local times, although it has been difficult to make a positive identification of the emission during the times when Geotail was in the late evening or early morning local time sector when AKR was active [19]. From Geotail and IMAGE observations, Hashimoto et al. [19] and Green et al. [11] have found that the kilometric continuum is confined to a narrow latitude range of approximately ±15° about the magnetic equator. The hourly occurrences as a function of geomagnetic latitude and local time as observed near solar minimum are shown in Fig. 2.4. The almost equatorial orbit of Geotail was advantageous to detect this emission.

Although these characteristics make it different from the lower frequency continuum discussed in the previous section, the similar spectral characteristics of the emission and its relationship to the plasmapause support the conclusion of Menietti et al. [39] from Polar high-resolution electric and magnetic field observations of KC that the radiation is generated by the same mechanism. Through the high-resolution Polar and Cluster observations of the normal continuum, Menietti et al. [40] confirmed that they are analogous to those of KC.

At lower frequencies, beaming of continuum radiation around the magnetic equator to latitudes as high as 50° has also been observed by Jones et al. [25] (from 80 to 100 kHz), Morgan and Gurnett [41] (from 45 to 154 kHz), and by Green and Boardsen [9] (from 24 to 56 kHz). The narrow beaming of the kilometric continuum in magnetic latitude has made this emission difficult to observe routinely or observable for only short periods of time except for equatorial orbiting spacecraft with the proper instrumentation, such as Geotail.
Fig. 2.5. KC wave observations from Geotail/PWI (top panel) map to a plasmaspheric notch structure as observed by IMAGE/EUV (middle panel) where the resulting emission cone pattern (bottom panel) is modelled with ray tracing calculations [10, 11] (Reprinted with permission of the American Geophysical Union)

The source region for KC was originally identified by Carpenter et al. [4] as coming from emissions trapped in plasmaspheric cavities from CRRES observations [Anderson et al., 1]. More recently, Green et al. [10] and Green et al. [11] clearly identified KC as being generated at the plasmapause, deep within notch structures that corotate with the Earth. Figure 2.5 has been adapted from Fig. 8 of Green et al. [10] and Fig. 1 of Green et al. [11] and illustrates that the location of the KC source region and resulting emission cone pattern of the radiation is consistent with the observations. The top panel of Fig. 2.5 is a frequency-time spectrogram from the PWI instrument on Geotail showing the banded structure of KC. The middle panel shows the
magnetic longitude versus the equatorial radial distance of the plasmapause (derived from the inserted EUV image of the plasmasphere) and the position of Geotail during the KC observations of the top panel. The bottom panel is a ray tracing analysis which shows that the structure of the plasmaspheric notch has a significant effect on the shape of the resulting emission cone through refraction. The process by which the notch structure is produced in the plasmasphere is not completely understood at this time.

Figures 2.6 and 2.7 show other source regions observed by CRRES [20]. The plasma frequency at the plasmapause is 200 to 300 kHz in Fig. 2.6. KC is radiated from the plasmapause and is a simple extension of the normal continuum. Emissions trapped in a notch are seen at about 300 kHz near 16 UT. If a satellite moves across a notch structure, the emissions look trapped inside the structure as stated by Carpenter et al. [4]. This phenomenon is also called “donkey ear” in EXOS-D (Akebono) observations [43]. Based on IMAGE observations, the structure is open to the magnetosphere, and waves

Fig. 2.6. CRRES observations on October 10, 1990. Notch-like structure is seen around 1600 UT and the emissions above 200 kHz starting from 1640 UT are kilometric continuum [20] (Reprinted with permission of the American Geophysical Union)

Fig. 2.7. CRRES observations on September 6 and 7, 1990. The electromagnetic radiation starting from 0010 at about 200 kHz is kilometric continuum [20] (Reprinted with permission of the American Geophysical Union)
are not really trapped. On the other hand, kilometric continuum is generated at density irregularities deep inside the plasmapause in the case of Fig. 2.7.

The Christmas-tree emission pattern of KC (see Fig. 2.2) provides important information on the emission mechanism. The characteristic pattern observed by IMAGE in a polar pass across the equator shows that KC at higher frequencies tends to have smaller beaming angles (see Fig. 2.2). This suggests that the higher frequency waves are generated deeper in a plasmapause notch and thus are more confined, while the lower frequency waves may be produced along the sides of the notch. Similar patterns have been analyzed by Hashimoto et al. [20] where it has been clarified that KC is observed at the equator contrary to the beaming predicted by the linear mode conversion of Jones [23, 26].

While IMAGE RPI can observe frequencies higher than 800 kHz and Geotail PWI cannot, IMAGE RPI never observed KC at such high frequencies. Therefore, we can conclude that the maximum frequency of KC is around 800 kHz.

Kilometric “continuum”\(^2\) is also observed by the AKR-X spectrum analyzer of INTERBALL-1 [Kuril’chik et al., 34, 35]. Their observing frequencies were at 252 and 500 kHz, and they claim that the occurrence of the emission was extremely rare during a time of high solar activity (1999–2000).

2.5 Geomagnetic Activity Dependence of Kilometric Continuum

Statistics on Geotail observations of the kilometric continuum radiation were derived for a one year period from July 2000 through June 2001 near solar maximum. The results for the dependence of the hourly occurrence on the geomagnetic latitude are shown in Fig. 2.8a and on the magnetic local time in Fig. 2.8b. Although these results are quite similar to those of Fig. 2.4, there are a few differences which may be attributed to the solar cycle. In the data

Fig. 2.8. (a) (left) Hourly occurrence as a function of geomagnetic latitude and (b) (right) hourly occurrence as a function of geomagnetic local time for 2000-2001

\(^2\)They quoted the term “continuum” throughout their papers.
in Fig. 2.8 at solar maximum there is no dip near the equator on the latitude dependence, the occurrence probabilities are higher, kilometric continuum radiation was observed at more than 20° in the northern and southern latitudes, and more observations were made at the morning hours. These results are in direct conflict with Kuril‘chik et al. [35].

The Kp dependencies of the kilometric continuum radiation are shown in Fig. 2.9a for 1996 and Fig. 2.9b for 2000–2001. The solid and dashed lines indicate the hourly occurrence probability in percent and one tenth of the number of observed cases in hours, respectively. The maximum Kp for the three hours preceding the observation is used. Although Fig. 2.9a shows almost no Kp dependence, Fig. 2.9b shows a modest Kp dependence that increases dramatically for Kp > 5. There were almost no Geotail kilometric continuum radiation observations when Kp > 5 in 1996. Figure 2.9 provides dramatic evidence for the enhancement of KC at solar maximum (right panel) over solar minimum (left panel). The cause of this solar cycle difference is unknown.

Both studies show that kilometric continuum radiation is observed even if Kp = 0. In order to check the Kp dependence, an example when kilometric continuum radiation was observed and Kp = 0 is shown in Fig. 2.10. The kilometric continuum is observed from 06–18 UT on Geotail on December 20, 1996, as shown in the top dynamic spectra. The magnetic latitudes of the satellite are shown for one day in the center of the upper right panel next to the spectrogram and the circles indicate the observations of kilometric continuum. Kp indices are shown above the panel for the day in the second line and for the previous day in the first line. Kp had been less or equal to 1 for more than 24 hours. This demonstrates that kilometric continuum occurs even in such a very quiet time. Dst had been almost zero as seen from the lower right panel. These observations pose a problem for the energy source of the emissions.
Fig. 2.10. Geotail observations for December 20, 1996, when Kp was always less than 1. Kilometric continuum radiation is observed from 06 UT to 18 UT.

Fig. 2.11. Geotail observations April 8, 2001, when Kp ranged from 2 to 7. Kilometric continuum radiation was not observed until after 22 UT even though Geotail was within 10 degrees of the equator since 09 UT.

Figure 2.11 is an example of occurrence of large Kp without kilometric continuum. The continuum is observed only after 22 UT although the satellite was within 10 degrees of the equator since 09 UT, Kp was large for a long time, and AKR was often observed. It should be noted that the kilometric continuum radiation from about 600 kHz to about 800 kHz was quite strong from 22 UT to 05 UT the following day.
2.6 Simultaneous Wave Observations by Geotail and IMAGE

Data from the extreme ultraviolet (EUV) imager [47] of the IMAGE satellite demonstrated the existence of notches, where the electron densities are low near the equatorial plasmapause, and the notches are the source of kilometric continuum radiation. The radio plasma imager (RPI) of the satellite indicated that the electromagnetic waves were not only trapped in the low density region but also escape radially out or are generated outside as kilometric continuum. The IMAGE satellite observed the notch near 4 UT in the dayside as shown in Fig. 2.12 [10]. The orbit is the black curve and the plasmapause is shown as the light curve. Near 190° in the magnetic longitude, the density is decreased and the plasmapause position was inside the normal one. Kilometric continuum is observed inside the notch region.

On the same day, Geotail did not observe kilometric continuum under very high Kp as shown in Fig. 2.11 until 18 hours later. The notch was observed around local noon, but Geotail was in the nightside. This fact indicates that kilometric continuum is radiated during high Kp, but Geotail was not able to observe it. The satellite position could be the cause of the low occurrence probability at high Kp.

Simultaneous observations of kilometric continuum with IMAGE RPI and Geotail PWI are displayed in a frequency range of 300 – 800 kHz in the top and the bottom of Fig. 2.13, respectively [Hashimoto et al., 20]. Intense kilometric continuum was received during the disturbed time, especially for Kp > 7 from 20 UT to 03 UT. It should be noted that both kilometric continuum spectra show quite good similarity including the fine structures from 21 UT to 06 UT. IMAGE moved from the southern hemisphere to 30°N. On the other hand, Geotail moved in the equatorial region from 4.4°N to 12.3°N at 01 UT and...
then back down to $2.4^\circ$ N as shown in the right hand panel of Fig. 2.13. Both satellites observed almost the same spectra in a wide latitude range of more than $30^\circ$. Their longitudes are close within $10^\circ$. IMAGE RPI observed the emission in a wide latitudinal range different from general trends reported by Hashimoto et al. [19] and Green et al. [10].

The vertical line at 0420 UT is a type III burst. The intensity observed by IMAGE is weaker around 400 kHz after 0430 UT when the satellite is at latitudes higher than $25^\circ$. It would be difficult to explain these quite similar spectra by multiple narrow beam sources. Rather, this can be explained if the sources radiate uniformly in wide emission cones in latitude and both satellites receive the emissions from the same sources, which is contrary to the beaming theory.

2.7 Summary and Conclusions

Non-thermal continuum radiation is one of the fundamental electromagnetic emissions in planetary magnetospheres [cf. the review by Kaiser, 27]. It has been observed in every planetary magnetosphere visited by spacecraft armed with wave instruments and has even been found to be generated in the magnetosphere of the Galilean moon Ganymede [Kurth et al., 33]. Although
this emission has been observed and studied for more than 35 years, there are still several unverified theories on how this emission is generated. There is also much more which we do not know about this emission and its relationship to the dynamics of the plasmasphere.

Many of the characteristics of the lower frequency portion of the non-thermal continuum (trapped component) have been difficult to determine due to the multiple reflections of the emission from the magnetopause and plasmapause. Recently there is renewed interest in studying the high frequency extension of this emission (the escaping component), especially the extension into the kilometric frequency range. Kilometric continuum has been reported to be observed by Polar and Cluster [Menietti et al., 39, 40] and INTERBALL-1 [Kuril'chik et al., 34, 35] in addition to Geotail, IMAGE, and CRRES [10, 11, 19, 20, and the present paper].

It has been confirmed that the kilometric continuum is generated at steep density gradients at density irregularities in the equatorial region. These irregularities do not only exist at the plasmapause, but also inside the plasmapause and in notches. Although the observations are consistent with the mode conversion mechanism at the plasma frequency, they are not consistent with the beaming model of Jones [22, 23]. The simultaneous observations given in Fig. 2.13 provide striking evidence against the latter although this is discussed in more detail by Hashimoto et al. [20]. The relations to solar and geomagnetic activities are also interesting topics.

Several new features of the high frequency escaping kilometric continuum, such as the narrow latitudinal beam structure and relationship to plasmaspheric notch or notch structures, provide a new opportunity to observe the triggering of this emission and its relationship to plasmaspheric dynamics. The insight gained in performing multi-spacecraft correlative measurements should provide key measurements on separating spatial from temporal effects that are essential to verifying existing theories. Observing the radiation while the instability has been initiated and grows, and examining the dynamics of the large-scale plasmasphere should lead to significant advances in delineating the best theory for the generation of this emission.

References

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