Kilometric Continuum Radiation

James L. Green
NASA/Goddard Space Flight Center
Greenbelt, MD 20771

Scott Boardsen
L3 Communications GSI.
NASA Goddard Space Flight Center
Greenbelt, MD

ABSTRACT

Kilometric continuum (KC) is the high frequency component (~100 kHz to ~800 kHz) of nonthermal continuum (NTC). Unlike the lower frequency portion of NTC (~5 kHz to ~100 kHz) whose source is around the dawn sector, the source of KC occurs at all magnetic local times. The latitudinal beaming of KC as observed by GEOTAIL is, for most events, restricted to +/- 15° magnetic latitude. KC has been observed during periods of both low and strong geomagnetic activity, with no significant correlation of wave intensity with K_p index. However statistically the maximum observed frequency of KC emission tends to increase with K_p index, the effect is more pronounced around solar maximum, but is also detected near solar minimum. There is strong evidence that the source region of KC is from the equatorial plasmapause during periods when a portion of the plasmapause moves significantly inwards from its nominal position. Case studies have shown that KC emissions are nearly always associated with plasmaspheric notches, shoulders, and tails. There is a recent focus on trying to understand the banded frequency structure of this emission and its relationship to plasmaspheric density ducts and irregularities in the source region.

1. Introduction

There are two escaping electromagnetic emissions at radio frequencies that can be measured outside the influence of the Earth's magnetic field that are generated within the Earth's magnetosphere. They are auroral kilometric radiation (AKR) and the nonthermal continuum radiation (NTC). Even though they are generated over nearly the same frequency range (~5 kHz to 800 kHz) their sources and generation mechanisms are completely different. As its name implies AKR, is associated with discrete auroral arcs and is generated by the Doppler shifted gyroemission. On the other hand, the source region of NTC is believed to be embedded in the plasmapause or outer plasmasphere region (see *Carpenter*, 2004 for an explanation of the plasmasphere) and its generation mechanism is not well understood.

NTC is one of the fundamental electromagnetic emissions in planetary magnetospheres [c.f. review by *Kaiser*, 1989]. It has been observed in every planetary magnetosphere visited by spacecraft with wave instruments and even found to be generated in the magnetosphere of the Galilean moon Ganymede [*Kurth et al.*, 1997]. 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 and much more we don't know about the emission and its relationship to plasmaspheric dynamics.

NTC is observed over a very broad frequency range from as low as 5 kHz [*Gurnett*, 1975; *Brown*, 1973] to as high as 800 kHz [*Hashimoto et al.*, 1999] and is observed to propagate largely in the free space L-O mode. Even though its name, nonthermal continuum, refers to an emission with a continuous spectrum this is only the case for the lowest frequency portion of the emission. In fact, NTC is typically made up of discrete narrow frequency emission bands and is found, in some cases, to be associated with

strong narrow-band electrostatic emissions at the plasmapause at low latitudes [*Kurth,* 1982]. The NTC emission spectrum has been delineated as either "trapped" within the Earth's magnetosphere or "escaping" from the magnetosphere but it is now clear that from recent observations a new component of NTC has now been determined called kilometric continuum (KC) where the emission is generated only at the high frequency portion of the spectrum (above 100 kHz) by the same mechanism as the lower frequency NTC emission. It is important to note that another low frequency continuous electromagnetic emission in the 1 to 4 kHz frequency range, believed to be generated in the plasmasheet boundary layer of the distant magnetotail, named lobe trapped continuum radiation or LTCR [see for example: Coroniti et al., 1984; Takano et al., 2005] has been observed to be trapped in the tail lobes. But it is uncertain if LTCR and NTC are generated by the same mechanism and therefore LTCR will not be discussed further in this review.

The purpose of this paper is to provide a review of the current state of knowledge about KC and to suggest future research directions that would yield a better understanding of the NTC emission mechanism.

2. Overview of Nonthermal Continuum

Recent NTC research has focused on improving our understanding of the source location, emission cone 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 Figure 1 [adapted from *Green and Fung,* 2005]. The lower frequency trapped and escaping continuum is typically generated in the pre-noon local time sector [*Gurnett,* 1975; *Kurth et al.,* 1975] and has been called the "normal continuum" by a number of authors [e.g., *Kasaba et al.,* 1998; *Hashimoto et al.,* 1999], the continuum enhancement is generated in the morning sector [*Kasaba et al.,* 1998; *Gough,* 1982; *Filbert and Kellogg,* 1989], and the KC is generated in deep plasmaspheric notch structures that corotate with the plasmasphere [*Green et al.,* 2002]. Figure 1 shows that NTC is made up of narrow emission bands except for the trapped continuum (lower left panel), observed by the wide-band instrument on IMP-6, that has a much more continuous in frequency emission structure. It was from observations of the trapped component of continuum that the name of this emission originates.

2.1 Trapped and Escaping Nonthermal Continuum

From its unique polar orbiting vantage point the IMAGE/RPI instrument has observed NTC over a large frequency range at many local times. Figure 2 shows a frequency time spectrogram from the RPI instrument during a pass of IMAGE through the magnetic equator. The NTC extends from about 30 kHz to about 500 kHz forming a Christmas tree pattern in the spectrogram nearly symmetric about the magnetic equator that is clearly delineated by the increased intensity of the $(n+1/2)f_{ce}$ (cyclotron frequency) electrostatic emission bands. The orbital position of the IMAGE during these observations is shown in the upper left panel of the spectrogram in Figure 2. Due to the relative weak nature of the emission, NTC observations in Figure 2 are made during quiet geomagnetic times on the

dawn side of the magnetosphere. At frequencies less than the magnetopause plasma frequency (~ 40 kHz in this example), the continuum radiation has been referred to as the "trapped" component [*Gurnett and Shaw*, 1973] since it is observed primarily in the magnetospheric density cavity between the plasmapause and 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 Figure 2 the trapped continuum is observed first (the widest part of the Christmas tree pattern) since multiple reflections from the magnetopause broadens its angular distribution [*Green and Boardsen*, 1999].

NTC at frequencies above the magnetopause plasma frequency has been referred to as the "escaping" component [*Kurth et al.*, 1981] since it propagates from the Earth's plasmapause to well outside the magnetosphere. From Figure 2 the escaping component extends from above ~40 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, Figure 2 shows that the high frequency portion of the NTC is beamed within a few degrees around the magnetic equator and is the weakest portion of the emission in this example.

2.2 Enhanced Continuum

Another type of continuum that is also observed is called the enhanced continuum (see upper right panel of Figure 1). The enhanced continuum is characterized by a strong variation in intensity and frequency and has been observed to last for several hours [*Kasaba et al.*, 1998; *Gough*, 1982; *Filbert and Kellogg*, 1989]. The spectrum of enhanced continuum is distinct, with discrete emissions at almost uniform spacing. The spacing of the discrete enhanced continuum is believed to be at the electron cyclotron frequency with the source embedded in the plasmapause. This has allowed one to predict 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 finding indicate that these emissions originate at midnight and propagate dawnward. *Gough* [1982] interpreted this to be due to the inward motion of the plasmapause due to enhanced convection, while *Filbert and Kellogg* [1989] associated it with the dusk-to-dawn motions of injected electrons.

2.3 Kilometric Continuum

Kilometric continuum (KC) is observed in the 100 - 800 kHz frequency range and as such, once generated, escapes the magnetosphere. It is important to note that KC is always observed without an accompanying lower frequency trapped component. *Hashimoto et al.* [1999] discovered this type of emission and have sparked considerable

interest in further understanding various aspects of this radiation that make it different from its lower frequency trapped and escaping counterpart generated in the pre-noon sector and shown in Figure 1. The lower right hand panel of Figure 1 clearly shows the discrete emissions bands of KC extending from 17-24 UT. The frequency range for kilometric continuum is approximately the frequency range of auroral kilometric radiation (AKR), but as shown in the lower right hand panel of Figure 1, there are significant differences that can be used to easily distinguish between these two emissions. KC has a narrow band structure over a number of discrete frequencies while AKR is observed to be a broadband and sporadic emission and can be seen from 16-17:00 and from 21:30 to 24:00 UT in that spectrogram.

KC 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 (see *Matsumoto et al.*, 1994 for an overview of wave observations by GEOTAIL) was in the late evening or early morning local time sector when AKR was active [*Hashimoto et al.*, 1999]. From GEOTAIL and IMAGE observations *Hashimoto et al.* [1999] and *Green et al.* [2004] have found that kilometric continuum is confined to a narrow latitude range of approximately $15°$ about the magnetic equator. Although these characteristics make it different from the normal continuum discussed in the previous section, the similar spectral characteristics of the emission and its relationship to the plasmapause supports the conclusion by *Menietti et al.* [2003] from Polar observations that the radiation is generated by the same mechanism.

Recent observations from the Whisper instrument on Cluster by *Décréau et al.* [2004] and *Darrouzet et al.* [2004] point out the importance of small-scale density structures in locally amplifying the low-frequency component of NTC. For KC, *Green et al.* [2002] showed that the field-lines threading the KC source region, in one example, supported high frequency RPI sounder echoes. The conditions in the plasma that support field-aligned high frequency sounder echoes were shown by *Fung and Green* [2005] to be field-aligned density ducts with from 2% to 10% density variations perpendicular to the local magnetic field. The density ducts associated with the KC sources appear to be completely consistent with the Cluster observations of density variations in the low-frequency NTC source regions since field-aligned density ducts would have the appearance of small-scale density structures by the *in situ* Cluster observations. The similarities in these observations also lend support to the conclusion that KC is generated by the same mechanism as the lower frequency NTC.

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.* [1988] (from 80 to 100 kHz), by *Morgan and Gurnett* [1991] (from 45 to 154 kHz), and by *Green and Boardsen* [1999] (from 24 to 56 kHz). The narrow beaming of kilometric continuum in magnetic latitude has made this emission difficult to observe routinely or for only short periods of time except for equatorial orbiting spacecraft with the proper instrumentation, such as GEOTAIL.

Kuril'chik et al. [2004] presented observations of KC at 252 kHz and 500 kHz from the AKR-X experiment on Interball-1 Tail Probe and found that the latitudinal extent of the emission cone varied from $1° - 6°$ during solar minimum and from $10° - 20°$ during solar maximum. *Hashimoto, et al.* [2005] using PWI data on board the GEOTAIL spacecraft could not confirm this latitudinal difference with solar cycle. In addition, *Kuril'chik et al.* [2004] also noted that KC was observed more often during solar minimum than solar maximum. Once again in contrast, *Hashimoto, et al.* [2005] found only a slight occurrence difference with solar cycle having more observations of KC during solar maximum than in solar minimum. However, both papers confirmed a high occurrence probability of observing KC about the magnetic equator. The difference between these studies may be the result of viewing perspective, with GEOTAIL largely orbiting in the equatorial region and Interball-1 in a more polar ($65°$ inclination) orbit with overall significantly fewer chances to observe KC emissions.

Due to the high emission frequency of KC and its lack of correlation with geomagnetic activity, the source of KC was originally believed to lie deep within the plasmasphere [*Hashimoto et al.*, 1999]. Although there are still some instances of KC observed deep within the plasmasphere [see *Hashimoto et al.*, 2005] it is now generally believed that the majority of KC emissions originate from the equatorial plasmapause under conditions where a small part of the plasmapause has moved inwards from its nominal position. This is indirectly supported by Figure 3, which is a scatter plot of the maximum frequency of KC observed by GEOTAIL versus K_p index using observations from the study by *Green et al.* [2004]. The red line is the median, the blue line is the 25% percentile, and the green line is the 75% percentile, computed by binning the upper frequency data in bins of K_P in ranges of 1. Figure 3 shows that, even though KC occurs at all ranges of K_p, its maximum frequency tends to increase as K_p index increases, a similar but weaker trend was observed by *Hashimoto et al.* [1999] using GEOTAIL observations nearer to solar minimum. Since statistically the plasmapause moves inwards as K_p increases resulting in a greater plasma density drop across the plasmapause one would expect NTC to be generated at higher frequencies in the KC range if these emissions originated from the plasmapause.

The source region for KC was originally suggested by *Carpenter et al.* [2000] as coming from plasmaspheric cavities, but more recently *Green et al.* [2002] and *Green et al.* [2004] clearly identified KC as being generated at the plasmapause, deep within notch structures that approximately co-rotate with the Earth. Figure 4 has been adapted from Figure 8 of *Green et al.* [2002] and Figure 1 of *Green et al.* [2004] and illustrates that the location of the KC source region, within a plasmaspheric notch, and the resulting emission cone pattern of the radiation, as shown from ray tracing calculations, is consistent with the observations. The top panel of Figure 4 is a frequency-time spectrogram from the PWI instrument on GEOTAIL showing the banded structure of KC. The slanted vertical emissions are all Type III solar radio bursts. The center panel of Figure 4 shows the magnetic longitude versus the equatorial radial distance of the plasmapause (derived from the inserted extreme ultraviolet (EUV) image of the plasmasphere from the IMAGE spacecraft) and the position of GEOTAIL during the KC observations of the top panel. The bottom pane is a ray tracing analysis showing that the

structure of the plasmaspheric notch has a significant effect on the shape of the resulting emission cone through refraction.

The correspondence of KC observations with plasmaspheric notches, as shown in Figure 4, is not an isolated instance. Green et al. [2004] found that from a year's worth of observations of GEOTAIL KC observations and IMAGE EUV images of plasmaspheric notches the vast majority (94%) of the 87 cases studied showed this correspondence. Their results also showed that a density depletion or notch structure in the plasmasphere is typically a critical condition for the generation of KC but that the notch structures do not always provide the conditions necessary for the generation of the emission.

3. Generation Theories

There are three types of theoretical models [see Barbosa, 1982; Lee, 1989; for reviews] that try to explain the generation of continuum radiation. These are: 1) synchrotron radiation [Frankel, 1973; Vesecky and Frankel, 1975], 2) linear mode conversion models [Jones, 1976; Jones, 1980; Jones, 1981] and 3) nonlinear mode conversion models [Melrose, 1981; Fung and Papadopoulos, 1987].

The synchrotron radiation model is believed to be a factor of 10 too weak for NTC generation and is generally disregarded. The linear and nonlinear theories both assume that strong-trapped waves at the plasmapause in the magnetic equator are converted into electromagnetic O mode waves as NTC. The free energy source, generating the trapped waves, are most likely energetic electrons in the 10's of keV energy range with highly anisotropic phase-space density distributions [Gurnett and Frank, 1976] which become unstable when the resonant wave-particle interaction conditions are satisfied. Sharp boundaries like the plasmapause are good regions for instabilities to occur because the resonance conditions vary greatly as the particles are moving across that boundary.

Figure 5 illustrates how the banded structure of NTC is generated in the linear mode conversion theory (LMCT). Figure 5 shows profiles (black traces) of plasmaspheric plasma frequency (f_p) from the empirical model of Gallagher et al. [1988] for different K_p, with the (n+1/2) harmonics of the equatorial cyclotron frequencies (f_{ce}) plotted as blue traces, and with the Z mode cutoff (L=0) frequency plotted as green traces. As K_p index increases the plasmapause is observed to occur at lower L values. The key feature of LMCT is that trapped Z mode waves are converted into free escaping L-O mode electromagnetic waves [Budden, 1980: Budden, 1986; Jones, 1976; Jones, 1980; Jones, 1981] at selected wave normal angles (angles with respect to the geomagnetic field). For example, for K_p of 5 (see inset in Figure 5), one emission band is predicted at ~150 kHz where the (n+1/2) f_{ce} line (blue) crosses the f_{uhr} line (red), the quasi-electrostatic emissions at this point propagate inwards as Z mode waves (green) where they refracted outwards by the Z mode cutoff finally reaching the radio window where their frequency equals f_p (black). The Z to L-O mode radio window occurs where the wave frequency is equal to f_p and the wave vector is either parallel or antiparallel to the ambient magnetic field, at this point the index of refraction for these two modes are equal. Efficient conversion requires that the local plasma density gradient be strong and nearly

perpendicular to the ambient magnetic field. Under these conditions the wave vector of the L-O mode after leaving the radio window will rapidly rotate to the angle α given by the formula shown in the inset in Figure 5. This formula is an approximation that only strictly holds for a constant magnetic field and a planar density gradient perpendicular to the ambient magnetic field. *Horne* [1989] performed detailed ray tracing calculations of this propagation process showing that wave energy can be efficiently transported into the radio window using the linear theory.

If the LMCT is generating NTC then Figure 5 illustrates the number of expected NTC emissions bands and their location as a function of K_p. Since KC is generated at the plasmapause, in the magnetic equator, the maximum observed NTC frequency should increase with increasing K_p as illustrated in Figure 5. Although this figure suggests qualitative trends, it is not quantitatively correct. Figure 3 shows that for $K_p < 2$ the maximum observed frequency for a number the events is greater than 200 kHz, however, Figure 5 would predict no emissions above ~150 kHz, using the *Gallagher et al.* [1988] model, this is true regardless of the MLT. The current empirical plasmasphere models do not reflect the dynamical nature of the plasmasphere, failing to model such observed plasmaspheric structures like shoulders, notches or plumes.

Over the frequency range from about 350 kHz to 600 kHz there are 8 KC emission bands in Figure 1 and 10 bands in Figure 4. Assuming that a plasmapause density profile for a KC source region in a notch structure can be represented, regardless of K_p, by the f_p curve at $L = 2.5$ then only 2 or at most 3 emission bands would be predicted with deeper notch structures producing even fewer band. Based on these results the LMCT does not appear to adequately account for the large number of observed bands of the higher frequency KC emissions that are generated in deep plasmaspheric notch structures.

In the nonlinear model of *Melrose* [1981] density irregularities formed by low frequency waves coalesce with upper hybrid waves generating this radiation. In the nonlinear model of *Fung and Papadopoulos* [1987] electrostatic waves propagating into a density gradient can nonlinearly interact with its reflected wave to generate an electromagnetic wave at twice the electrostatic wave frequency. Both linear and nonlinear theories 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.

Recently, research has focused on plasmaspheric density irregularities in the emission spectra of electrostatic waves that then mode convert to NTC or KC. A theory by *Yoon and Menietti* [2005] used eigenvalue analysis of upper-hybrid/Langmuir waves in cavities and found that emission spectra with spacing less than f_{ce} can be generated. *Menietti et al.* [2005], using wideband data from Polar and Cluster, found NTC near the source with banded spectra line spacing much less than f_{ce}. More theoretical work needs to be done in order to encompass all the characteristics of NTC that are observed.

4. Concluding Remarks

Many of the characteristics of the lower frequency portion of the nonthermal continuum (trapped component) have been difficult to determine due to the multiple reflections of the emission from the magnetopause and plasmapause. Recently there is a renewed interest in studying the high frequency extension of this emission (the escaping component) especially in the kilometric frequency range [see for example: *Hashimoto et al.*, 1999; *Green et al.*, 2002; 2004]. Several new features of the high frequency escaping KC, such as the narrow latitudinal beam structure and relationship to plasmaspheric notch structures provides 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 in verifying existing theories. Observing the radiation while the instability has been initiated and grows and by examining the dynamics of the large-scale plasmasphere should lead to significant advances in delineating the best theory for the generation of this emission.

There are a number of outstanding questions that need to be addressed concerning the generation and propagation of KC:

1) Is the movement of the plasmapause inwards coupled with a sufficiently large density gradient necessary and sufficient for the generation of KC? Is the free energy source necessary for the creation of electrostatic waves that are precursors to KC always present, or is the free energy source dependent on the state of the magnetosphere?

2) KC has been detected over a wide range of geophysical conditions, what is the statistical dependence on geomagnetic activity of plasmaspheric structures like shoulders and notches that are good locations for KC generation? Since KC is also detected during low geophysical activity, something must happen to move part of the plasmapause inwards. Can the observation of KC during quite times only be accounted for by the presence of shoulders or notches?

3) KC often exhibits a banded frequency structure consistent with $(n+1/2)$ f_{ce} source, but frequently the structure appears more complex. Can density ducts near the plasmapause explain the more complex structure or do other mechanisms need to be investigated like dynamic motion of the plasmapause boundary layer? Sounding of the plasmapause by IMAGE RPI indicates that the plasmapause surface is far from smooth [*Carpenter*, 2004], what effect does this non-smoothness have on the emission of KC and NTC in general?

4) Does the KC emission 'Christmas tree' patterns detected by IMAGE exhibit the same frequency dependence with K_p as observed by GEOTAIL near solar minimum and near solar maximum?

5) For highly disturbed times *Tsyganenko and Sitnov* [2005] found that large changes occur in the inner magnetosphere magnetic field intensity. Can this change be detected

remotely in the spectral band spacing of escaping NTC and KC? Can the analysis of the frequency structure of escaping NTC and KC indicate the state of the plasmasphere and the inner magnetosphere magnetic field?

REFERENCES

Barbosa, D. D., Low-level VLF and LF radio emissions observed and earth and Jupiter, *Rev. of Geophys. and Space Phys.*, *20*, 2, 316-334, 1982.

Budden, K. G., The theory of radio windows in the ionosphere and magnetosphere, J. *Atmos. Terr. Phys.*, *42*, 287-298, 1980.

Budden, K. G., The theory of radio windows in the ionosphere and magnetosphere II, J. *Atmos. Terr. Phys.*, *48*, 663-641, 1986.

Brown, L. W., The galactic radio spectrum between 130 kHz and 2600 kHz, *Astrophys. J.*, *180*, 359-370, 1973.

Carpenter, D.L., R. R. Anderson, W. Calvert, and M. B. Moldwin, CRRES observations of density cavities inside the plasmasphere, *J. Geophys. Res.*, *105*, 23323-23338, 2000.

Carpenter, D.L., Remote sensing the Earth's plasmasphere, *Radio Sci. Bull.*, 308, 19-30, 2004.

Coroniti, F. V., F. L. Scarf, C. F. Kennel, and D. A. Gurnett, Continuum radiation and electron plasma oscillations in the distant geomagnetic tail, *Geophys. Res. Lett.*, *11*, 661-664, 1984.

Darrouzet, F., P. M. E. Décréau, J. De Keyser, A. Masson, D. L. Gallagher, O. Santolik, B. R. Sandel, J. G. Trotignon, J. L. Rauch, E. Le Guirriec, P. Canu, F. Sedgemore, M. André, and J. F. Lemaire, Density structures inside the plasmasphere: Cluster observations, *Ann. Gephys.*, *22*, 2577-2585, 2004.

Décréau, P. M. E., C. Ducoin, G. Le Rouzic, O. Randriamboarison, J.-L. Rauch, J.-G. Trotignon, X. Vallieres, P. Canu, f. Darrouzet, M. P. Gough, a. M. Buckley, and T. D. Carozzi, Observation of continuum radiations from the Cluster fleet: first results from direction finding, *Ann. Geophys*, 22, 2607-2624, 2004

Filbert, P. C., and P. J. Kellogg, Observations of low-frequency radio emissions in the Earth's magnetosphere, *J. Geophys. Res.*, *94*, 8867-8885, 1989.

Frankel, M. S., LF radio noise from the earth's magnetosphere, *Radio Sci.*, *8*, 991-1005,1973.

Fung, S. F. and K. Papadopoulos, The emission of narrow-band Jovian kilometric radiation, *J. Geophys. Res.*, *92*, 8579-8593, 1987.

Fung, S. F., and J. L. Green, Modeling of field-aligned radio echoes in the plasmasphere, *J. Geophys. Res.*, *110*, A01210, doi:10.1029/2004JA010658, 2005.

Gallagher, D. L., P. D. Craven, and R. H. Comfort, An empirical model of the Earth's Plasmasphere, *Adv. Space Res.*, 8(8), (8)15– (8)24, 1988.

Gough, M. P., Nonthermal continuum emissions associated with electron injections: Remote plasmapause sounding, *Planet. Sp. Sci.*, 30, 657, 1982.

Green, J. L., and S. A. Boardsen, Confinement of nonthermal continuum radiation to low latitudes, *J. Geophys. Res.*, *104*, 10307-10316, 1999.

Green, J. L., B. R. Sandel, S. F. Fung, D. L. Gallagher, and B. W. Reinisch, On the origin of kilometric continuum, *J. Geophys. Res., 107(A7)*, 1105, doi:10.1029/2001JA000193, 2002.

Green, J. L., S. Boardsen, S. F. Fung, H. Matsumoto, K. Hashimoto, R. R. Anderson, B. R. Sandel, and B. W. Reinisch, Association of kilometric continuum radiation with plasmaspheric structures ,*J. Geophys. Res., 109*, A03203, doi:10.1029/2003JA010093, 2004.

Green, J. L., and S. F. Fung, "Advances in inner magnetospheric passive and active wave research," Physics and Modeling of the Inner Magnetosphere, AGU Monograph Vol.155, Washington DC, pp. 181-202, 2005. Gurnett, D. A., and L. A. Frank, Continuum radiation associated with low-energy electrons in the outer radiation zone, *J. Geophys. Res., 81*, 3875-3885, 1976.

Gurnett, D. A., and R. R. Shaw, Electromagnetic radiation trapped in the magnetosphere above the plasma frequency, *J. Geophys. Res., 78*, 8136-8149, 1973.

Gurnett, D. A., The Earth as a radio source: The nonthermal continuum, *J. Geophys. Res., 80*, 2751-2763, 1975.

Hashimoto, K., W. Calvert, and H. Matsumoto, Kilometric continuum detected by GEOTAIL, *J. Geophys. Res., 104*, 28645-28656, 1999.

Hashimoto, K., R. R. Anderson, J. L. Green, and H. Matsumoto, Source and propagation characteristics of kilometric continuum observed with multiple satellites, *J. Geophys. Res., 110*, A09229, doi:10.1029/2004JA010729, 2005.

Horne, R. B., Path-integrated growth of electrostatic waves: the generation of terrestrial myriametric radiation, *J. Geophys. Res., 94*, 8895-8909, 1989.

Jones, D., Source of terrestrial nonthermal radiation, *Nature, 260*, 686-689, 1976.

Jones, D., Latitudinal beaming of planetary radio emissions, *Nature, 288*, 225-229, 1980.

Jones, D., Beaming of terrestrial myriametric radiation, *Adv. Space Res., 1*, 373-376, 1981.

Jones, D., Planetary radio emissions from low magnetic latitudes – observations and theories, *Planetary Radio Emissions II,*. edited by H. O. Rucker, S. J. Bauer, and B.-M. Pedersen, Austrian Acad. of Sci., Vienna, Austria, 255 – 293, 1988.

Kaiser, M. L., Observations of nonthermal radiation from planets, *Plasma Waves and Instabilities at Comets and in Magnetospheres,* edited by Tsurutani and Oya, AGU, Washington, 221-237, 1989.

Kasaba, Y., H. Matsumoto, K. Hashimoto, R. R. Anderson, J.-l. Bougeret, M. L. Kaiser, X. Y. Wu, and I. Nagano, Remote sensing of the plasmapause during substorms: GEOTAIL observation of nonthermal continuum enhancement, *J. Geophys. Res.,* 103, 20389-20405, 1998.

Kuril'chik, V. N., I. F. Kopaeva, and S. V. Mironov, INTERBALL-1 Observations of the Kilometric "Continuum" of the Earth's Magnetosphere, *Cosmic Research, 42*, 1-7, 2004.

Kurth, W. S., M. M. Baumback, and D. A. Gurnett, Direction-finding measurements of auroral kilometric radiation, *J. Geophys. Res., 80*, 2764-2770, 1975.

Kurth, W. S., D. A. Gurnett, and R. R. Anderson, Escaping nonthermal continuum radiation, *J. Geophys. Res., 86*, 5519-5531, 1981.

Kurth, W. S., Detailed observations of the source of terrestrial narrowband electromagnetic radiation, *Geophys. Res. Lett., 9*, 1341-1344, 1982.

Kurth, W. S., D. A. Gurnett, A. Roux, and S. J. Bolton, Ganymede: A new radio source, *Geophys. Res. Lett., 24,* 2167-2170, September 1997.

Lee, L. C., Theories of nonthermal radiations from planets, *Plasma Waves and Instabilities at Comets and in Magnetospheres,* edited by Tsurutani and Oya, AGU, Washington, p. 239-249, 1989.

Matsumoto, H., I. Nagano, R. R. Anderson, H. Kojima, K. Hashimoto, M. Tsutsui, T. Okada, I. Kimura, Y. Omura and M. Okada, Plasma Wave Observations with GEOTAIL Spacecraft, *J. Geomag. Geoelectr., 46,* 59-95, 1994.

Melrose, D. B., A theory for the nonthermal radio continuum in the terrestrial and Jovian magnetospheres , *J. Geophys. Res., 86,* 30-36, 1981.

Menietti, J. D., R. R. Anderson, J. S. Pickett, and D. A. Gurnett, Near-source and remote observations of kilometric continuum radiation from multi-spacecraft observations, *J. Geophys. Res., 108,* 11, 1393, doi:10.1029/2003JA009826, 2003.

Menietti, J. D., O. Santolik, J. S. Pickett, and D. A. Gurnett, High resolution observations of continuum radiation, *Planetary and Space Sci.,* 53, 283-290, 2005.

Morgan, D. D., and D. A. Gurnett, The source location and beaming of terrestrial continuum radiation, *J. Geophys. Res., 96,* 9595-9613, 1991.

Takano, H., I. Nagano, S. Yagitani, and H. Matsumoto, Lobe trapped continuum radiation generated in the distant magnetotail, *Frontiers of magnetospheric Plasma Physics: Celebrating 10 Years of GEOTAIL Operation,* Elsevier, 224-227, 2005.

Tsyganenko, N. A., and M. I. Sitnov, Modeling the dynamics of the inner magnetosphere during strong geomagnetic storms, *J. Geophys. Res., 110,* A03208, doi:10.1029/2004JA010798, 2005.

Vesecky, J. F., and M. S. Frankel, Observations of a low-frequency cutoff in magnetospheric radio noise received on IMP 6, *J. Geophys. Res., 80,* 2771-2774, 1975.

Yoon, P. H. and J. D. Menietti, On fine structure emission associated with plasmaspheric density irregularities, accepted for publication by *Geophys. Res. Lett.,* 2005.
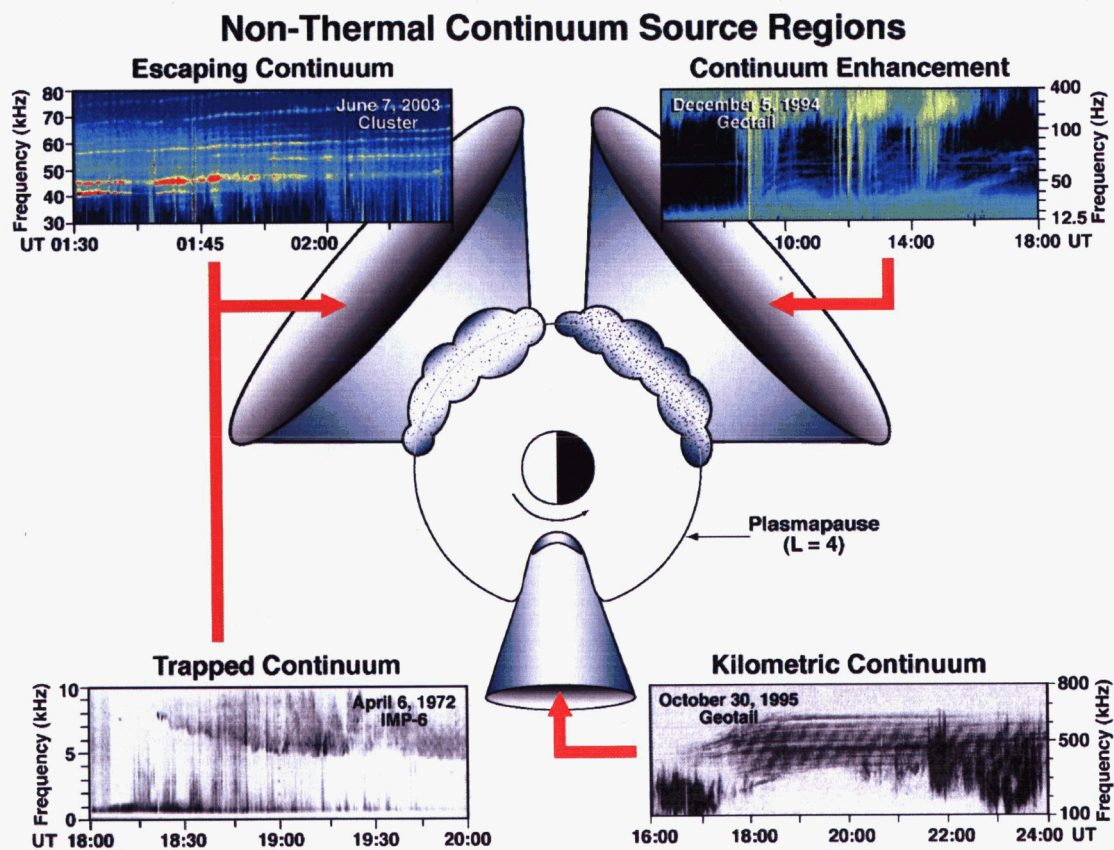
Figure Captions

Figure 1. The observed source locations of the escaping [after *Décréau, et al.*, 2004], trapped [after *Gurnett and Frank*, 1976], kilometric [after *Hashimoto et al.,* 1999] and continuum enhancement [after *Kasaba, et al.*, 1998] emissions.
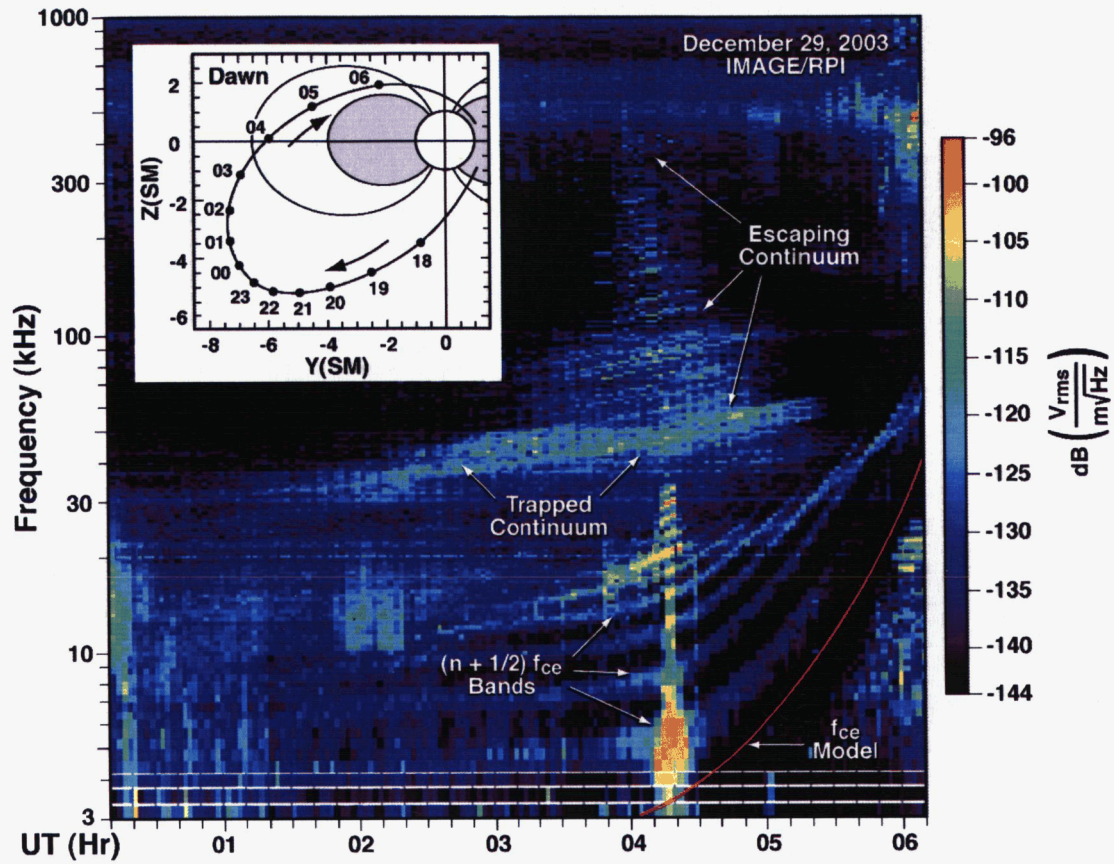
Figure 2. An RPI frequency-time spectrogram taken during a passage through the magnetic equator on the dawn side (see orbit insert). The Christmas tree pattern of nonthermal continuum is clearly shown nearly centered about the magnetic equator delineated by the intense electrostatic emissions. These "normal continuum" emissions contain both magnetospherically trapped and escaping emissions.
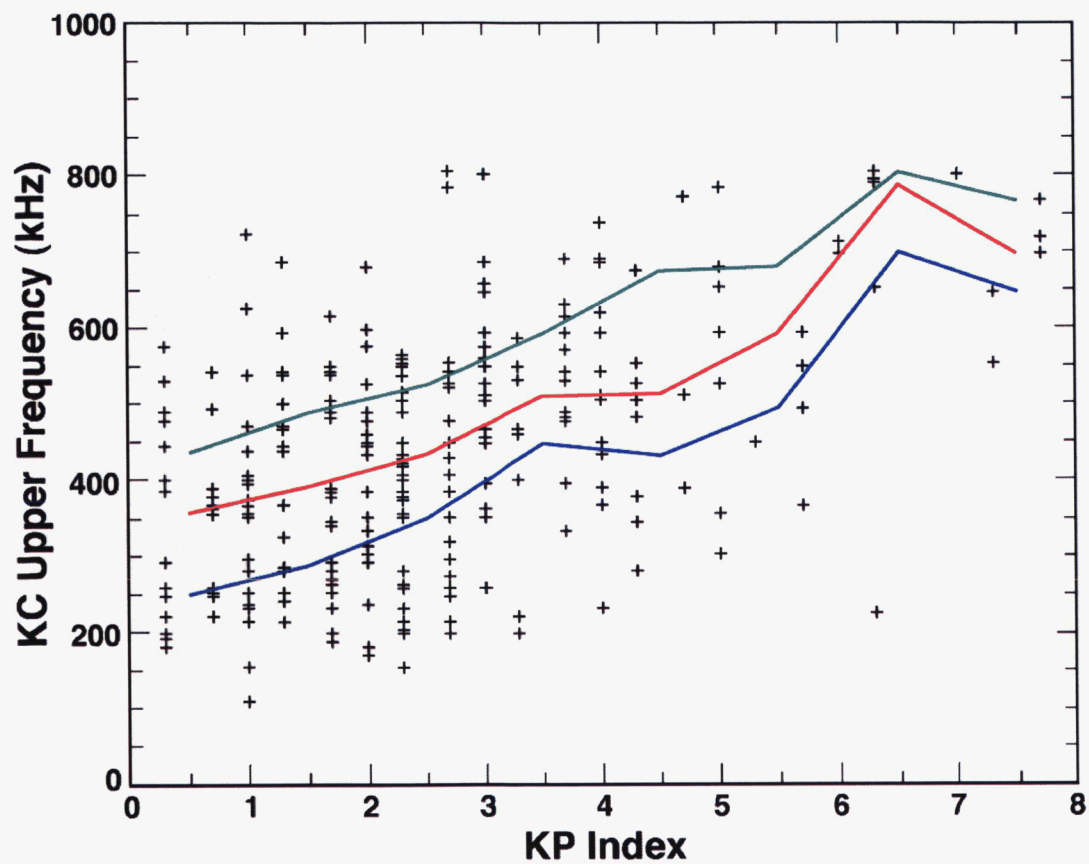
Figure 3. A scatter plot of the maximum frequency of KC as observed by GEOTAIL around solar max versus K_p index.
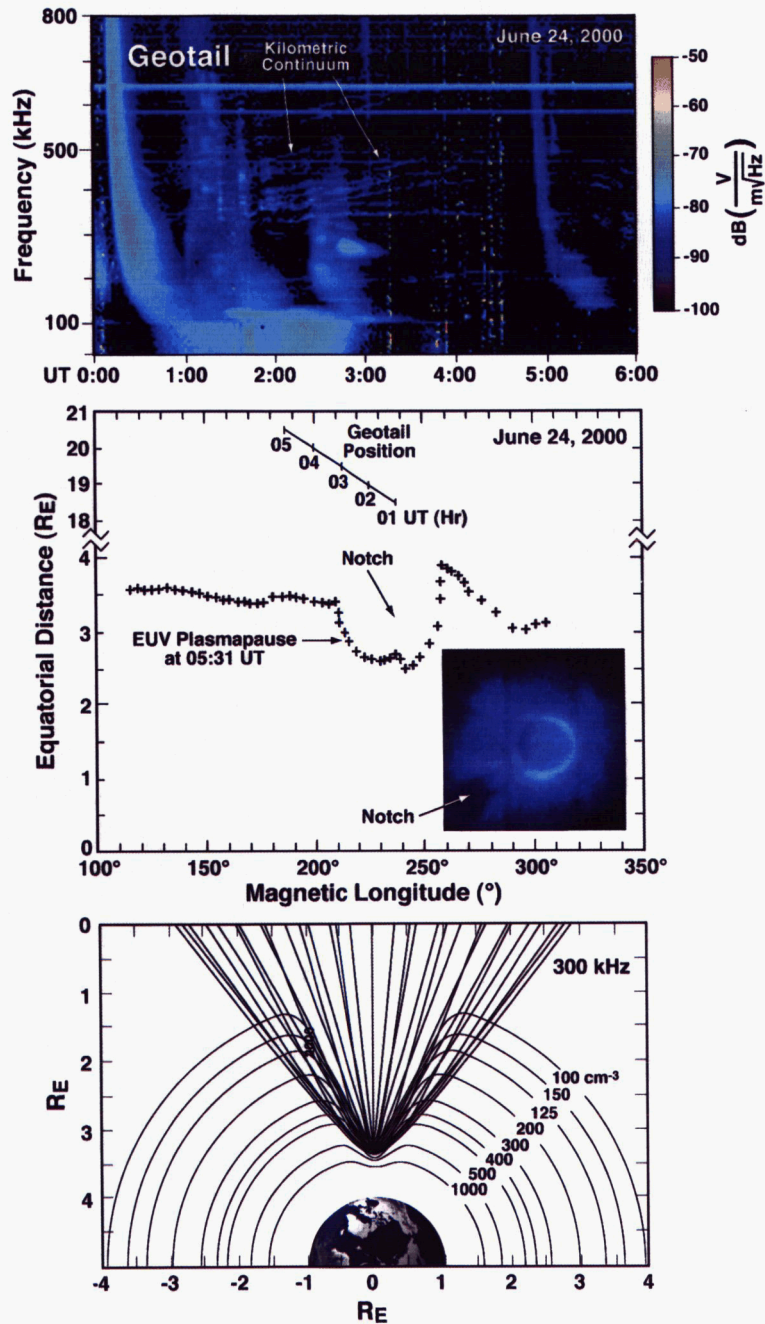
Figure 4. KC wave observations from GEOTAIL/PWI (top panel) map to a plasmaspheric notch structure as observed by IMAGE/EUV (middle panel) where the resulting emission cone pattern (bottom panel) is modeled with ray tracing calculations [after *Green et al.,* 2002 and 2004].
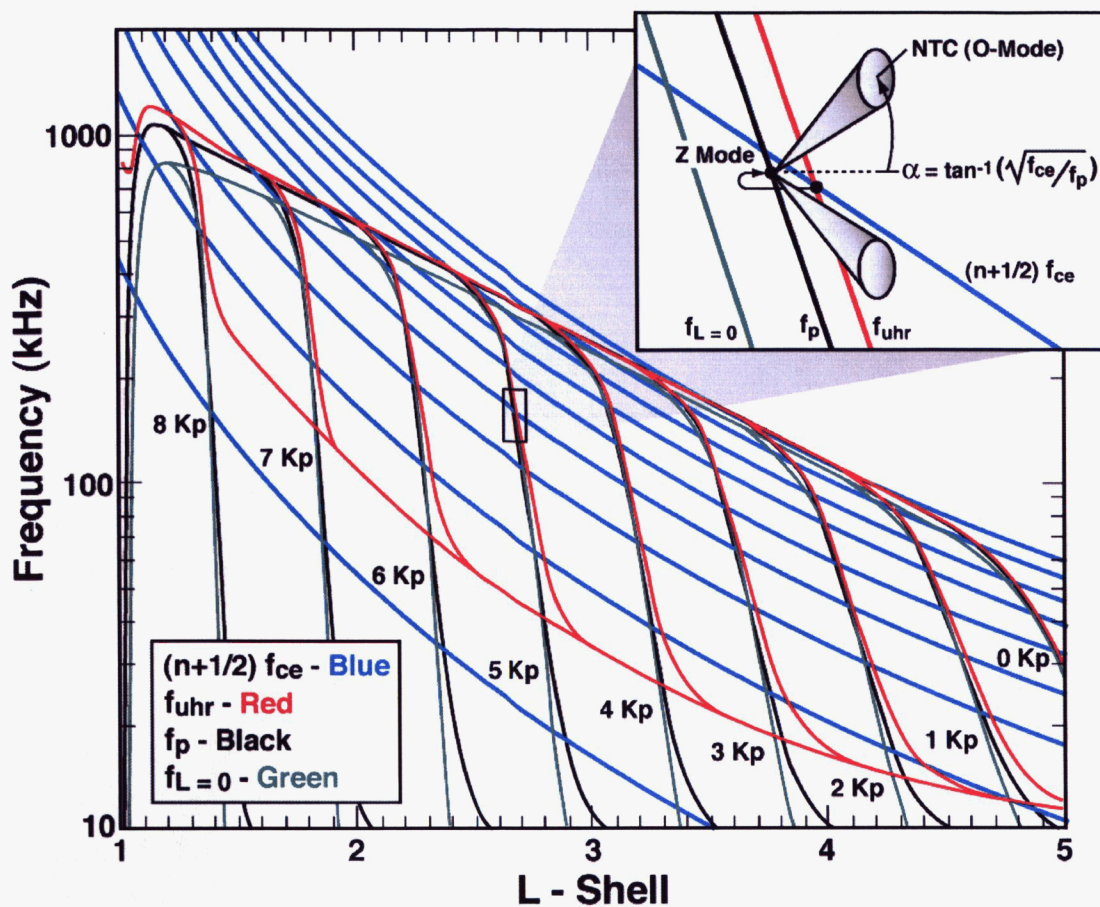
Figure 5. Plasmaspheric f_p curves (black traces) for different K_p indices are plotted versus L-shell at the magnetic equator. Also shown are curves for $(n+\frac{1}{2})f_{ce}$ (blue traces), $f_{L=0}$ (green) and f_{uhr} (red). In the linear mode Z to O mode conversion theory, regions of sharp plasma gradient at the plasmapause are potential source regions of NTC as shown in the inset. .