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TRANS-POLAR PROPAGATION OF Pi1 WAVE BURST AS OBSERVED BY AN ANTARCTIC ARRAY DURING THE THEMIS 2007/03/23 SUBSTORM

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Abstract. We have analyzed bursty Pi1 emissions that occurred during an interval of substorm activity on March 23, 2007. Magnetometer observations from the multi-spacecraft Themis mission and from the search-coil magnetometers in Antarctica are augmented by UVI images from the Polar satellite. Dynamic spectra from high-latitude stations reveal that Pi1 bursts can propagate poleward, even across the polar cap. Surprisingly, Pi1 propagation at high latitudes is more efficient than that of Pi2 pulsations. We infer that the propagation mechanism for Pi1 is the partial wave energy trapping in the ionospheric waveguide. The band-limited spectral structure of Pi1 burst can arise owing to the combination of a cutoff at lower frequency, and a weaker excitation and stronger attenuation at higher frequencies.

Introduction

Accurate timing and locating of substorm onsets continues to be a matter of considerable importance as the space physics community tries to evaluate competing onset mechanisms [*Liou et al.,* 1999]. Although UV satellite imagers provide ionospheric projection of electron precipitation related to the onset, the satellite limited imaging cadence underscore the need for complementary ground-based monitoring techniques. Pi 2 observations can be made over a large latitudinal range, but the long-period nature of these signals provides only approximate timing (~few min) [*Liou et al.,* 2000]. Observations of Pi1 bursts (so called PiB emission), because of their higher frequency, hold the promise of providing better temporal resolution (~few sec) [*Bossinger and Yahnin,* 1987].

ULF waves in the Pc1/Pi1 band are expected to be produced through field-aligned injection of localized Alfven waves into the ionosphere. MHD waves in the frequency range around 1 Hz can propagate in the horizontal direction, being trapped in the upper ionosphere. Thus, the spatial structure of Pc1/Pi1 magnetic signals is determined by both mode conversion from incident Alfven waves into horizontally propagating fast magnetosonic waves and trapping of fast waves in the ionospheric F-layer [*Greifinger and Greifinger*, 1968]. Therefore, the spatial and frequency dependences of the magnetic signals observed on the ground are expected to be different in regions near the injection center than in regions with distance much larger than the scale of the incident wave.

A non-monotonic Alfven velocity profile in the upper ionosphere results not only in the occurrence of the fast mode waveguide, but also the ionospheric Alfven resonator (IAR). The IAR is bounded from below by the highly-conductive E-layer, and from above by the steep vertical gradient of $V_A(z)$. In the auroral region, additional effective reflection of Alfven waves may occur from the bottom boundary of the auroral acceleration region (AAR) [*Pilipenko et al.,* 2002]. The propagation effects of structured Pc1 waves from various sources [e.g., *Pilipenko et al.,* 2005] have been studied by many researchers, and those studies confirmed most of the theoretical predictions. However, we are not aware of any observational study that has unambiguously shown that Pi1 propagation along the Earth's surface is due to the ionospheric waveguide.

Pi1B as well as Pi2 are closely associated to the substorm onset, so Pi1B are sometimes described as a high frequency extension of Pi2. Pi1 bursts are not sudden enhancements of broad-band power, but have a fine structure: the frequencies around 0.2-0.3 Hz are often highlighted [*Kangas et al.,* 1978]. This fine spectral feature of Pi1B was suggested to be related to the IAR occurrence [*Lysak,* 1988], or the oscillatory nature of the anomalous conductivity regime in the region of field-aligned currents [*Pilipenko et al.,* 1999]. The temporal evolution of Pi1B is sometimes observed to be composed of two stages [*Arnoldy et al.,* 1998]. First, a weak increase of emission intensity occurs in a wide spatial range practically simultaneously at widely separated stations, caused by the propagation in the ionospheric waveguide. In the second stage, the main increase of intensity occurs at individual stations, which moves relatively slowly from one station to another. This stage is caused by the approaching of the auroral intensification region.

There is still no generally accepted view of the mechanism of the primary Pi1 source. There were suggestions that Pi1 is either an ionospheric phenomenon, caused by fluctuations of the electron precipitation [*Arthur and McPherron,* 1980], or a magnetospheric phenomenon, caused by bursty plasma flow in the magnetotail [*Lessard et al.,* 2006].

The substorm on March 23, 2007 has been studied by the Themis community [*Keiling et al.,* 2008]. In this paper we will augment their analysis by examining the data from an array of magnetometers in Antarctica. Though it is commonly believed that Pi1 activity is limited in both local time and latitude [*Posch et al.*, 2005], we will show that Pi1 bursts observed during this event could be detected at much larger distances than had been expected.

Search-coil magnetometer array

The locations of the Antarctic search-coil magnetometers used in this study are shown in Fig. 1. The array includes US observatories South Pole (SPA); McMurdo (MCM); US AGO stations P1, P2, P3, and P5; Australian stations Casey (CSY), Davis (DVS), and Mawson (MAW); Italian stations Terra Nova Bay (TNB) and Dome C (DMC); and UK station Halley (HBA). The Antarctic array is augmented by a conjugate station Poker Flat in Alaska (POK) and Macquarie Island (MCQ) in the Southern Pacific. The recording cadence at all stations is 0.5 sec.

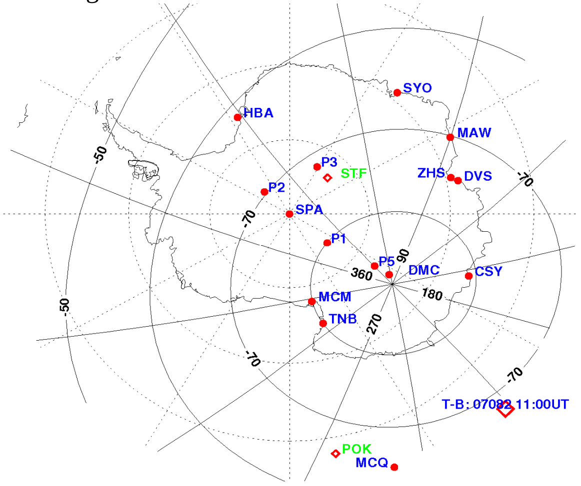

Fig.1. Map of search-coil magnetometers in Antarctica. The open diamond denotes the geomagnetic projection of the Themis-B satellite location at 1100 UT.

The substorm event of March 23, 2007

The substorm on March 23, 2007 (day 082) has multiple onsets: at ~1110 UT, ~1115 UT, and most intensely at ~1120 UT, each accompanied by Pi2 burst. Fig. 1 also shows the geomagnetic projection (according to the T-96 model) of the Themis-B satellite at 1100 UT on this day. Themis constellation is in the evening sector: three near-by spacecraft A, B, and D are at X~-6.9 R_E, Y~9.2 R_E, Z~-0.5 R_E. The ionospheric projection of central probe B is ~15^o eastward from MCQ (Fig. 1). However, a thorough examination of this event showed that in fact the geomagnetic field in this event was substantially twisted, so the actual ionospheric projection should be shifted more to MCQ [*Keiling et al.*, 2008].

Plots of UVI images from Polar spacecraft with superposed location of Antarctic stations show that the first auroral activation occurred ~15^o eastward from MCQ at ~1110 UT. Another, more intense activation occurred at ~1120 UT (Fig. 2). The center of this activation has leaped westward, so MCQ happened to be just beneath this auroral activation.

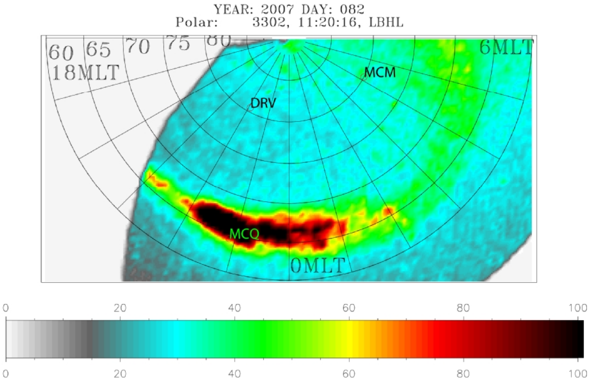

Fig. 2. UVI images (LBHL filter) of auroral activations at 11:20:16 UT from Polar mapped onto the Antarctic stations.

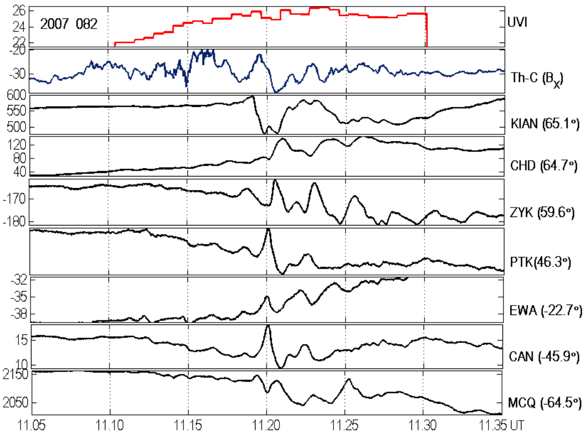

Fig. 3. Spatially-integrated UV intensity from Polar, Themis-C magnetogram (Bx-component) and magnetograms (H-components) of flux-gate magnetometers in Northern and Southern hemispheres.

At nearly-conjugate stations MCQ and POK the emission in the band 0.1-0.5 Hz sharply increased nearly simultaneously during the moment of first activation (Fig. 5). However, the intensification of emission was much stronger during the final auroral activation, when MCQ was covered by the intensified auroral bulge. Most probably, the source of the Pi1 burst was located in the epicenter of the auroral activation. Thus, a comparison of two subsequent intensifications shows that the Pi1 power drops off rapidly away from the source.

Though the auroral activation starts at ~1110 UT, as evident from the variations of spatially-integrated UV intensity, the Pi2 signatures can be evidently seen on the ground during the main activation at ~1120 UT (Fig. 3). The dynamic spectra (sonograms) from the Antarctica search-coil array reveal the rapid enhancement of Pi1 power during each of the substorm onsets (at ~1110 UT and ~1120 UT). Fig. 5 shows that a very intense Pi1 burst was observed at the station nearest to the substorm epicenter MCQ. However, rather distinct Pi1 bursts can be seen at distant stations in the polar cap, at TNB, MCM, P5, and even at P1 and CSY (Fig. 4). The spectral content of the burst is not entirely irregular: frequencies $f>0.35$ Hz are highlighted. The enhancement of noise in the band around 0.3-0.4 Hz can be seen at all stations. Thus, Pi1 burst can propagate effectively (better than Pi2 pulsations) to very high latitudes, throughout the polar cap, and even on other side of the geomagnetic pole. The observed Pi1 bursts at distant stations from both activations are of comparable amplitudes. This indicates that away from the source the Pi1 attenuation becomes much weaker, enabling a signal to be detected at very large distances, up to a few thousands of km.

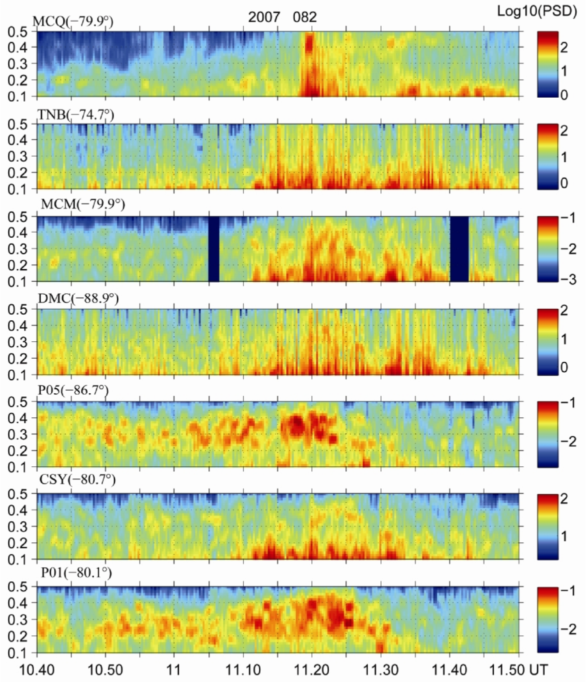

Fig. 4. Dynamic spectra of the nightside polar stations MCQ (D), TNB (D), MCM (H), DMC (D), P5 (D), CSY (D), and P1 (D) for the period 1040-1150 UT.

The spectra of Antarctic station in the time interval 1115-1125 UT (Fig. 6) demonstrate a tendency for the main frequency of the Pi1 enhancement to decrease with increase of distance from a source. This dependence may indicate an increase of damping with frequency.

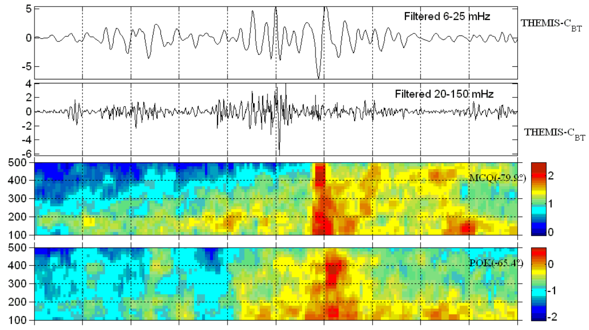

Fig. 5. Dynamic spectra of search coil magnetometer data from conjugate stations MCQ (D component) and POK (H component) for the period 1050-1140 UT, and fluxgate magnetometer (Bx – component) from Themis-C. Power is coded using log-scale according to the color bars at the right.

Discussion and conclusion

The comparison of two successive auroral intensifications show that Pi1 power drops rapidly away from a source. Indeed, during the first auroral activation at ~1110 UT which occurs ~15° eastward from MCQ, a sharp Pi1 power enhancement is evident, but it is not very strong at MCQ. However, during subsequent activation at ~1120 UT, when MCQ happens to be just beneath the auroral bulge, the intensification of emission is much stronger. Most probably, the source of the Pi1 burst is located in the epicenter of the auroral activation.

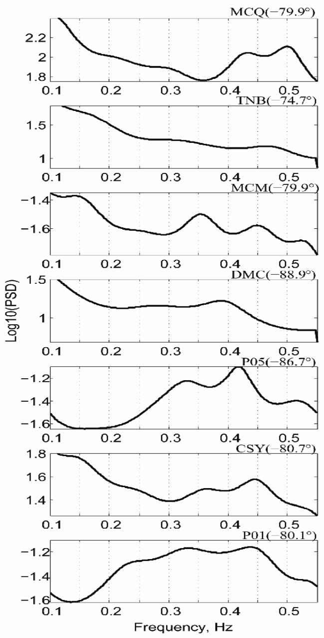

Fig. 6. Spectra (log-scale) of the nightside polar stations MCQ (D), TNB (D), MCM (H), DMC (D), P5 (D), CSY (D), and P1 (D) for period 1115-1125 UT.

The Pi1 bursts observed at distant stations during both activations are of comparable amplitudes. This indicates that away from a source the Pi1 attenuation becomes much weaker, enabling a signal to be detected at very large distances, up to a few thousands of km. It seems that Pi1 bursts can propagate poleward to large distances, even across the polar cap. At the same time, we could not identify any Pi2 wave pattern at the polar cap stations during the same substorm. Thus, in contrast to Pi2, the propagation of Pi1 bursts turns out to be more effective. We suppose that this difference is due to different transmission mechanisms: a quasi-static response for Pi2, and an ionospheric wave propagation for Pi1.

These propagation features are expected from basic analytical and numerical models of Pc1 MHD wave excitation and propagation in the ionosphere [*Greifinger,* 1972; *Fujita and Tamao,* 1988; *Fujita,* 1988]. Qualitatively different situations are expected to arise depending on the lateral distance from the center of the incoming wave: (a) For lateral distances $r<r_0$ that are small in comparison to the lateral size r_0 of the incoming disturbance (probably, ~100 km), one may expect that the ground magnetic structure is dominated by the incident disturbance (e.g. Alfven wave); (b) In

the distant region, $r>>r_o$, the electromagnetic field of the fast wave trapped in the ionospheric waveguide is dominant. In this region the direct signal falls off rapidly as $\propto r^{-2}$, but the waveguide field weakly depends on radial distance $B \propto r^{-1/2} \exp(-r/\Lambda)$, where attenuation length Λ is very large, especially for nighttime conditions. The ducted wave has a lower cutoff frequency. The fundamental cutoff frequency is $w^* \sim V_A / 2D$, where V_A is the characteristic Alfven velocity inside the waveguide, and D is its width.

The excitation factor of a waveguide mode decreases rapidly with increasing frequency, therefore the ground signal is expected to have a larger amplitude near cutoff frequencies. Attenuation of the ducted wave (mostly caused by the ionospheric Joule loss) is an increasing function of frequency, larger for out-of-geomagnetic meridian plane propagation, and is minimized at ω^*. Observations of Pc1 propagation at mid-latitudes have shown that the damping rate is ~10dB/100km as a maximum in the injection region and ~2.5dB/100km in the region beyond 500 km [*Hayashi et al.,* 1981]. Spatial attenuation is larger in the daytime than in the nighttime.

Thus, the band-limited enhancement of Pi1 bursts can arise owing to the combination of two factors: cutoff at lower frequency, and weaker excitation and more severe attenuation of higher frequencies. The observed tendency of diminishing frequency of the high-frequency enhancement agrees with the modeling predictions of the damping increase for higher frequency.

On the other hand, the band-limited enhancement may be caused by the resonant response/transmission of the auroral ionosphere [*Lysak,* 1988; *Pilipenko et al.,* 2002]. The IAR excitation may occur only in the region of the Pi1 source. Because the IAR fundamental frequency $w_A \sim V_A \sin I / 2D$ (I is the declination) is commonly less than the ionospheric waveguide cutoff frequency, $w_A < w_*$, the waveguide mode cannot excite the IAR upon its propagation. We suppose that at auroral latitudes the enhancements at ~0.42 Hz (MCQ) and ~0.35 Hz (POK) are caused by IAR effects. The difference in the highlighted frequencies is quite natural, because the conjugate ionospheres are not identical.

This study demonstrates that Antarctica has a unique dense array of search-coil magnetometers corresponding to all magnetospheric domains: the sub-auroral and auroral regions, cusp, and polar cap, which may be used by the space community as an effective tool for substorm-related research. This study is an additional demonstration of the ever growing potentialities of the Antarctic array for space physics.

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