Reply to “Comment on “On the origin of whistler mode radiation in the plasmasphere” by Green et al.”

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Received 18 January 2006; revised 12 April 2006; accepted 4 May 2006; published 16 September 2006.

Citation: Green, J. L., S. Boardsen, L. Garcia, S. F. Fung, and B. W. Reinisch (2006), Reply to ‘‘Comment on ‘‘On the origin of whistler mode radiation in the plasmasphere’’ by Green et al.,’’ *J. Geophys. Res.*, *111*, A09211, doi:10.1029/2006JA011622.

1. Introduction

[1] *Green et al.* [2005] used a statistical wave map technique to examine the wave spectrum of radiation trapped in the plasmasphere (with wave frequencies typically below the local electron gyrofrequency (f_g) and local electron plasma frequency (f_p)) to determine potential source locations and regions of wave-particle interactions. Regions where the spatial distributions of the emissions were identical were then classified together. From that analysis it was determined that the trapped wave spectrum in the plasmasphere has three basic broadband waves: equatorial EM emissions (~10–330 Hz), plasmaspheric hiss (~330–3.3 kHz), and ground transmitter radiation (~10–50 kHz). The mapping of plasmaspheric hiss over nearly its entire frequency range (starting at ~500 Hz to over 3 kHz) to geographic longitudes shows a number of features identical to that of lightning. In addition, the latitudinal structure of the plasmaspheric hiss over its entire frequency range (~330–3.3 kHz) was similar to that of very low frequency transmitters whose emission is well known to couple through the ionosphere and into the plasmasphere from the ground. Plasmaspheric hiss, like lightning, is stronger in the afternoon sector than any other local time sector. This analysis has led these authors to the conclusion that ‘‘lightning is an embryonic source for hiss as originally suggested by *Sonwalker and Inan* [1989] . . . however, it is not possible to determine if lightning is the sole source of plasmaspheric hiss as proposed by *Draganov et al.* [1992].’’ The conclusion reached by *Green et al.* [2005] has been called into question by *Thorne et al.* [2006]. The points in contention can be summarized by the following: (1) *Thorne et al.* [2006] disagree with our identification of the plasmaspheric hiss spectrum and our choice of frequencies to illustrate plasmaspheric hiss properties. (2) *Thorne et al.* [2006] claim that we have omitted the waves at the magnetic equator, ‘‘a key population for plasmaspheric hiss.’’ (3) *Thorne et al.* [2006] claim that plasmaspheric hiss is correlated with geomagnetic activity and that is a key characteristic of the emission and implies a nonlightning source. (4) *Thorne et al.* [2006] claim that the intensities of the waves above 1 kHz observed to have a geographical distribution similar to that of lightning are much smaller than the intensities of plasmaspheric hiss that is mainly below 1 kHz. Our reply to *Thorne et al.* [2006] will address each of these points.

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0148-0227/06/2006JA011622

2. Identification of the Hiss Spectrum and Properties

[2] *Thorne et al.* [2006] state that plasmaspheric hiss is responsible, through wave-particle interactions, for the creation of the slot region in the electron radiation belts and after over 40 years of research its origin remains controversial. It is important to point out that it is from this perspective that *Green et al.* [2005] decided to use a plasma wave intensity map technique with an extensive amount of data from the wave instruments on Dynamics Explorer-1 (DE-1) and the Imager for Magnetopause-to-Aurora Global Exploration (IMAGE) spacecraft to identify the hiss spectrum, based solely on its spatial distribution. This was a new approach not previously tried to this great an extent.

[3] From the new analysis of the resulting wave maps we believe significant progress has been made in understanding the origin of plasmaspheric hiss. To expand on Figures 1 and 2 of *Green et al.* [2005], Figure 1 illustrates the striking difference in the spatial distributions and sensitivity to geomagnetic conditions between the low-frequency EM equatorial emissions in the top two panels and plasmaspheric hiss at slightly higher frequencies (the bottom three panels). As mentioned previously, it is from the similarities in the spatial distributions of adjacent frequencies that *Green et al.* [2005] made an identification of the frequency range of plasmaspheric hiss (~330 Hz to 3.3 kHz). To illustrate other properties in this frequency range, *Green et al.* [2005] used 3 kHz to illustrate geographic control of a portion of the hiss spectrum (that they claimed exists to some extent above ~500 Hz). The choice of 3 kHz was made since that frequency is the lowest frequency that DE/PWI and IMAGE/RPI measurement can be correlated with, is within the plasmaspheric hiss frequency range, and has the same spatial distribution in latitude and local time as hiss frequencies above and below it. The geographic control was observed in both instruments from these two spacecraft and only from DE/PWI data below 3 kHz.

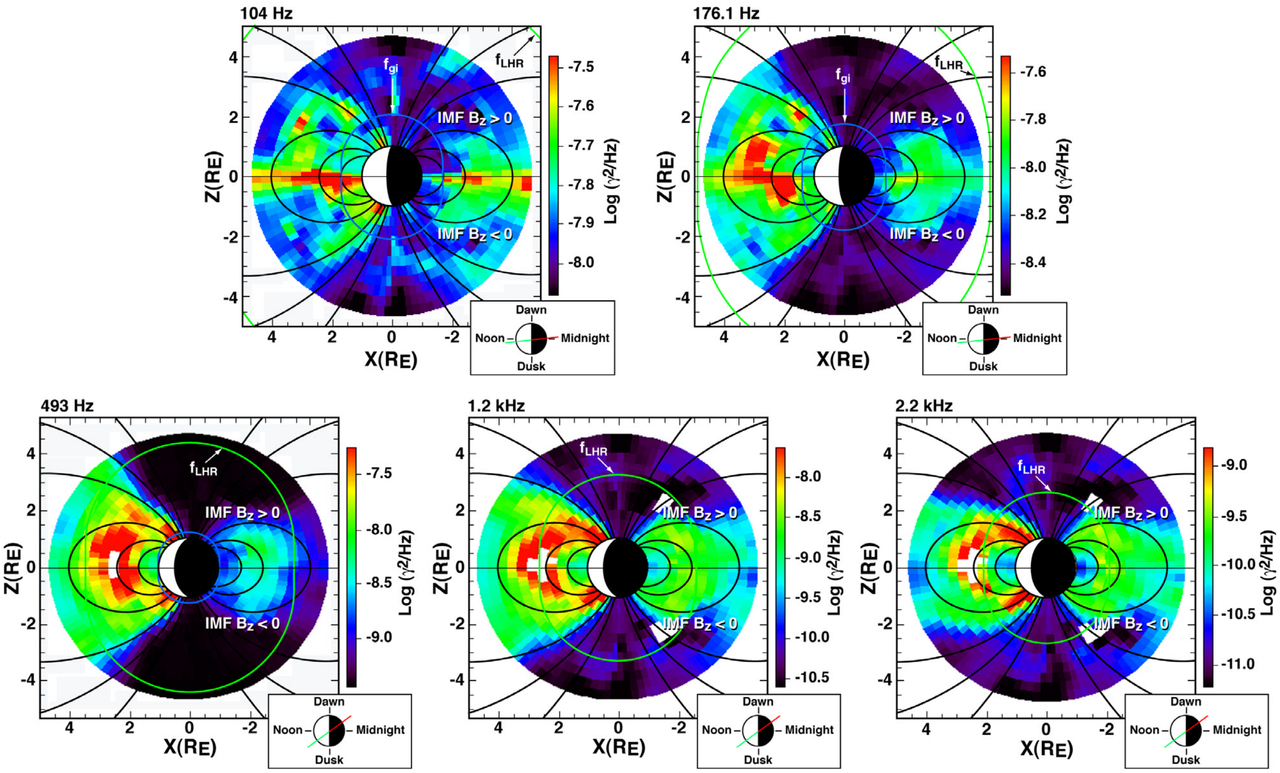

Figure 1. A summary of the latitudinal distributions between the low-frequency EM equatorial emissions in the top two panels and plasmaspheric hiss at slightly higher frequencies (the bottom three panels) across their spectrums. Data in each panel have been further sorted by using the sign of the z component of the interplanetary magnetic field (IMF B_z) as a measure of the level of geomagnetic activity. The top two panels illustrate the strong geomagnetic control of the EM equatorial emissions, while the bottom panels for plasmaspheric hiss do not.

[4] Geographic control of plasmaspheric hiss implies a lightning source but it is important to point out that plasmaspheric hiss, like lightning, is stronger in the afternoon sector than any other local time sector as shown in Figure 1 over its entire frequency range, with or without geographic control. When taken in total, these results support the conclusion that lightning is an embryonic source for hiss; however, it is not possible to determine if lightning is the sole source of plasmaspheric hiss. The authors never stated that lightning is the only source of plasmaspheric hiss.

3. Exclusion of Waves at the Magnetic Equator

[5] *Thorne et al.* [2006] claim that we have omitted the waves at the magnetic equator, "a key population for plasmaspheric hiss." It is important to point out that there are also a variety of waves at some frequencies that do exist around the magnetic equator. As a whistler mode emission, plasmaspheric hiss must propagate through the magnetic equator and so some component of the hiss spectrum must exist there. On the basis of the survey nature of our study, mapping of the wave observations to geographic coordinates along L values as done in Figures 5, 7, and 8 of *Green et al.* [2005] did exclude the magnetic equator. The magnetic equator is a well-known site of a variety of electrostatic and quasi-electromagnetic emissions unrelated to plasmaspheric hiss, such as the EM equatorial emissions. In addition, heating of the plasmaspheric cold plasma, most likely by electrostatic waves, has also been observed in the magnetic equator by a number of authors [cf. *Olsen et al.*, 1987; *Tu et al.*, 2003]. A strong quasi-electrostatic emission in the upper hybrid band (UHR) exists throughout the plasmasphere. At frequencies above the whistler mode the $(n + 1/2)f_g$ electrostatic emissions are observed mostly in the magnetic equator [cf. *Hubbard and Birmingham*, 1978] but can greatly intensify the UHR band when the (n + 1/2)fg electrostatic emissions equal the UHR frequency [*Kurth et al.*, 1979] to the point of even saturating plasma wave receivers. It is important to point out that the (n + 1/2)fg waves are observed both in the plasmapause region and outside the plasmasphere. Since the observations used in the *Green et al.* [2005] paper did not take into account the location of the plasmapause but simply binned and averages several thousand orbits of DE data, it was easiest to avoid all those non-hiss emissions which (unlike whistlers) are more confined to the magnetic equator (both inside and outside the plasmasphere) by omitting the waves within 10° of the magnetic equator.

[6] In a recent study of the long-term variations of the electron belt slot region, *Fung et al.* [2006] discovered a shift of the latitudinal position of the slot from lower to higher L values as solar activity levels change from a minimum to a maximum. Such migration of the slot

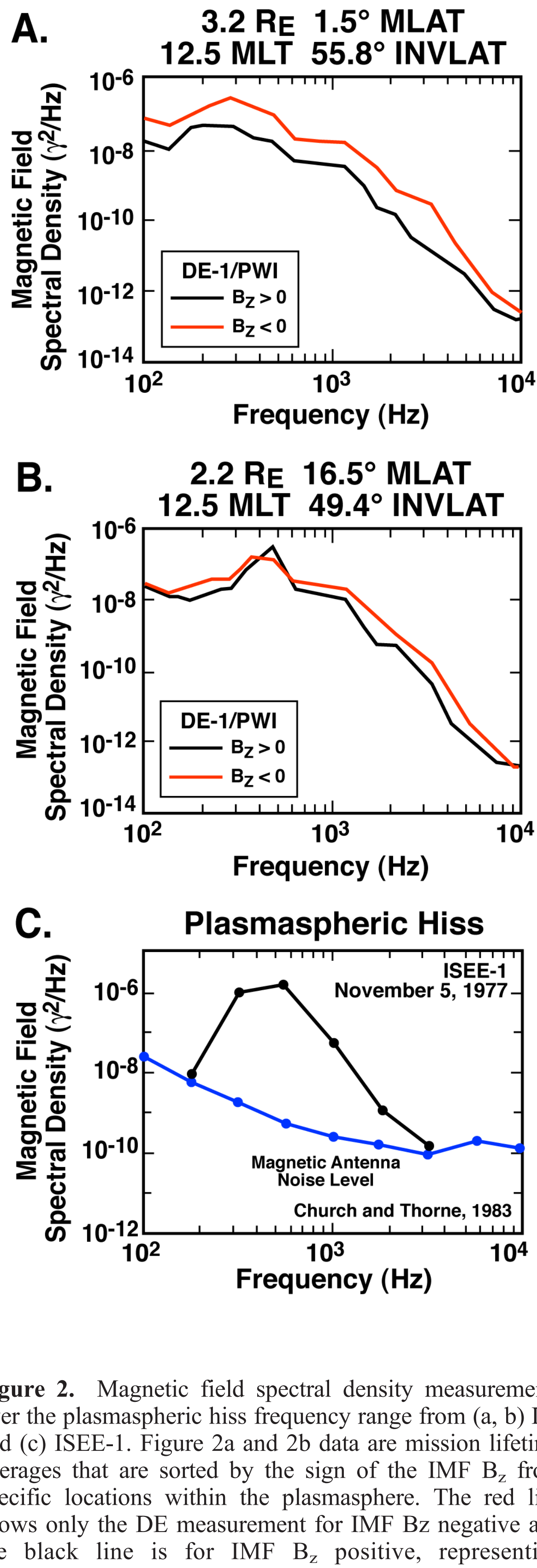

Figure 2. Magnetic field spectral density measurements over the plasmaspheric hiss frequency range from (a, b) DE and (c) ISEE-1. Figure 2a and 2b data are mission lifetime averages that are sorted by the sign of the IMF B_z from specific locations within the plasmasphere. The red line shows only the DE measurement for IMF Bz negative and the black line is for IMF B_z positive, representing geomagnetic substorm and no substorm conditions, respectively. For comparison, Figure 2c is a previously published in situ measurement.

location is inconsistent with a region of wave-particle interactions resulting in the slot formation to be located only at the magnetic equator. Thus studying plasmaspheric hiss by focusing only on the wave activities near the magnetic equator region may be inadequate.

[7] In summary, the magnetic equator is the site of some of the most intense electrostatic waves in the magnetosphere and these waves have not been shown to be related to plasmaspheric hiss. It is within this context that *Green et al.* [2005] chose to avoid the magnetic equator in the geographic analysis, since it was impossible to clearly distinguish plasmaspheric hiss waves from the unrelated electrostatic or quasi-electrostatic waves in the magnetic equator. We believe that the procedure used by *Green et al.* [2005] was completely justified, since hiss whistler mode waves spend only a limited time within the magnetic equator making their identification more certain when observations in the magnetic equator are excluded.

4. Correlation With Geomagnetic Activity

[8] *Thorne et al.* [2006] claim that plasmaspheric hiss is correlated with geomagnetic activity and that is a key characteristic of the emission that then implies a non-lightning source. Although this point was not extensively addressed by *Green et al.* [2005], Figure 2 here shows an additional analysis using the data from that study.

[9] Figures 2a and 2b are average magnetic field spectral density measurements, sorted by the interplanetary magnetic Z component (IMF B_z), from the DE-1 plasma wave instrument (PWI). The red line shows only the DE plasmaspheric measurement for B_z negative and the black line is for B_z positive, representing geomagnetic substorm and no substorm conditions, respectively. Figure 2a is for a location close to the magnetic equator while Figure 2b is for a location well above the magnetic equator. The spectra given in Figures 2a and 2b are nearly identical to Figure 7 (labeled as plasmaspheric hiss) of *Church and Thorne* [1983] and shown here for comparison Figure 2c. Figure 2 illustrates that significant spectral changes between quiet and disturbed conditions do exist near the magnetic equator (Figure 2a), particularly at low frequencies, but for observations off the magnetic equator (Figure 2b) these changes are much smaller. Similar variations also exist in the average electric field measurements (not shown). It is important to point out that the sign of the IMF B_z is not necessarily a completely encompassing index to all types of storm activity but is a sensitive input parameter for geomagnetic substorms. It is beyond the scope of this reply to reanalyze the data using different indices.

[10] The claim that plasmaspheric hiss is correlated with the geomagnetic activity is largely based on a recent paper by *Meredith et al.* [2004] using CRRES data averaged over the frequency range from 100 Hz to 3 kHz. On the basis of the spatial distributions presented by *Green et al.* [2005] and shown in Figure 1, it is clear that at frequencies below about 330 Hz the trapped electromagnetic (EM) equatorial noise (which is correlated with geomagnetic activity) and can be relatively intense as shown in the top two panels of Figure 1. By adding the EM equatorial emission into the averages with the plasmaspheric hiss, as done by *Meredith et al.*

[2004], there is no clear way to determine how that may have affected their results and conclusions.

5. Intensities of Plasmaspheric Hiss

[11] *Thorne et al.* [2006] claim that the intensities of the waves above 1 kHz observed to have a geographical distribution similar to that of lightning are much smaller than the intensities of plasmaspheric hiss that is mainly below 1 kHz. As shown in all three panels of Figure 2, the emission above 1 kHz is about an order of magnitude weaker than emissions below 1 kHz, with the emission peak near 500 Hz and therefore it is critical to pin down the transition frequency. It is important to note that there is a fundamental difference in these spectra: Figure 2c is from a single inbound pass of ISEE-I near the equatorial plane, while Figures 2a and 2b are long-term averages from observations of many tens to hundreds of passes of the polar orbiting DE spacecraft. It is therefore expected that the average peak intensity would be lower in Figures 2a and 2b than in the more nearly instantaneous spectrum of Figure 2c. Nevertheless, the spectra are all very similar in shape and within less than an order of magnitude in intensity at any one frequency. *Green et al.* [2005] examined the data below 1.2 kHz only in a qualitative manner. We are in the process of reanalyzing this data and providing a more precise location in the hiss spectrum where the geographic control begins and ends.

[12] **Acknowledgment.** Arthur Richmond thanks Hiroshi Fukunishi for the assistance in evaluating this paper.

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