Radar Observations of Pulsed Ionospheric Flows at the Ionospheric Projection of the Plasmapause Produced by a Bursty Bulk Flow at Substorm Onset

N. A. Frissell,¹ J. B. H. Baker,¹ J. M. Ruohoniemi,¹ R. A. Greenwald,¹ e.t. al.

Recent expansion of the SuperDARN network to mid-latitudes and the addition of a new high-time resolution mode provides opportunities to observe mid-latitude ULF waves and other ionospheric sub-auroral features. During a substorm on 22 February 2008, Pi2 pulsations with a period of 172 s were observed simultaneously by the Blackstone, VA SuperDARN radar and magnetometers around the globe. Very similar pulsations were detected by the BKS radar and a nearby magnetometer at Remus, MI, which suggests that a single source generated the Pi2. Due to the localized nature of the radar measurements, the radar data contains significantly more spatial and temporal structure than data recorded by the magnetometers. A cross-phase analysis of magnetometer data places these measurements in the vicinity of the ionospheric projection of the plasmapause. About one minute prior to ground Pi2 onset, two Earthward-moving BBFs were observed by the THEMIS D and E probes in the near-Earth plasma sheet. Based on observations and previous studies, we suggest that the observed Pi2 pulsations are the result of either a plasmaspheric surface wave or a direct compressional response due to the braking of the BBF on the inner magnetosphere.

1. Introduction

Magnetospheric substorms are organized responses of the magnetosphere caused by increased energy transfer between the solar wind and the magnetosphere. Substorms consist of growth, expansion, and recovery phases. During the growth phase, the interplanetary magnetic field (IMF) is typically southward and there is increased energy transfer from the solar wind into the magnetosphere. The magnetic flux content of the tail lobes increases and the auroral oval thins and moves equatorward. The onset of the expansion phase is signaled by the brightening of the equatorward arc at midnight in the discrete auroral oval, followed by a rapid poleward expansion and westward traveling surge [Akasofu, 1964; Rostoker et al., 1980]. Concurrent with the expansion phase onset, Pi2 pulsations are observed in the ground magnetic record [e.g., Sato, 1969; Liu et al., 2000].

The term Pi2 refers to a class of ultra-low frequency (ULF) geomagnetic pulsations with an irregular waveform and a period of 40 - 150 s [Jacobs and Simno, 1960]. They are generated by a variety of mechanisms which are driven by current-carrying shear Alfvén waves or compressional fast-mode waves produced during substorm onset [Olson, 1999]. Shear Alfvén waves are generated by the diversion of the cross-tail current during the formation of the substorm current wedge (SCW) [Baumjohann and Glassmeier, 1984], but Olson [1999] notes that the generating mechanism of compressional waves at substorm onset is unknown. Kepko and Kivelson [1999] and Kepko et al. [2001] present events which link certain Pi2 observations to the braking of Earthward-moving bursty bulk flows (BBFs) against the inner magnetosphere. BBFs are high speed, convective plasma flow bursts found in the inner plasma sheet that are thought to be caused by transient magnetic reconnection in the magnetotail [Sergeev et al., 1992; Angelopoulos et al., 1994]. The braking of BBFs could provide the necessary compressional energy to drive Pi2 generating mechanisms. Generally, mechanisms driven by shear Alfvén waves are associated with high-latitudes, while mechanisms driven by fast-mode waves are associated with low-latitudes.

Because of the spatial integration inherent in the ground magnetometers traditionally used for Pi2 studies, confusion may arise at mid-latitudes due to mixing of high- and low-latITUDE signals. Improvements to observations could be made through the use of a mid-latitude radar system that takes spatially localized measurements of ionospheric plasma flow. The SuperDARN radar network [Greenwald et al., 1995; Chisham et al., 2007] has recently been expanded to mid-latitudes. In this paper, we present the first observations of Pi2 pulsations observed by the mid-latitude SuperDARN radar in Blackstone, VA (BKS) in conjunction with data from instruments in the NASA THEMIS project [Burch and Angelopoulos, 2008]. Pi2 pulsations observed by BKS are found to be similar to Pi2 observations from the THEMIS ground magnetometer at Remus, MI (RMUS). It is shown that the radial measurements are in the vicinity of the ionospheric projection of the plasmapause and are preceded by two Earthward-moving BBFs with initial waveforms similar to that of the ground-observed Pi2s, suggesting that the observed Pi2 is the result of a plasmaspheric response to the observed BBF.

2. Observations

On 22 February 2008 at 0436 UT, the auroral electrojet (AE) index rose from 25 to 175 nT over a 25 min period. For at least 2 hours prior to this time, the AE index had remained steady around 25 nT. The planetary Kp index for this time was 1. The solar wind IMF $B_x$ at the nose of the Earth’s bow shock from the OMNI database [King and Papitashvili, 2006] turned southward at 0415 UT and varied between -2 and +1 nT until 0500 UT. During this time period solar wind velocity $V_w$ was approximately 490 km s$^{-1}$ and proton density was about 3.0 cm$^{-3}$. Additional study of this event has been conducted by Liu et al. [2009].

Figure 1 presents a map showing the locations of instrumentation used during this study. Brown asterisks indicate
the locations of THEMIS ground-based magnetometers. At 0436 UT, the Eastern portion of the ground based observatory (GBO) network was centered around midnight magnetic local time (MLT), which allowed for good coverage of substorm activity. Beginning at 0436 UT, Pi2 pulsations were observed in magnetometer data at all GBOs shown in Figure 1. The pulsations were also seen in southern hemisphere magnetometers in the SAMBA (South American B-Field Array) chain and dayside magnetometers in the STEP chain [Yamada and Group, 2001]. The pulsations are observed simultaneously, have a period of 172 seconds, and have amplitudes that are strongest on the nightside and decrease by orders of magnitude on the dayside. Optical observations from the Total Energy Detector (TED) instrument on the NOAA Polar Orbiting Environmental Satellite (POES) [Evans and Greer, 2006] have been overlaid on the map and provide reasonable agreement with the Holzworth and Meng [1975] model. Using ground magnetometer data, Liu et al. [2009] fit parameters of a SCW model to determine the longitudinal locations of the associated upward (duskside) and downward (dawnside) field aligned currents (FACs). These are shown in Figure 1. Also, the pink region of the auroral oval in Figure 1 indicates the position of the westward electrojet. Using a cross-phase analysis technique [Waters et al., 1991], we estimate the ionospheric projection of the plasmapause to be located between $L = 3 - 3.71$ (54$^\circ$ - 58$^\circ$ invariant latitude). This estimate is indicated by the black dotted box towards the bottom of Figure 1.

Figure 1 also shows the magnetic footpoints of both THEMIS probes D and E. These footpoints were determined using the Tsyganenko 96 magnetic field model and are both located pre-midnight in the auroral zone. These probes observed BBFs just prior to the appearance of ground-observed Pi2 pulsations. At 0436 UT, these spacecraft were located at $(-10.9, 3.3, -2.3)$ and $(-10.2, 4.1, -2.1)$ $R_E$ GSM, respectively, and were within 0.20 $R_E$ of the neutral sheet.

An estimate of the location of the auroral oval for $K_p = 1$ [Holzworth and Meng, 1975] is shown in Figure 1. Measurements from the Total Energy Detector (TED) instrument on the NOAA Polar Orbiting Environmental Satellite (POES) [Evans and Greer, 2006] have been overlaid on the map and provide reasonable agreement with the Holzworth and Meng [1975] model. Using ground magnetometer data, Liu et al. [2009] fit parameters of a SCW model to determine the longitudinal locations of the associated upward (duskside) and downward (dawnside) field aligned currents (FACs). These are shown in Figure 1. Also, the pink region of the auroral oval in Figure 1 indicates the position of the westward electrojet. Using a cross-phase analysis technique [Waters et al., 1991], we estimate the ionospheric projection of the plasmapause to be located between $L = 3 - 3.71$ (54$^\circ$ - 58$^\circ$ invariant latitude). This estimate is indicated by the black dotted box towards the bottom of Figure 1.

Figure 1. Spatial overview plot on a magnetic grid for the substorm on 22 Feb 2008 at 0436 UT. The plot includes line-of-sight Blackstone velocity data at 0444-0446 UT (green-red-blue colors), POES auroral precipitation flux at 0430-0530 UT (blue colors), locations of ground magnetometers (brown asterisks), footprints of two THEMIS spacecraft (letters D and E), estimates of the auroral oval (grey circles), westward traveling surge (pink color), SCW FACs (encircled dots), and plasmapause (black dotted box). See text for more details.

Figure 2. A collection of time-series data for the substorm on 22 Feb 2008. (a) BKS radar line-of-sight (LOS) velocity radar data from Beam 8 with 2 min resolution. (b) BKS Beam 7 shows Pi2 pulsations which cannot be observed in Beam 8. (c) LOS velocity data from BKS Beam 7, Range Gate 21. (d) RMUS magnetometer component resolved to the LOS direction of the radar, baseline removed. (e) 3-component RMUS data, baseline removed. (f) Ion velocity data from THEMIS D.
frissell et al.: superdarn observations of ulf pulsations

are located in the pre-midnight subauroral sector between the SCW FACs and within the vicinity of the ionospheric projection of the plasmapause.

Figure 2 presents time-series data from the BKS radar, the RMUS magnetometer, and THEMIS Probe D. Both Figures 2a and 2b show BKS radar plasma velocity data from 54° to 58° magnetic latitude. Figure 2b shows data taken from the 6-second resolution camping beam while Figure 2a shows data from an adjacent 2-minute resolution beam. The camping beam data of Figure 2b reveals fine structure in both time and space that can not be observed in Figure 2a. In the camping beam data, ULF pulsations which have a period of approximately 170 s and a distinctive latitudinal saw-tooth structure in the first two oscillations are observed. The sawtooth structure implies a north-south propagation of the pulsation. First a pulsation of southward (blue) connection appears to propagate from low to high latitudes, and then a northward (red) pulse propagates from high to low latitudes. The pulses are estimated to have a north-south phase velocity of 9 km s⁻¹.

Figure 2c and 2d compare measurements from the BKS radar camping beam at range gate 21 (54.79°, -12.49° AACGM) with the RMUS magnetometer located at (54.65°, -12.64°) AACGM. The data from the RMUS magnetometer has been average subtracted and resolved along the LOS look direction of the radar. Figure 2e shows the original 3-component RMUS data for comparison. Many similarities can be seen when comparing the BKS data to the RMUS data. Beginning at 0436 UT, Pi2 pulsations can be observed in both the BKS radar data in Figure 2c and in the RMUS magnetometer data in Figure 2d. These pulsations have a period of 172 s, are in phase for the first few oscillations, and correspond in time to the observed AE index enhancement and auroral brightening at GILL. The localized nature of radar measurements as opposed to the spatially integrating nature of magnetometer measurements reveals additional fine-scale structure in the radar data that the magnetometer data lacks, particularly after the first two cycles.

Figure 2f shows THEMIS D Electrostatic Analyzer (ESA) [McFadden et al., 2008] ion velocity BBFs consisting of two earthward-moving velocity pulses each with a velocity increase of 650 km s⁻¹ and a separation time of 140 s. When comparing these pulses with the first two pulses observed by both the BKS radar and the RMUS magnetometer, a striking resemblance is seen. The THEMIS D pulses occur 67 s prior to the ground-based observation of the Pi2. Data from the THEMIS E spacecraft (not shown) also contains BBFs similar to those seen by THEMIS D.

3. Discussion

Pi2 pulsations may be generated by a variety of physical mechanisms. These mechanisms include transient response (TR) of substorm FACs, field line resonances (FLRs), global cavity mode oscillations, plasmaspheric surface modes, and direct compressional response to BBFs braking on the inner magnetosphere [Olson, 1999; Kepko and Kivelson, 1999]. Magnetospheric configuration, location of substorm current systems, and the current state of the plasmasphere all play important roles in governing which Pi2 generating mechanisms are active and which signatures are observed. From knowledge of these current systems and generating mechanisms, we can work to determine the mechanism(s) responsible for a given Pi2 observation. Figure 1 shows that observations by the BKS radar and the RMUS magnetometer are located in the pre-midnight sector of the sub-auroral mid-latitude region in the vicinity of the ionospheric projection of the plasmapause. Because stations in the mid-latitude region can see Pi2 pulsations that are the result of both high- and low-latitude processes, it is possible that more than one mechanism may contribute to the observations during this event.

TR Pi2s are generated as the SCW is created. In this process, the cross-tail current in the plasma sheet is disrupted and a current pulse is carried along field lines into the polar ionosphere by shear Alfvén waves. Due to impedance mismatches, the wave is reflected between the ionosphere and the neutral sheet with a period that falls within the Pi2 band. On the ground, mid- and high-latitude magnetometers observe this as Pi2 pulsations. [Bennett and Glassmeier, 1984]. Kepko and Kivelson [1999] notes that for mid-latitude magnetometers, these Pi2s appear simultaneously with optical auroral expansion phase onset, have an amplitude of less than 10 nT, and are superimposed on a positive magnetic Bz bay. All of these characteristics are seen in the RMUS magnetometer data shown in Figure 2e; therefore, the TR mechanism is a possible contributor to the RMUS magnetometer observations. However, the BKS radar is measuring sub-auroral flow in the vicinity of the plasmapause therefore is unlikely to detect this type of pulsation.

FLR Pi2s are generated when compressional energy couples with the closed dipolar field lines of the inner magnetosphere to excite a global magnetohydrodynamic (MHD) Alfvén wave [Takahashi et al., 1988]. In this case, the resonance frequency is a function of field line length and plasma mass density. A key characteristic of the FLR signature is an amplitude maximum of the FLR frequency at the resonant L-shell and a 180° phase shift as one moves latitudinally across the resonance. Neither BKS radar data nor magnetometer data in a latitudinal chain from L = 3.0 to 5.0 shows these signatures for FLRs. Therefore, the FLR is an unlikely contributor to the pulsations measured by the BKS radar.

Global cavity mode oscillations cannot be directly observed by ground magnetometers or SuperDARN radars, although indirect observations are possible. Cavity modes can be excited either within the plasmasphere or in the region between the plasmasphere and the neutral sheet as a result of compressional energy from a fast mode wave generated during a substorm event [Olson, 1999]. Theoretical [Kivelson and Southwood, 1986], numerical [Allan et al., 1986], and observational [Sutcliffe and Yumoto, 1989; Lin et al., 1991] evidence has been found in support of these modes. Cavity mode oscillations can couple with Alfvén mode FLRs which can be observed by radars and magnetometers. This is typically seen at very low latitudes [Lin et al., 1991; Allan et al., 1996] and would generate Pi2s with a frequency related to the size and mass density of the plasmasphere. As this event includes pulsations observed both poleward and equatorward of the plasmapause, it is unlikely that these pulsations are due to a global cavity mode oscillation.

Plasmapause surface waves are damped, sinusoidal oscillations whose frequency depends on both the magnetic field and plasma mass density on the boundaries of the plasmapause region. An impulse of energy on the plasmapause can excite this magnetohydrodynamic (MHD) surface eigenmode of the plasmasphere [Lanzerotti et al., 1973; Chen and Hasegawa, 1974]. Kepko and Kivelson [1999] state that such an impulse could be created by an Earthward-moving BBF which brakes against the quasi-dipolar field line region of the inner magnetosphere. In our event, this type of BBF is observed by both THEMIS satellites D and E (Figure 2f) 67 seconds prior to the appearance of the ground-observed Pi2 pulsations. Additionally, the pulsation can be seen to propagate in a East-West direction on the nightside. These measurements are consistent with the idea of a plasmapause surface wave.
Kepko and Kivelson [1999] and Kepko et al. [2001] introduce the concept of directly driven Pi2 pulsations, which is another mechanism of Pi2 generation that could involve the plasmasphere. These papers present events in which ground-observed Pi2s are seen approximately one minute after BBFs in the near-Earth tail with waveforms similar to the ground Pi2s are observed. They suggest that such BBFs could couple to Alfvénic or compressional modes and then appear as low-latitude Pi2s in all MLT sectors of the Earth. Like these events, the 22 February 2008 substorm studied in this paper includes Earthward-moving BBFs located in the near-Earth plasma sheet observed by THEMIS D and E just over one minute prior to the appearance of the ground-observed Pi2 pulsations. The observed BBF, as seen in Figure 2f, has two peaks with a waveform very close to that of the first two pulses of the ground Pi2. It is possible that the BBFs break against the inner magnetosphere and produce plasmaspheric compressions that are directly observable to the radar.

It should be noted that the Pi2 pulsations measured by the radar are similar to the measurements of the magnetometer beneath it. This is critical, because it suggests that the pulsations seen by the radar and the magnetometer are from the same source. If only magnetometer measurements were available, it could be concluded that the Pi2 observed is a TR Pi2, related to the formation of the SCW. However, the radar provides very localized measurements and can only sense sub-aурoral flow in this region. Because we were able to show that the radar measurements are in the vicinity of the ionospheric projection of the plasmapause, it is reasonable that the generating mechanism of the observed Pi2 is connected with the plasmapause. Therefore, it is likely that the radar is seeing pulsations resulting from either a plasmaspheric surface wave excitation or a direct compressional response to the BBF, not from a TR current system.

4. Conclusions

During a substorm on 22 February 2008 at 0436 UT, Pi2 pulsations with a period of 172 s were observed simultaneously by the BKS SuperDARN radar and magnetometers across the THEMIS, SAMBA, and Step210 arrays. This study focuses on Pi2s observed in the BKS radar and the RMUS magnetometer, which were located in the premidnight subauroral region. The pulsations observed by both stations are similar, which suggests that a single plasmaspheric source generated the Pi2. Due to the localized nature of of radar measurements, the BKS radar data contains significantly more spatial and temporal structure than the data recorded by the magnetometer. A cross-phase analysis of magnetometer data places these measurements in the vicinity of the ionospheric projection of the plasmapause. About one minute prior to ground Pi2 onset, two Earthward-moving BBFs were observed by THEMIS D and E in the near-Earth plasma sheet. Based on observations and previous studies, it is suggested that the Pi2 pulsations observed by BKS and RMUS are the result of either a plasmaspheric surface wave or a direct response due to braking of the BBF on the inner magnetosphere.

These observations demonstrate the ability and value of using SuperDARN radars for the investigation of midlatitude ULF waves. Future work will include studies of the latitudinal details of these radar measurements, a search for additional similar events, and further investigation of Pi2 generating mechanisms involving the plasmapause.

Acknowledgments. Support for this research and funding for the construction of the Blackstone, VA SuperDARN radar is provided by NSF grant ATM-*****. K. Oksavik thanks the Research Council of Norway for financial support. KEp and AE indices were obtained from the World Data Center in Kyoto. We acknowledge NASA contract NASS-02099 and V. Angelopoulos for use of data from the THEMIS Mission. Specifically C. W. Carlson and J. P. McFadden for use of ESA data. S. Mende and C. T. Russell for use of the GMAG data, and I. Mann for use of the GMAG data, and the CSA for support of the CARISMA network. We thank J. Green for providing data from the NOAA/POES TED instrument, and E. Zesta for SAMBA magnetometer data. STEP 210 magnetometer data was copied from the Solar-Terrestrial Environment Laboratory, Nagoya University. Solar wind data was obtained from the CDAWeb OMNI database by J. H. King and N. Papatashvili. Satellite positions and magnetic footprints were obtained with the TIPSOD program by NASA GSFC SSC.

References


King, J., and N. Papatashvili (2006), *One Minute and Five Minute Solar Wind Data Sets at the Earth’s Bow Shock Nose*, use data from the THEMIS Mission. Specifically C. W. Carlson and J. P. McFadden for use of ESA data. S. Mende and C. T. Russell for use of the GMAG data, and I. Mann for use of the GMAG data, and the CSA for support of the CARISMA network. We thank J. Green for providing data from the NOAA/POES TED instrument, and E. Zesta for SAMBA magnetometer data. STEP 210 magnetometer data was copied from the Solar-Terrestrial Environment Laboratory, Nagoya University. Solar wind data was obtained from the CDAWeb OMNI database by J. H. King and N. Papatashvili. Satellite positions and magnetic footprints were obtained with the TIPSOD program by NASA GSFC SSC.


N. A. Frissell, Bradley Department of Electrical and Computer Engineering, Virginia Polytechnic Institute and State University, 1991 Kraft Drive, Suite 2019, Blacksburg, VA 24060, USA. (nafrissell@vt.edu)