

Upstream Pc3–4 waves: Experimental evidence of propagation to the nightside plasmopause/plasmatrough

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[1] Compressional magnetohydrodynamic (MHD) waves in the Pc3–4 frequency range ($\simeq 10$ –50 mHz) are generally believed to be generated upstream of the Earth’s bow-shock in reflected proton beams. Inside the closed field-line geometry, these waves are conventionally considered to be a dayside phenomenon. However, recent studies suggest that some of the nighttime Pc4 pulsations may in fact have an upstream origin. In this letter, we report synchronous variations of the Pc3–4 spectra near post-dawn cusp and nightside plasmopause/plasmatrough as observed by HF radar and ground magnetometers. The measured Pc3–4 frequency closely follows that of the upstream waves theoretically predicted based on the dynamics of the interplanetary magnetic field, which presents the most convincing evidence to date of upstream-generated Pc3–4 waves propagating to the nightside magnetosphere in the closed field-line geometry. We conclude the letter with a brief discussion of a possible propagation scenario. **Citation:** Ponomarenko, P. V., C. L. Waters, and J.-P. St-Maurice (2010), Upstream Pc3–4 waves: Experimental evidence of propagation to the nightside plasmopause/plasmatrough, *Geophys. Res. Lett.*, 37, L22102, doi:10.1029/2010GL045416.

1. Introduction

[2] Daytime geomagnetic pulsations in the Pc3–4 range (frequencies $f \simeq 10$ –50 mHz) are regularly observed across a broad range of latitudes, from the equator to the polar cap. Numerous studies show that in the closed field-line geometry their power maximizes near the auroral/cusp region at around 10–11 MLT. Pulsation frequencies over the Pc3–4 range have been found to be proportional to the magnitude of the interplanetary magnetic field (IMF), $|\mathbf{B}_{\text{IMF}}|$, while the power is maximum at low cone angles, $\theta_{B_{\text{IMF}}}$, and sharply increases with increasing solar wind speed (for the extensive reference list see, e.g., Ponomarenko et al. [2002]). By contrast, Pc3–4 wave characteristics in the polar cap have not been firmly established yet although the available information suggests rather different morphology and propagation characteristics compared to lower latitudes [e.g., De Laet et al., 2005; Pilipenko et al., 2008].

[3] The presence of daytime Pc3–4 pulsations across a broad range of magnetic latitudes makes these waves potentially very useful for remote sensing of the near-Earth’s plasma environment [e.g., Baransky et al., 1985; Price et al.,

1999]. However, developing a ULF-based diagnostic requires an intimate knowledge of the wave generation and propagation mechanisms.

[4] Daytime Pc3–4 pulsations are generally believed to be related to compressional magnetohydrodynamic (MHD) waves produced at the Earth’s foreshock by the ion-cyclotron instability [Fairfield, 1969; Paschmann et al., 1979; Hoppe and Russell, 1983; Yumoto, 1985]. These waves are generated at a Doppler-shifted ion-cyclotron frequency and are commonly referred to as upstream waves, UW. Ponomarenko et al. [2002] showed that the ground signatures of UW at auroral/cusp latitudes are characterized by a band-limited spectrum between $\simeq 10$ and 50 mHz which is superimposed on a frequency power-law background with spectral density $s(f) \propto f^{-3} - f^{-4}$, where f is the wave frequency, and proposed a robust algorithm to separate the band-limited component from the power-law frequency dependent background. This two-population composition of the day-time Pc3–4 spectrum was subsequently observed in the polar cap and plasmatrough/plasmopause regions [De Laet et al., 2005; Ponomarenko et al., 2005]. While UW signatures in magnetometer data are conventionally considered to be a dayside phenomenon, Takahashi et al. [2005] reported ground and satellite observations of nighttime Pc4 pulsations which were also attributed to the upstream wave activity. However, this association was indirect and based on the observed difference in day/night power ratio between the assumed nighttime Pc4 and Pi2 pulsations. Pilipenko et al. [2008] reported an early morning maximum of Pc3 power at very high latitudes, ~ 87 MLAT, but pointed out that the “open” field-line topology effectively maps this location to vicinity of the dayside cusp. In this letter we study in detail an example of nighttime Pc3–4 waves from 60–65 MLAT that appear to be directly driven by the IMF dynamics and, therefore, present the most convincing evidence to date of upstream wave propagation to the nightside in the closed field-line geometry.

2. Experimental Setup and Data Processing Details

[5] Doppler velocity variations in the ionosphere were measured by the Super Dual Auroral Radar Network (SuperDARN) radar located on Bruny Island, Tasmania (TIGER radar) during a pilot study of ULF wave activity in the southern plasmatrough/plasmopause region. Normally, the SuperDARN sampling rate is set to $\Delta t \simeq 1$ or 2 min where 16 beams are sequentially sampled with an integration time $t_{\text{int}} \simeq 3.5$ or 7 s per beam. This is not suitable for studying Pc3–4 waves with periods of 20–100 s. To overcome this limitation, a special “ULF” radar operating mode was designed in which only 3 beams were utilized with the integration time set to $t_{\text{int}} \simeq 3$ s resulting in $\Delta t \simeq 9$ s (Nyquist

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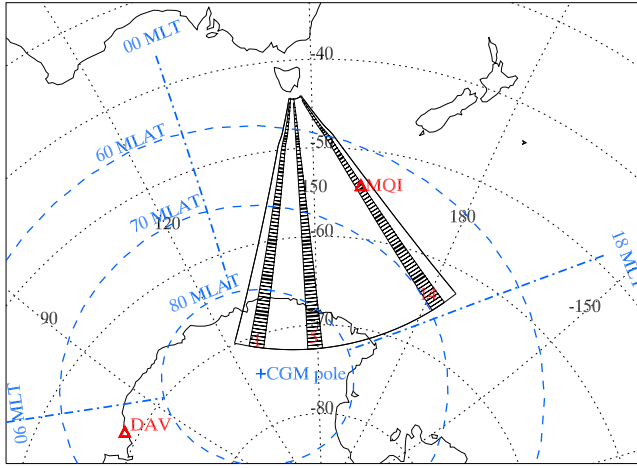


Figure 1. Experimental set-up showing spatial coverage by TIGER beams 1, 5, and 14 (black mesh and red numbers; thick mesh lines are separated by 10 range gates) and ground magnetometers (red triangles) at Macquarie Is (MQI) and Davis (DAV). AACGM latitude contours are marked in blue (dash), while geographic coordinates are shown by black dotted lines. MLT contours (blue dash-dot) correspond to 09UT.

frequency $f_{Ny} \approx 55.6$ mHz). The positioning of radar beams is shown in Figure 1, where beams 1 and 5 point toward the Altitude Adjusted Corrected Geomagnetic (AACGM) and geographic poles, respectively, and beam 14 covers the induction magnetometer site on Macquarie Island (MQI, CGM $64^{\circ}18'S$, $248^{\circ}21'E$, MLT C UT + 12). The black mesh shows the approximate locations of effective scatter volumes separated in range by 45 km, which are conventionally referred to as range gates. To achieve co-located ground-ionosphere measurements the TIGER FOV was rotated by $\approx 7^{\circ}$ anticlockwise using a specially designed phasing matrix.

3. Case Study 15 May 2006

[6] For the visual identification of ULF waves in the 2D time-range radar velocity data we applied a technique described by Ponomarenko *et al.* [2003], which utilizes time series detrending and saturated gray-scale maps. Among a multitude of ULF wave signatures, the procedure revealed regular wave activity on the dusk side over range gates 10–30. A typical example is presented in Figure 2, which shows a range-time map of detrended (3 min box-car) Doppler velocity variations for beams 1, 5 and 14 over 08:00–09:30 UT (≈ 20 –22 MLT) on 15 May, 2006. The blue shading indicates regions devoid of data. The present case study focuses on the close-range band of radar echoes observed between range gates 10 and 22 that correspond to 60–65MLAT and statistically cover plasmopause/plasmatrough region. A detailed analysis involving HF ray-tracing showed that these echoes were produced by 0.5-hop ionospheric scatter so that the vertical stripes of alternating shades of gray represent modulation of the line-of-sight plasma drift velocity, v_{LOS} , by the passage of ULF waves. Importantly, no substorm activity was observed during the said interval.

[7] Figure 3 shows the average frequency spectra (Fourier analysis length 450 s; 50% overlap, Hanning window) from the ground magnetometer records at MQI and those from TIGER v_{LOS} (the DAV record will be discussed below). Radar range gates 17–18 for beams 1 and 5 and gate 30 for beam 14 cover the same MLAT as the MQI magnetometer. While beams 1 and 5 provided a continuous coverage of the required MLAT during 08:00–09:30 UT, valid echoes in beam 14 at gate 30 are present only between $\approx 08:00$ –08:45 UT. To represent beam 14 we used Doppler data at closer gates (15–20) which were available for almost the whole 1.5-hour interval under study. This replacement is justified because whenever we observed co-existing oscillations across range gates 15–35, they were highly coherent. Therefore, the radar time series for all three beams were calculated as median v_{LOS} values over range gates 17–19.

[8] Spectra for the AACGM north-south (NS) and east-west (EW) magnetometer time series components are represented by thick black solid and thick black dashed lines, respectively. The radar spectra for beams 1, 5 and 14 are shown by the green, red and blue lines, respectively.

[9] The NS magnetometer spectrum from MQI represents a combination of a power-law background $\propto f^{-4}$ and a band-limited component covering $f \approx 8 - 50$ mHz that is typical for daytime upstream-related Pc3-4 waves [Ponomarenko *et al.*, 2002]. In addition, it shows a narrow spectral peak

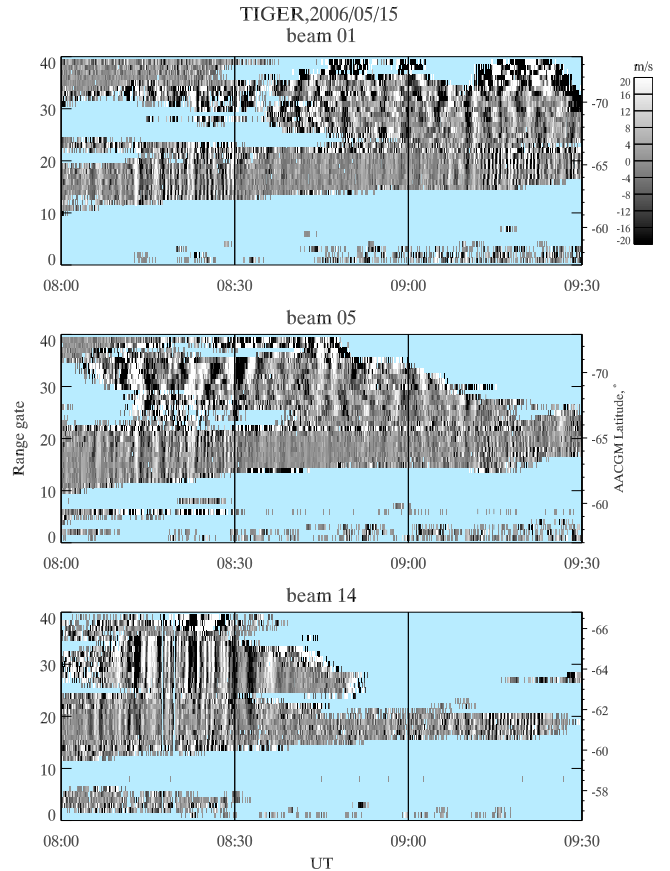


Figure 2. Range-time maps of detrended (3 min box-car) Doppler velocity variations recorded by TIGER beams 1, 5 and 14 during 08:00–10:00 UT on 15 May 2006. Missing data regions are shown in light blue shading.

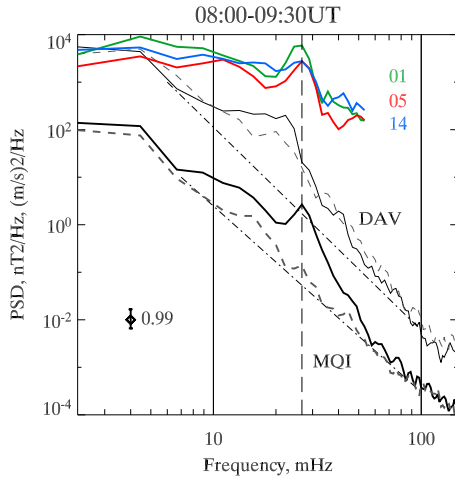


Figure 3. Average power spectra for 08:00–09:30 UT, 15 May 2006. Green, red and blue curves correspond to TIGER beams 1, 5, and 14, respectively. Thick solid and dashed black lines show CGM NS and EW component spectra for MQI, while thin black lines show the same characteristics for DAV. Black dash-dot lines correspond to power-law variations with $s(f) \propto f^{-4}$.

near $\simeq 27$ mHz (vertical dashed line) that is also apparent in all radar spectra. In contrast, the band-limited and narrow-band components are virtually absent from the EW magnetometer spectrum. The relatively low Nyquist frequency for the radar data, $f_N \simeq 55.6$ mHz, does not allow us to estimate the power-law component in this dataset.

[10] The observation of the dayside-like Pc3-4 activity on the nightside requires further clarification. The dayside oscillations are believed to be signatures of the UW that are governed by the magnitude and orientation of the interplanetary magnetic field, \mathbf{B}_{IMF} , so that their central frequency increases in proportion to $|\mathbf{B}_{\text{IMF}}|$ and their amplitude sharply decreases when the IMF cone angle, $\theta_{Bx} = \arccos(B_x/|\mathbf{B}_{\text{small IMF}}|)$, approaches 90° [Bol'shakova and Troitskaya, 1984; Ponomarenko et al., 2002].

[11] In order to determine whether the nighttime Pc3-4 activity is related to dayside UW, the simultaneously observed day- and nightside ULF waves were analyzed for their response to changes in the IMF. The top and middle panels of Figure 4 show dynamic power spectra of v_{LOS} from TIGER beam 1 and from the ground magnetic field measured at MQI, respectively. The same dynamic spectra were used to calculate the average spectra shown in Figure 3. The bottom panel shows magnetometer spectra from Davis in Antarctica (DAV, CGM 74°44'S 100°53'E, MLT \simeq UT-2hr). DAV lags MQI by C10 hr in MLT providing a useful dayside (post-dawn) reference for UW signatures. The spectra from MQI and DAV in Figure 4 represent the sum of NS and EW spectral densities.

[12] The data from all three instruments shows synchronous variations across the 10–50 mHz band with Pc3-4 activity increasing over $\sim 08:00$ – $08:30$ UT, decreasing over $\sim 08:30$ – $09:00$ UT and then increasing again over $\sim 09:00$ – $09:30$ UT, arguing for a common source for these oscillations. In particular, the previously described narrow-band component at $\simeq 27$ mHz in the TIGER and MQI spectra (marked by dashed lines in panels 1 and 2) appears when the

band-limited continuum is enhanced and disappears when the latter weakens. Finally, in contrast to the NS-dominated Pc3-4 signatures at MQI, both horizontal components at DAV exhibit comparable spectral powers (Figure 3).

[13] In Figure 4, the white circles represent the predicted values of the UW frequency, calculated using a theoretical expression $f_{\text{UW}} [\text{mHz}] \simeq 7.6 |\mathbf{B}_{\text{IMF}}| [\text{nT}] \cos^2 \theta_{Bx}$ derived by [Takahashi et al., 1984]. The IMF data were obtained from the Advanced Composition Explorer (ACE) spacecraft and time-shifted to the bow-shock nose position (http://omniweb.gsfc.nasa.gov/form/sc_cat_m1.html). For all datasets f_{UW} closely follows the spectral power variations in the ionospheric and ground data, indicating their UW origin.

4. Discussion and Conclusion

[14] Some Pc4 oscillations observed on the nightside have been previously linked to the upstream wave source by [Takahashi et al. 2005], who studied simultaneous magnetic field variations from several locations on the ground and in space. This link was mainly inferred from the observed difference in dayside-nightside power ratio between “classical” Pi2 accompanying auroral activity and broadband nighttime Pc4 waves recorded during magnetically quiet intervals. In contrast, in this paper we have presented direct evidence of a common source for the day- and nightside Pc3-4 ULF waves registered on the ground and in the ionosphere. To achieve

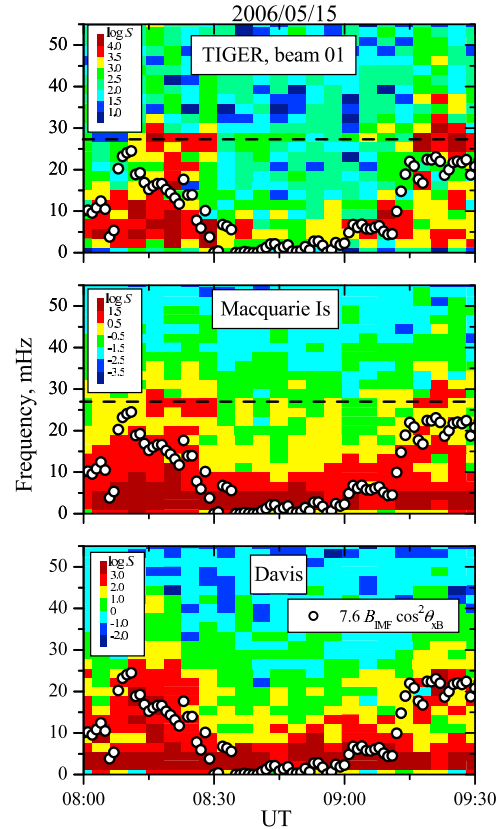


Figure 4. Dynamic power spectra for LOS velocity data in (top) beam 1 for TIGER radar and trace spectra for ground magnetometer data from (middle) MQI and (bottom) DAV. The white circles represent theoretically predicted values of f_{UW} based on the work by [Takahashi et al. 1984].

this, we selected an interval when the IMF exhibits well-defined dynamics which implies sharp changes in the UW spectra. The observed nightside Pc3-4 oscillations exhibit a pronounced dependence on the IMF parameters that replicates the behavior of simultaneous, dayside data with frequency varying in accordance with the theoretically predicted variations in f_{UW} [Takahashi *et al.*, 1984].

[15] The observation of the UW signatures on the nightside may be accommodated into one of the previously discussed Pc3-4 wave propagation scenarios. Ponomarenko *et al.* [2005] analyzed dayside band-limited Pc3-4 activity in radar and ground magnetometer records and suggested, following Howard and Menk [2001], that "...compressional Pc3-4 waves produced in the upstream solar wind travel earthward from the magnetopause in the magnetic equatorial plane depositing energy into the Alfvénic modes ... that reach ionospheric heights along magnetic field lines." The compressional waves may then continue to travel through the plasmatrough to the nightside and generate Alfvén waves along the way. These Alfvén waves then propagate earthward along \mathbf{B}_0 and produce Pc3-4 signatures in radar and magnetometer records. The estimated time-of-flight of the ULF wave from the magnetopause to the high-latitude ionosphere at Alfvénic speed of $\simeq 200\text{--}1000$ km/s is comparable to or less than the temporal resolution of the spectral analysis (450 s) leading to synchronous Pc3-4 variations on the dayside and nightside (Figure 4).

[16] The virtual absence of any previous reports of UW signatures on the nightside can be attributed to two main factors: (i) the pre-midnight ULF spectrum at high latitudes is usually dominated by intense, irregular variations caused by substorms in this MLT sector and (ii) the significantly lower magnitude of UW signatures on the nightside, presumably due to amplitude decrease away from the source and the Earth's "screening effect" as discussed by Takahashi *et al.* [2005].

[17] The narrow-band enhancement at $\simeq 27$ mHz embedded in the band-limited Pc3-4 continuum on the nightside might probably results from a resonance near the plasma-pause which amplifies part of the original upstream wave spectrum. The uniform "resonance" frequency observed at locations with different magnetic latitudes and longitudes would indicate a possible cavity mode scenario but an accurate interpretation of this effect would require a more detailed study of the wave polarization and phase characteristics. In pursuing this goal, we attempted to measure ULF phase velocity using spatially separated radar beams. However, the results were inconclusive due to distortions caused by the 27-mHz resonance. Also, with only v_{LOS} available it appeared impossible to separate phase changes due to propagation from those caused by polarization rotation.

[18] In summary, in this study we have presented the most convincing experimental evidence to date of an upstream wave source for the Pc3-4 ULF wave activity simultaneously observed by the HF radar and ground magnetometers near the nightside plasmapause/plasmatrough. Future work will

focus on clarifying the dayside-to-nightside propagation mechanism using experimental data and model calculations as well as on utilizing the nightside Pc3-4 waves for remote sensing of the near-Earth's plasma environment.

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