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Dayside distribution of Pc5 wave power in the quiet magnetosphere and its response to the solar wind

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ABSTRACT

This paper is a statistical study of Pc5 activity in the quiet magnetosphere based on magnetic field data from the THEMIS mission. During the period under consideration (2007–2009), there were many extended intervals of low geomagnetic activity, defined here as $10 \geq Dst \geq -20$ nT. This criterion, along with the availability of solar wind data and THEMIS magnetic field data when the spacecraft were on the dayside between 4 and $9R_E$ provided over 400,000 data points for our plots of dayside Pc5 compressional and transverse wave power. We examined the response of the wave power to the solar wind bulk velocity V, dynamic pressure P, and fluctuations in the dynamic pressure P_{var}. The compressional and transverse power enhancements associated with the three parameters were comparable and were observed to a depth within the magnetosphere of about $L=5$. Power plots based on the combined effects of the dynamic pressure P, which controls the position of the magnetopause, and the bulk velocity V, the mechanism behind the KHI-driven waves on the magnetopause, reflected the solar wind dynamic pressure control of the magnetopause location. A comparison of the Pc5 power response to V and P_{var} showed that the greater power enhancement was associated with V in the outer magnetosphere beyond $L \sim 6$ but with P_{var} at distances farther from the magnetopause and closer to Earth.

1. Introduction

Since their discovery in the mid-nineteenth century, ultralow frequency (ULF) waves have been the subject of numerous investigations whose results have provided a significant contribution to our understanding of the dynamics of Earth's magnetosphere. ULF pulsations are classified as either continuous, with a quasi-sinusoidal signature, or irregular, with a noise-like signature. The five subclasses of continuous pulsations are distinguished by period as Pc1 (0.2–5 s), Pc2 (5–10 s), Pc3 (10–45 s), Pc4 (45–150 s), and Pc5 (150–600 s), while the two subclasses of irregular pulsations are Pi1 (1–40 s) and Pi2 (40–150 s) (Jacobs et al., 1964).

Numerous surveys of the occurrence rate and properties of ULF pulsations have been made at ground stations and by spacecraft. Some examples of ground surveys are Saito et al. (1989), who studied the seasonal dependence of Pc3–5 wave power using auroral zone stations; Dyrud et al. (1997), who investigated the latitudinal and local distributions of Pc1–2 events using stations in Arctic Canada and Antarctica; and Howard and Menk (2005), who used the IMAGE magnetometer array to study dayside Pc3 - 4 waves. Statistical in situ surveys include the work of Anderson et al. (1990), who developed a comprehensive database of Pc3–5 activity observed from $L=5$ to $L=9$ by the AMPTE/CCE satellite; Zhu and Kivelson (1991), who employed ISEE 1 and 2 measurements to investigate compressional ULF waves in the outer magnetosphere; Lessard et al. (1999) who determined occurrence rates of different types of pulsations over all local times from $L=6$ to $L=20$ using dynamic spectra of magnetic field data from the AMPTE/IRM spacecraft; and Liu et al. (2009) who surveyed Pc4 and Pc5 pulsations in the inner magnetosphere using both electric and magnetic field measurements from the THEMIS spacecraft.

Results from a number of studies have indicated that ULF waves, primarily in the Pc5 frequency band, play a fundamental role in the rapid enhancement in relativistic electron fluxes during some magnetic storms. Some examples of theoretical works on this topic include Elkington et al. (1999, 2003) who developed a model for the adiabatic acceleration of electrons through a drift-resonant interaction with Pc5 waves; Summers and Ma (2000a, 2000b), who formulated a model kinetic equation on momentum diffusion due to interactions between electrons and ULF waves; and Fei et al. (2006), who simulated storm-time electron transport based on ULF-wave driven radial diffusion coefficients. Experimental investigations of storm-time electron energization include

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O'Brien et al. (2001), who found that long-duration elevated Pc5 power during the recovery phase of magnetic storms is instrumental in producing relativistic electrons; Posch et al. (2003), who suggested that broadband ULF activity must play the dominant role in the energization process; and Sanny et al. (2009), who noted a preponderance of Pc5 power at the flanks during the recovery phase of storms with energetic electrons, an observation consistent with the modeling study of Elkington et al. (2003). Finally, a global ULF wave index was developed by Kozyreva et al. (2007), who found that enhancements in relativistic electron fluxes during several storms correlated well with increases in the index, primarily due to higher levels of Pc5 power.

Although ULF pulsations may be generated by various mechanisms, their energy must ultimately originate from the solar wind. As noted by Takahashi et al. (2012), approximately 40–60% of magnetic field variations in the Pc5 band are accounted for by mechanisms related to solar wind bulk velocity V and dynamic pressure fluctuations P_{var}, with the degree of dependence varying with the location of observation and the solar activity phase. There have been a large number of studies relating ULF occurrence rate and power to each of these two solar wind properties. Examples of investigations on the relationship between ULF pulsations and solar wind bulk velocity are Engebretson et al. (1998), Mathie and Mann (2001), Mann et al. (2004), and Pahud et al. (2009), while representative works on the relationship between ULF pulsations and solar wind dynamic pressure fluctuations include Kepko et al. (2002), Kepko and Spence (2003), Takahashi and Ukhorskiy (2007), and Kessel (2008). Comparative studies of V and P_{var} as controlling factors for the production of ULF pulsations were made in two recent studies (Liu et al., 2010; Takahashi et al., 2012).

The mechanism by which Pc5 waves are produced through high-speed solar wind flow is generally considered to be the Kelvin–Helmholtz instability (KHI) at the magnetopause (Southwood, 1968). Modeling studies by Claudepierre et al. (2008; 2010) indicate that although ULF waves driven by the KHI and fast mode ULF waves driven by solar wind pressure fluctuations are both present at the magnetopause, the former type is localized to the vicinity of the magnetopause whereas the latter is able to better propagate throughout the dayside magnetosphere. Using GOES 8 magnetic field data, Takahashi and Ukhorskiy (2007) found that at geosynchronous orbit, Pc5 power did indeed correlate best with solar wind dynamic pressure and dynamic pressure fluctuations.

The abundance of spacecraft data from the THEMIS mission together with recent geomagnetic conditions provide an unprecedented opportunity for studying magnetospheric Pc5 wave activity under very special circumstances. From 2006 to 2008, during the most recent minimum in the sunspot cycle, the average annual number of magnetic storms was the fewest for nearly the past 40 years (for example, see the British Geological Survey, 2008). This period was marked by extended intervals during which the magnetosphere was in a quiet, steady state. In contrast to the intense research that has been focused on storm-time characteristics of Pc5 waves and their correlation to enhanced fluxes of relativistic electrons, investigations of the distribution of Pc5 wave power during extended geomagnetically quiet periods have been far less profuse. During such quiet intervals, the influence of solar wind on Pc5 wave power distribution should be well characterized since the variability injected by magnetic storms into the relationship between the solar wind and its driving of Pc5 oscillations is minimized.

Using magnetic field data from THEMIS over a time interval of nearly three years, and corresponding solar wind and geomagnetic data downloaded from OMNIWEB, we determine the dayside distribution of wave power in the Pc5 frequency band throughout the quiet magnetosphere and its dependence on solar wind properties. In particular, the solar wind properties considered are the ones that have been found to have the most profound influence on the generation and observation of Pc5 pulsations: the bulk velocity V, dynamic pressure P, and dynamic pressure fluctuation P_{var}. The Pc5 power distributions are determined for high and low values of these three parameters, and are binned into three local time (LT) sectors: morning (6–10 LT), noon (10–14 LT), and afternoon (14–18 LT). The radial bins are $0.5L$ and extend from $L=9$ inward to $L=4$. Additional details on our power calculations and a discussion of these plots are provided in the sections to follow.

2. Data

Magnetic field data are from the fluxgate magnetometers on the five THEMIS spacecraft (Auster, 2008). From March 2007 to 2009, the spacecraft had apogees between 10 and $30R_E$ and perigees between 1.2 and $1.5R_E$. The apogees of the spacecraft slowly rotated from dawn through midnight, dusk, and noon such that each spacecraft passed through all local times at least twice over the two and half year interval. In order to analyze both compressional wave power (fluctuations in the total field strength) and transverse wave power (fluctuations perpendicular to the field direction) we adopt a field-aligned coordinate system similar to the one used by Liu et al. (2010). The unit vector parallel to the magnetic field is found by taking a 30 min running average of the magnetic field:

$$\mathbf{e}_{||} = \frac{B_x i + B_y j + B_z k}{B_{avg}}$$

where B_x, B_y, and B_z are the average x, y, *and* z components of the magnetic field, $\boldsymbol{i}$, $\boldsymbol{j}$, and $\boldsymbol{k}$ are unit vectors in the GSE x, y, and z, directions, and B_{avg} is the magnitude of the average field over the 30 min interval centered on the data point being processed. To complete the orthogonal coordinate system we must find two more unit vectors perpendicular to $\mathbf{e}_{||}$ and each other. The unit vector in the azimuthal direction is found by taking the cross product of $\mathbf{e}_{||}$ and the radial position vector, $\boldsymbol{r}$:

$$\mathbf{e}_{\Phi} = \frac{\mathbf{e}_{||} \times \mathbf{r}}{|\mathbf{e}_{||} \times \mathbf{r}|}$$

The third unit vector $\boldsymbol{e_r}$ is found by taking the cross product of the other two. The magnitude of the transverse component of the magnetic field is then $B_\perp = \sqrt{(\mathbf{B} \cdot \mathbf{e_\Phi})^2 + (\mathbf{B} \cdot \mathbf{e_r})^2}$.

We calculate Pc5 power every 15 min using a 30 min window centered on the time we are analyzing. The power is calculated by integrating the power spectral density of B and $B_\perp$ over the Pc5 band (2–7 mHz). For this study, we only include times when the spacecraft are between 4 and 9 R_E and on the dayside of the magnetosphere, $6 < LT < 18$.

Solar wind parameters (dynamic pressure and bulk velocity) are obtained through the OMNI database (http://omniweb.gsfc.nasa.gov). We define the variation in the solar wind dynamic pressure as the standard deviation of the pressure using a 30 min window centered on the time being analyzed.

3. Statistical survey and discussion

Since we are interested in the relationship between the distribution of Pc5 wave power and solar wind properties during periods of reduced geomagnetic activity, we considered only intervals from 2007 to 2009 when $10 \geq Dst \geq -20$ nT. This criterion along with the availability of solar wind data and THEMIS magnetic field data when the spacecraft were on the dayside between 4 and $9R_E$ provided over 400,000 data points for our plots.