Association of kilometric continuum radiation with plasmaspheric structures

James L. Green,[1] Scott Boardsen,[2] Shing F. Fung,[1] H. Matsumoto,[3] K. Hashimoto,[3] R. R. Anderson,[4] B. R. Sandel,[5] and B. W. Reinisch[6]

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[1] A year's worth of observations of kilometric continuum (KC) from the plasma wave instrument (PWI) on GEOTAIL and extreme ultraviolet (EUV) images of the plasmasphere from IMAGE are compared. In the vast majority (~94%) of the 87 cases when simultaneous data from both spacecraft were available, KC was observed to be associated with density depletions or notch structures in the plasmasphere. From a careful analysis of 1 month of EUV data comprising 13 notch structures, only one notch structure was found in which no accompanying KC was observed when GEOTAIL was in a low-latitude position and therefore should have observed the emission if it were generated. IMAGE observations from the radio plasma imager (RPI) during passage through a plasmaspheric notch structure found that KC was generated in or very near the magnetic equator at steep gradients in density and associated with emissions in the upper hybrid resonance band as previously reported by others at lower frequencies. Statistical analysis of the KC events associated with plasmaspheric notch structures shows that the typical source region is at an equatorial radial distance of ~2.4 R_E (Earth radii) in the magnetic equator and produces an emission cone that is ~40° in longitude and ~20° in latitude. These results show 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. *INDEX TERMS:* 2772 Magnetospheric Physics: Plasma waves and instabilities; 2740 Magnetospheric Physics: Magnetospheric configuration and dynamics; 2730 Magnetospheric Physics: Magnetosphere—inner; *KEYWORDS:* kilometric continuum, plasma waves, plasmasphere, plasmapause

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1. Introduction

[2] The Earth's nonthermal continuum radiation is observed from 10 to 800 kHz [see, e.g., *Gurnett*, 1975; *Hashimoto et al.*, 1999]. At frequencies less than the magnetopause plasma frequency (~30 kHz) the continuum radiation has been referred to as the "trapped" component [*Gurnett and Shaw*, 1973]. At frequencies above the magnetopause plasma frequency, the emission has been referred to as the "escaping" component [*Kurth et al.*, 1981]. *Hashimoto et al.* [1999] recently identified in the GEOTAIL Plasma Wave Instrument (PWI) data a distinct component of the continuum radiation in the 100 kHz to 800 kHz frequency range confined to the equatorial region. They named this radiation "kilometric continuum" or KC. The name "continuum" in these various radiations was derived from the appearance the radiation made on spectrograms from the earliest observations using receivers with much coarser frequency resolution than available today. Even today the trapped continuum, generated as closely spaced nearly monochromatic emission lines, can appear to observers as a true continuum because of the summation of a large number of different frequency sources and Doppler broadening due to multiple reflections from the plasmapause and magnetopause [see *Green and Boardsen*, 1999]. The PWI instrument on the GEOTAIL spacecraft has also observed another distinct component of continuum radiation that *Kasaba et al.* [1998] referred to as "continuum enhancement." This emission may be generated at the plasmapause in the premidnight to dawnside sector, is a short-lived enhancement and is associated with substorms. In some cases the continuum enhancement has a discrete emission line structure from 20 kHz up to 300 kHz where it could then be called KC. The continuum enhancement, unlike KC,

[1]NASA Goddard Space Flight Center, Greenbelt, Maryland, USA.
[2]L3 Communications Analytics Division, NASA Goddard Space Flight Center, Greenbelt, Maryland, USA.
[3]Radio Science Center for Space and Atmosphere, Kyoto University, Kyoto, Japan.
[4]University of Iowa, Iowa City, Iowa, USA.
[5]Lunar and Planetary Laboratory, University of Arizona, Tucson, Arizona, USA.
[6]Center for Atmospheric Research, University of Massachusetts, Lowell, Massachusetts, USA.

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is observed from midnight to the dawn sector and is believed to be generated by electrons injected from the tail.

[3] In a recent paper, *Green et al.* [2002] presented an example of KC being associated with a plasmaspheric bite-out structure as observed by the radio plasma imager (RPI) and the extreme ultraviolet (EUV) imager on the Imager for Magnetopause-to-Aurora Global Exploration (IMAGE) spacecraft. These authors showed that the RPI detected KC as the IMAGE spacecraft passed through a plasmaspheric bite-out structure around the magnetic equator. Ray tracing calculations, consistent with their observations, revealed that the KC source region was deep within the bite-out near the plasmapause and in the magnetic equatorial plane, with the longitudinal extent of the emission largely confined to the bite-out structure. The IMAGE EUV team has investigated these bite-out structures and has renamed them as plasmaspheric notches in an effort to better describe a whole family of plasmaspheric density depletion features. This paper will adopt that naming convention. The purpose of this paper is to further investigate the initial results presented in the work of *Green et al.* [2002] and determine if plasmaspheric notch structures are a sufficient or a necessary condition for the generation of KC.

2. Simultaneous GEOTAIL PWI and Image EUV Observations

[4] The GEOTAIL spacecraft was launched on 24 July 1992. On 19 February 1995 the spacecraft was placed in a ~10 by ~30 Earth radii (R_E) near-equatorial orbit about the Earth where the PWI routinely observes KC [*Hashimoto et al.*, 1999]. Figure 1a is a typical observation of kilometric continuum in a frequency-versus-time spectrogram observed by the PWI instrument on 24 June 2000 (see *Matsumoto et al.* [1994] for more details on the PWI instrument). A common characteristic of the escaping continuum radiation, as shown in Figure 1a, is the narrow discrete frequency bands of emissions from ~0100 to 0500 UT.

[5] The IMAGE spacecraft was launched on 25 March 2000 into a highly elliptical polar orbit with initial geocentric apogee of 8.22 R_E and perigee altitude of 1000 km. From this position, IMAGE is able to image the entire plasmasphere by the EUV instrument repeatedly over a period of many hours. The EUV instrument measures the He^+ resonance scattering of sunlight at 30.4 nm from the plasmasphere with a time resolution of 10 min and a spatial resolution of 0.1 R_E [*Sandel et al.*, 2001] when IMAGE is at apogee. A typical example of an EUV image of the plasmasphere is shown in the insert of Figure 1b. The Sun is to the right in this image with the Earth's shadow being cast directly behind the Earth and to the left in the image. A distinct notch (darkened) feature is observed at about 3–4 hours local time below the Earth's shadow in this image. This notch structure is characterized by significant density depletions in the outer plasmasphere, which presents itself in EUV images as a very distinctive feature. From a series of EUV images the notch structure typically is observed to roughly corotate with the Earth. On 24 June 2000 this notch structure corotated with the Earth for at least one full day. The perspective of the notch structure, shown in Figure 1, was chosen to clearly illustrate the dramatic density depletion and the establishment of a new plasmapause deep inside the notch structure. For the purposes of scale, a white circle has been drawn around the Earth in the EUV image which was observed at 0531 UT. An arrow points in the direction to the Sun. This time has been chosen since the perspective is right over the notch region and clearly shows the plasmapause structure that does not significantly change over this KC event.

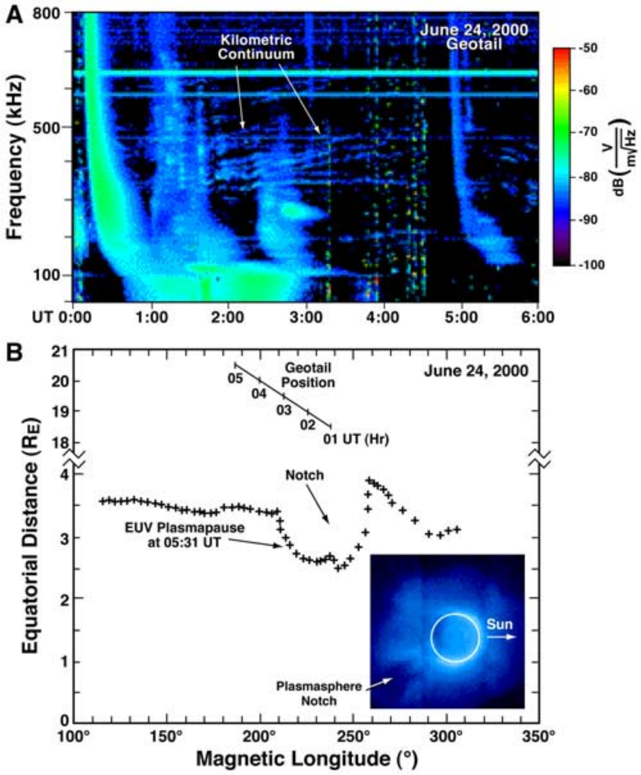

Figure 1. (a) Frequency-time spectrogram from the PWI instrument on GEOTAIL showing the banded structure of KC. (b) Magnetic longitude versus the equatorial radial distance of the plasmapause (derived from an EUV image of the plasmasphere, inserted) and the position of GEOTAIL during the KC observations Figure 1a. The excellent correspondence shows that KC is generated in notch structures in the plasmasphere as previously reported. The inserted EUV image has an outline of the Earth (white circle) as a measure of the scale size of the notch structure and the direction toward the Sun is also labeled.

[6] Figure 1b is a plot of the plasmapause location in equatorial radial distance and magnetic longitude. The plasmapause location corresponds to the region of the steep gradient in the line-of-sight integrated EUV luminosity. A number of comparisons with RPI data have identify this gradient with the plasmapause [*Goldstein et al.*, 2003]. Within the notch, the luminosity is above the background but much lower than at neighboring longitudes. Since magnetic longitude is anchored to the rotating Earth, it is the best coordinate system to study corotating features of the plasmasphere. The notch structure in Figure 1 extends approximately 45° in longitude. The magnetic longitude of GEOTAIL during the time when the PWI instrument observes KC, as shown in Figure 1a, is also

plotted in Figure 1b. At ~0100 UT GEOTAIL was near 10° magnetic latitude (MLAT) and moving toward the magnetic equator. It exited the KC emission near ~0500 UT at ~5° MLAT. As shown in Figure 1a, there is an outstanding match to the location of the notch structure and that of GEOTAIL during the time that the PWI observed KC. These observations provide strong evidence that the KC observed by GEOTAIL/PWI is emanating from the plasmaspheric notch structure and is completely consistent with the previous results of *Green et al.* [2002].

[7] The KC observation in Figure 1, from the GEOTAIL/PWI, shows a gradual increase in frequency with time. *Kasaba et al.* [1998] has interpreted the increases in harmonic spacing of previous continuum enhancement events as caused by the pealing off of plasmas from the outer plasmasphere during individual substorms. This may be the case under certain circumstances. There has been no study to date that has definitively determined if the spectral changes observed in the continuum radiation spectrum are due to spatial or temporal variations. In this context, variations observed by GEOTAIL could be due to a moving source region (the entire spectrum changes over the entire emission cone), or due to spectral changes across the emission cone (i.e., changes in frequency occurring at the edges of the emission cone due to an extended source region in either longitude or latitude), or at the time the emission frequency starts to rise GEOTAIL may be viewing the source at the deepest part of the notch structure. It is important to note that the EUV data of Figure 1 shows a complicated notch structure, which remains relatively constant over many hours. Typical notch structures observed by EUV show that the plasmapause is much more of a single concaved structure. One way to clarify which explanation is the most viable would be to have simultaneous observations of continuum radiation by two or more spacecraft that are in distinctly different regions of the emission cone but that effort is beyond the scope of this current study.

[8] There were 246 observations of KC events observed by the PWI instrument on GEOTAIL from May 2000 through July 2001. In order to determine any local time or latitudinal dependences in this sample of events Figure 2 is a plot of the normalized frequency of occurrence of these events. Figure 2 shows that the magnetic latitude of the KC events were well confined to within 20° of the magnetic equator and they were observed at all magnetic local times, completely consistent with previously reported results of *Hashimoto et al.* [1999]. It is important to note that there is a slight increase in the frequency of occurrence in the midnight to dawn sectors that is consistent with the continuum enhancement events studied by *Kasaba et al.* [1998]. The 246 KC events used in this study were qualitatively compared with the location of GEOTAIL and the corresponding IMAGE EUV observations of the plasmasphere within a 6-hour MLT spatial extent and were categorized. Times when there were no EUV data or when there were abnormally low or high EUV fluxes observed making direct comparison with the KC events from GEOTAIL ambiguous or impossible to correlate were excluded from the survey. This left 87 events to analyze. Five categories of the EUV images of the plasmasphere were established and compared with the remaining events with the following results: (1) smooth plasmasphere, 6%; (2) a notch structure(s), 48%; (3) ledge with a large density depletion extending many hours in local time, 29%; (4) plasmaspheric tail, 14%; (5) an interior density depletion or cavity, 3%. *Sandel et al.* [2001] has provided an illustration of nearly all these categories. Much attention has been made of the new IMAGE EUV observations of plasmaspheric tails (also called plumes) [see, e.g., *Burch*, 2004]. These structures are regions in the late afternoon or early evening local time sectors in which plasmaspheric material is siphoned off from the plasmasphere and convected toward the dayside magnetopause. Therefore together categories 2, 3, 4, and 5 represent a variety of well-defined density depletions from a smooth unaltered plasmaspheric structure. In order to understand how frequent these structures are observed in general one year of EUV observations (2001) were used during the time when the IMAGE apogee was directly over the northern polar cap. A total of 611 orbits of EUV data were examined for which 23% had notches, 1.6% had ledge structures, 7.4% had tail or plume structures, and ≪0.1 had a depletion or cavity. A smooth plasmasphere can be seen at some local time in over 90% of the orbits. These results show that the notch structures are the most common density depletion structure of plasmaspheric and are also the most likely to support the generation of kilometric continuum.

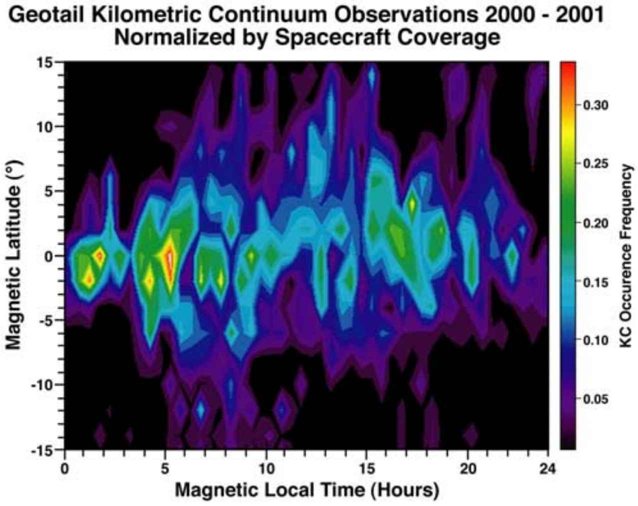

Figure 2. A frequency of occurrence plot from two years (2000–2001) of GEOTAIL PWI observations of KC in magnetic latitude and local time. KC events are observed at all local times and within about 10° of the magnetic equator.

[9] From this survey the largest category of plasmaspheric features related to kilometric continuum has been plasmaspheric notch structure. In order to further investigate the role of the plasmaspheric notch structure in the generation of KC one month of EUV data were selected in which 13 well-defined notch structures were found first and then compared with the GEOTAIL PWI data. Electric field observations from PWI were only considered when the magnetic latitude of GEOTAIL was within 10° of the magnetic equator. Of the 13 cases examined only three examples were found of well-defined notch structures that did not correlate with KC observations by the PWI. In two of these three cases, PWI also observed strong and nearly continuous Type III solar burst storms especially above

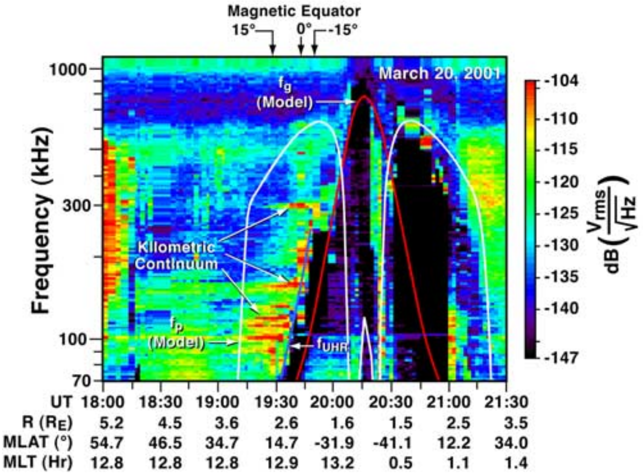

Figure 3. A frequency-time spectrogram from the IMAGE RPI instrument during its passage through the source region of KC. The observations of kilometric continuum in this figure are when the spacecraft was within 15° of the magnetic equator at a radial distance of about 2.5 R_E near 13 MLT. The narrow frequency banded structure of KC is observed to emanate from intensifications of the UHR band as clearly shown in the emissions from 1930 to 1945 UT. Models are used to determine the expected f_p and f_g values and are labeled with white and red lines, respectively. The actual plasmapause (where f_p is 100 kHz) is located at ~2.5 R_E which is significantly below the expected plasmapause location based on the model. These observations are consistent with the interpretation of KC sources observed at a plasmapause established at unusually small radial distances.

400 kHz that could easily hide the KC emissions. The last case was taken when GEOTAIL was near apogee and might not have observed KC if it had been extremely weak, however, nearly half of the KC cases used in this study were taken when GEOTAIL was near apogee. These observations still show that in the vast majority of cases large density depletions causing steep plasmapause structures at low radial distances are the likely source regions for KC.

3. RPI Observations in the KC Source Region

[10] The RPI instrument on IMAGE is a highly flexible radio sounder that transmits and receives coded radio frequency pulses in the frequency range from 3 kHz to 3 MHz [*Reinisch et al.*, 2000]. RPI also makes passive radio measurements. RPI utilizes three orthogonal dipole antennas of 325 m (X axis), 500 m (Y axis), and 20 m (Z axis). The X-axis antenna was originally extended to 500 m but was shortened to 325 m when it apparently collided with space debris on 3 October 2000. The RPI instrument alternates between making passive radio wave measurements and radio sounding measurements. Each of these modes of operation are analyzed and displayed differently.

[11] The passive radio wave measurements are displayed in a frequency-versus-time spectrogram shown in Figure 3. Since IMAGE does not carry a science magnetometer, the red line in Figure 3 is the electron gyrofrequency (f_g) calculated from the T96 magnetic field model [*Tsyganenko*, 1995] and the white line is the electron plasma frequency (f_p) determined from the plasmasphere model of *Gallagher et al.* [1988]. The observations of kilometric continuum in Figure 3 were obtained when the IMAGE spacecraft was within 15° of the magnetic equator at a radial distance of about 2.5 R_E near 13 hours magnetic local time (MLT). The narrow frequency banded structure of KC, as seen in Figure 3, is observed to emanate from intensifications of the upper hybrid frequency (UHR) band from 1930 to 1945 UT in particular. The UHR emission (f_{uhr}) is inferred from the spectrograms (blue line) and is a local electrostatic emission and is commonly used to determine the local electron plasma frequency from the equation

$$f_{uhr}(\text{kHz}) = \left[f_g^2 + f_p^2\right]^{1/2},$$

where

$$f_p(\text{kHz}) \cong 9[N_e]^{1/2}$$

$$f_g(\text{kHz}) \cong 0.028|\mathbf{B}|$$

and N_e is the electron density (cm^{-3}) and **B** is the magnetic field in nT.

[12] *Kurth et al.* [1979] have shown that emissions in the UHR band are closely associated with the plasmapause and with anisotropic features in the 1 to 20 keV electron distributions during times when lower frequency (>100 kHz) nonthermal continuum radiations is generated. As shown in Figure 3, there is a large discrepancy between the observed f_{uhr} and the model f_p of the plasmasphere, indicating that relative to nominal expected plasmaspheric conditions there is a major depletion of plasmaspheric density in the source region of KC. From these observations the plasmapause is estimated to be at less than 2.5 R_E. These observations are consistent with those presented by *Green et al.* [2002] and supports the result presented in section 2 that KC is typically generated in regions of depleted plasmaspheric density with steep density gradient at the plasmapause. Figure 3 also shows that the higher frequency KC emissions are generated at lower L values.

[13] Emissions in the UHR band are always observed by IMAGE RPI in the plasmasphere. The observations presented Figure 3 show that intense emissions (red pixels) are found in the UHR band. The UHR band is also referred to as the Z mode band and exists at frequencies between the local plasma frequency and the local f_{uhr}. The Z mode radiation is an electrostatic to quasi-electrostatic local emission. The radiation above the local UHR band in Figure 3 is electromagnetic and is KC. Since all of the KC bands are observed to emanate from intensifications in the local UHR band (see for example at 1943 UT and 175 kHz), these emissions are related. At much lower frequencies there has also been strong evidence of this nature presented by *Kurth et al.* [1979] and others that show that intense UHR emissions are the most likely source of nonthermal continuum radiation. The banded structure of the KC emission makes harmonics theories of generation a possible candidate. However, the striking similarities between the source region characteristics of the KC and the lower-frequency

nonthermal continuum emissions strongly suggest that the high frequency KC emissions are probably not generated as harmonics of the lower-frequency component.

[14] The generation mechanism for KC may be similar to the Z mode conversion process believed to be responsible for the lower frequency nonthermal continuum radiation observed at Earth and Jupiter. Mode conversion processes can transform intense quasi-electrostatic emissions in the Z mode or UHR band to produce KC electromagnetic emissions in regions of steep density gradients. Intensifications in the UHR band have been observed to occur when the $(n + 1/2)f_g$ electrostatic emissions equal f_{uhr} [*Kurth et al.*, 1979]. The two classes of mode conversion mechanisms that have been considered are the linear [see, e.g., *Jones*, 1976; *Budden*, 1980] and nonlinear [see, e.g., *Melrose*, 1981; *Ronnmark et al.*, 1983; *Fung and Papadopoulos*, 1987]. The source of free energy for KC may be the same as that found for the much lower frequency nonthermal continuum radiation. *Gurnett and Frank* [1976] found that enhanced continuum radiation intensities were closely correlated with the injection of very intense fluxes of 1–30 keV electrons. Unfortunately, IMAGE does not have a proton or electron particle instrument, and therefore the RPI observations as it passes through the plasmaspheric density depletions and observes KC are without this type of correlative measurements. Therefore all that can be said is that the new observations presented in this study now show a strong relationship between KC and plasmaspheric notch structures as another condition on the generation of this emission.

4. Statistical Studies

[15] The KC events observed by GEOTAIL used in this study can be used to determine the average longitudinal extent of the KC emission cone. The vast majority of simultaneous observations of KC with plasmaspheric structures shows a high percentage (~94%) of events occur when there are notches, ledges, plasmaspheric tails, or large depressions in density. As previously demonstrated by *Green et al.* [2002] (see their Figure 4) a notch structure, which contained a KC source region, corotated with the plasmasphere for more than 5 hours. In fact, movies of EUV images show that these structures typically corotate. We can use this characteristic of corotation to investigate the longitudinal extent of the KC emission cone. The assumption here is that any asymmetries in the emission cone in latitude can be ignored due to its smaller angular size in comparison to the longitudinal extent. Figure 4a shows the number of occurrences of KC with the magnetic longitudinal extent of the emission for those events associated with corotating density depletions (categories 2, 3, and 5). The magnetic longitudinal extent of the emission is determined by taking the difference in spacecraft magnetic longitude at the start and stop times of the event. The magnetic longitude is used since it corotates with the Earth and therefore the plasmasphere. Those KC events associated with plasmaspheric tails are not included in Figure 4 since they do not typically corotate with the plasmasphere. From this analysis the median of the distribution shows the emission cone extent at ~40° in longitude. A rapid drop off in the distribution is seen when the longitudinal extent of the emission cone is smaller than ~10° or exceeds about ~55°.

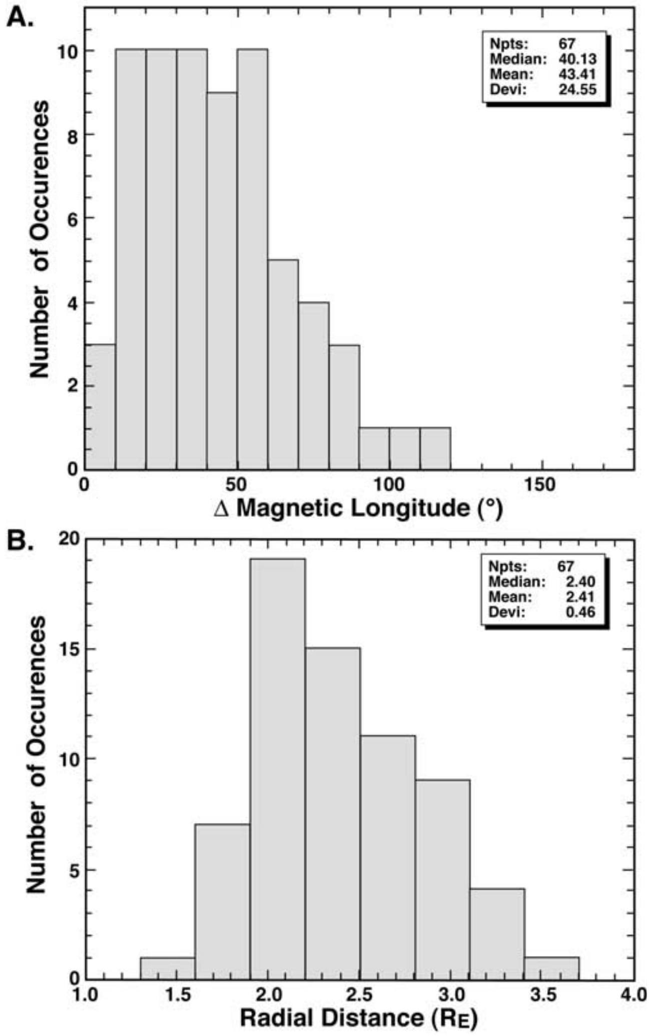

Figure 4. (a) Number of occurrences of KC (observed by PWI on GEOTAIL) associated with plasmaspheric density depletions (observed by EUV on IMAGE) with the magnetic longitudinal extent of the emission (assuming corotation). From these events the median is at ~40° in longitude. (b) Number of occurrences of the highest frequency source of the same KC events versus equatorial radial distance as an estimation of the deepest location of the KC source region (assuming an average plasmaspheric model). The distribution has a large peak with the median and the mean of the distribution at approximately the same equatorial radial distance of ~2.4 R_E.

[16] The RPI observations presented in section 3 of this paper are consistent with KC emission being generated at the magnetic equator when the frequency of the emission is near peak intensities of the UHR band. If KC is generated in deep depressions or notch structures of the plasmasphere, a histogram of the probable source locations for the associated KC events used in this study can be developed. To investigate this, we assume that the source region of the upper frequency of a KC event is generated at the local UHR frequency at the magnetic equator within the

Gallagher et al. [1988] model plasmasphere. The *Gallagher et al.* [1988] plasmaspheric model does not have a notch or density depletion structures but the RPI and EUV observations infer the establishment of a new and very steep plasmapause in the plasmaspheric density depletion with all plasma on higher L shells being swept away leaving the L shells of plasma below these structures untouched. As an estimation of the deepest extent of the KC source region, we show in Figure 4b the number of occurrences of the highest frequency source of KC as if generated at the UHR band in the plasmasphere model at different equatorial radial distances using the same events as included in Figure 4a. The assumptions used here are that KC emissions are generated at a newly established steep plasmapause gradient in a region of depleted density and that plasmaspheric density at radial distance less than the plasmapause follow the expected model. The highest KC frequency would then correspond to the deepest portion of the source region and that would correspond to the UHR in the magnetic equator of the expected model. The resultant distribution, shown in Figure 4b has a large peak with the median and the mean of the distribution at approximately the same radial distant value of $\sim$2.4 R_E. This analysis is also consistent with the in situ KC observations by IMAGE/RPI shown in Figure 3.

[17] It is important to note that direction finding measurements of KC from GEOTAIL/PWI has been performed by *Hashimoto et al.* [1999] showing a plasmaspheric origin (see their Figure 2). This example has been reanalyzed by *Green et al.* [2002] (see their Figure 10). Each segment of the direction finding measurements was compared with a corotating notch structure and a KC emission cone of about 45° (which is consistent with the results in this study as shown in our Figure 4a). The *Green et al.* [2002] analysis, as shown in their Figure 10, presents the compelling result that the GEOTAIL direction finding measurements are completely consistent with a small KC source region located deep in the notch region that corotates with the Earth.

5. Conclusions

[18] A large percentage ($\sim$94%) of the cases of KC observed by the GEOTAIL PWI correspond to times when the IMAGE EUV instrument imaged a notch structure, a ledge, a plasmaspheric tail, or large density depletions in the plasmasphere extending over many hours of local time. For those examples in which the KC emission was associated with a well-defined notch structure, the observations are consistent with having the KC emission cone corotate with the plasmasphere, as shown in Figure 1. These observations support the conclusion of *Green et al.* [2002] that KC is generated in a plasmaspheric notch (bite-out) or density depleted region of the plasmasphere.

[19] Observations by the RPI instrument on IMAGE during a passage through the source region of KC within a deep density depletion in the plasmasphere show that the emission was generated in or very near the magnetic equator at a steep gradient in density and associated with enhancements in the intensity of the emission in the UHR band. These observations are similar to those presented by *Kurth et al.* [1981] of the association of the lower-frequency escaping and trapped nonthermal continuum radiation with emissions in the UHR band at the plasmapause.

[20] Of the 87 cases studied extensively, there were five cases in which no obvious density depletion was observed in the plasmasphere when PWI on GEOTAIL observed KC. Further statistical analysis of the KC events associated with plasmaspheric notch or density depletion structures shows that the typical source region is at an equatorial radial distance of $\sim$2.4 R_E (Earth radii) in the magnetic equator and produces an emission cone that is $\sim$40° in longitude and $\sim$20° in latitude. These results show 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.

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R. R. Anderson, Department of Physics and Astronomy, University of Iowa, 615 Van Allen Hall, Iowa City, IA 52242, USA. (rra@space.physics.uiowa.edu)

S. Boardsen, L3 Communications Analytics Division, NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA. (boardsen@mail630.gsfc.nasa.gov)

S. F. Fung, NASA Goddard Space Flight Center, Code 632, Greenbelt, MD 20771, USA. (shing.f.fung@nasa.gov)

J. L. Green, NASA Goddard Space Flight Center, Code 630, Greenbelt, MD 20771, USA. (james.green@nasa.gov)

K. Hashimoto and H. Matsumoto, Radio Atmospheric Science Center, Kyoto University, Uji, Kyoto 611, Japan. (matsumot@kurasc.kyoto-u.ac.jp)

B. W. Reinisch, Center for Atmospheric Research, University of Massachusetts-Lowell, 600 Suffolk Street, Lowell, MA 01854, USA. (bodo_reinisch@uml.edu)

B. R. Sandel, Lunar and Planetary Laboratory, University of Arizona, 1040 East Fourth Street, Room 901, Tucson, AZ 85721, USA. (sandel@arizona.edu)