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Key Points:
- Daytime Pc3 auroral pulsations occurred over South Pole Station, Antarctica
- The auroral pulsations result from repetitive episodes of fast-moving diffuse auroral patches
- The spatiotemporal behavior of the auroral patches may be a visible manifestation of compressional Pc3 waves in the outer magnetosphere

Supporting Information:
- Supporting Information S1
- Movie S1
- Movie S2

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Fast-moving diffuse auroral patches: A new aspect of daytime Pc3 auroral pulsations

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Abstract Auroral pulsations are a convenient diagnostic of wave-particle interactions in the magnetosphere. A case study of a daytime Pc3 (22–100 mHz) auroral pulsation event, measured with a ~2 Hz sampling all-sky camera at South Pole Station (74.4°S magnetic latitude) on 17 May 2012, is presented. The daytime Pc3 auroral pulsations were most active in a closed field line region where the aurora was dominated by diffuse green-line emissions and within ± 2 h of magnetic local noon. Usually, but not always, the corresponding periodic variations were recorded with a colocated search coil magnetometer. Of particular interest is the two-dimensional auroral signature, indicating that the temporal luminosity variations at a given point were due to repeated formation and horizontal motion of faint, nonpulsating auroral patches with scale sizes of ~100 km. The individual patches propagated equatorward with speeds of 15 km s^{-1} up to 20–25 km s^{-1} one after another along the magnetic meridian through local magnetic zenith. These properties differ considerably from typical pulsating aurorae, being periodic on-off luminosity variations in a particular auroral patch and drifting in accordance with the convection electric field in the magnetosphere. We speculate that such repetitive patterns of the fast-moving auroral patches, being another aspect of the daytime Pc3 auroral pulsations, may be a visible manifestation of compressional Pc3 waves which propagate earthward and cause modulation of precipitating keV electron fluxes in the dayside outer magnetosphere.

1. Introduction

Periodic auroral luminosity variations on time scales from a few to a few tens of seconds are frequently embedded within diffuse aurora. Such aurorae, indicated by the periodic nature of the optical intensity fluctuations, are called "pulsating aurorae (PsA)" or sometimes "auroral/optical pulsations." They—being a visible manifestation of periodic modulation of the flux of keV electrons precipitated by the pitch angle scattering through cyclotron resonance with plasma waves near the equatorial plane of the magnetosphere—are observed over a wide magnetic local time (MLT) region, most favorably in the postmidnight to morning sector [e.g., *Jones et al*., 2011, 2013]. However, understanding the global morphology still remains incomplete because of the lack of dayside optical observations from the ground. In particular, it is not well understood as to what determines the characteristic period on the dayside and what differences exist between the dayside and nightside auroral pulsations. Note that throughout this paper we will preferably use the term "auroral pulsations" instead of using the term "PsA" because some key spatiotemporal properties highlighted in the optical observations presented here are fundamentally different from the established properties of classical PsA, e.g., as described in the recent review of *Lessard* [2012].

Owing to sunlight interference, there are a very limited number of ground-based observatories being capable of measuring auroral pulsations optically in the auroral zone on the dayside, including midday hours. Around magnetic local noon most of the observatories are located at/near cusp and cleft latitudes, of which the closed magnetic field lines are mapped mostly to the Earth's outer magnetosphere ($L > 8$) or boundary layers, depending on upstream solar wind conditions. This implies that dayside auroral pulsations in the high-latitude ionosphere are potentially linked to the structure and dynamics of the outer magnetosphere that respond quickly/sensitively to the ever-changing solar wind, which is a significant contrast to nightside auroral pulsations that are most likely linked to the structure and dynamics of the magnetotail and inner magnetosphere.

Previous statistical studies of dayside auroral pulsations identified their morphological characteristics [*Brekke and Pettersen*, 1971; *Craven and Burns*, 1990; *Wu and Rosenberg*, 1992; *Engebretson et al*., 1994a; *Vorobjev et al*., 1999], including the following: (1) The periods mostly fall into the Pc3 ULF range (f = 22–100 mHz, T = 10–45 s); (2) they are observed most frequently a few hours prenoon and postnoon with the majority of events observed in the prenoon sector; (3) the MLT occurrence distribution depends on geomagnetic activity as measured by Kp; (4) they have a relatively high occurrence rate even during geomagnetically quiet periods ($Kp < 1$); and (5) they do not necessarily occur in association with substorm activity, which is obviously incompatible with the conventional view of postmidnight PsA generation discussed in the context of substorm recovery phases.

Auroral pulsations frequently, but not always, occur with the corresponding magnetic pulsations, as recorded in colocated ground magnetometers. For example, observations by *Engebretson et al*. [1990] showed that the simultaneous occurrence rates of dayside Pc3 auroral and magnetic pulsations accounted for 30–40% of the periods when Pc3 magnetic pulsations were observed. This suggests that the occurrence of dayside Pc3 auroral pulsations is associated, at least in part, with dayside Pc3 magnetic pulsations which are likely generated by an upstream wave source or processes at the magnetopause. Magnetic pulsations on the ground are widely regarded as the result of resonant field line oscillations excited in the magnetosphere through the mode coupling of compressional waves to shear Alfvén waves. Contrary to such a conventional mechanism, *Oguti et al*. [1984] and *Oguti and Hayashi* [1984] have claimed that ground magnetic pulsations which occur in concert with auroral pulsations result from fluctuations in the ionospheric current caused primarily by spatiotemporal variations in ionospheric conductivity produced by the pulsating precipitation of auroral electrons. A similar conclusion was reached by *Engebretson et al*. [1991, 1994b] from observations of dayside Pc3 pulsation activity at near-cusp latitudes.

In most of the early ground-based observations of dayside auroral pulsations, a zenith-viewing photometer was preferably used to obtain the temporal behavior of the optical intensity at a particular point(s) near magnetic zenith at high sampling rates. However, should a dayside auroral pulsation event have a spatially drifting structure (e.g., patch) in the ionosphere, the time variations arising from the horizontal drift would need to be included in the optical pulsation records, along with the time variations due to luminosity on-off changes. To distinguish temporal and spatial variations in the optical pulsation records, therefore, two-dimensional (2-D) optical imaging (such as all-sky camera/imager) with high temporal resolution (1 Hz or higher) would be far superior. To the best of our knowledge, detailed investigation of dayside auroral pulsations in terms of 2-D structure has never been reported, although *Engebretson et al*. [1990, 1994a, 1994b] briefly touched upon the presence of localized patches of dayside Pc3 auroral pulsations by using the all-sky image data taken with a sampling interval of 1 min.

This paper presents a case study of a daytime Pc3 (f = 22–100 mHz, T = 10–45 s) auroral pulsation event by using data acquired from an ~2 Hz all-sky camera measurement at South Pole Station, Antarctica (SPA). This particular case study aims to highlight the spatiotemporal 2-D optical signature in detail, providing us new important clues concerning the generation mechanism of the daytime Pc3 auroral pulsations.

The rest of this paper is structured as follows: In section 2 we present the data sources, including optical and magnetometer instruments at SPA, and then the data analysis results of the daytime Pc3 auroral pulsation event on 17 May 2012. We then conclude with a discussion in section 3.

2. Data Presentation

In this study we primarily employed data from optical and magnetic observations at SPA. In 2012 two optical instruments were operating: one is a white light all-sky camera (ASC, ~2 Hz sampling) [*Motoba et al*., 2014], and the other is a monochromatic all-sky imager (ASI, 32 s sampling) [*Ebihara et al*., 2007]. The high time-resolution ASC image data stored in gray scale 8bit JPG format were used to characterize the spatiotemporal behavior of daytime Pc3 auroral pulsations presented here. Data from the ASI, which is designed to mainly detect the electron 630.0 nm and 557.7 nm optical emissions, serve as an indicator of the hardness of

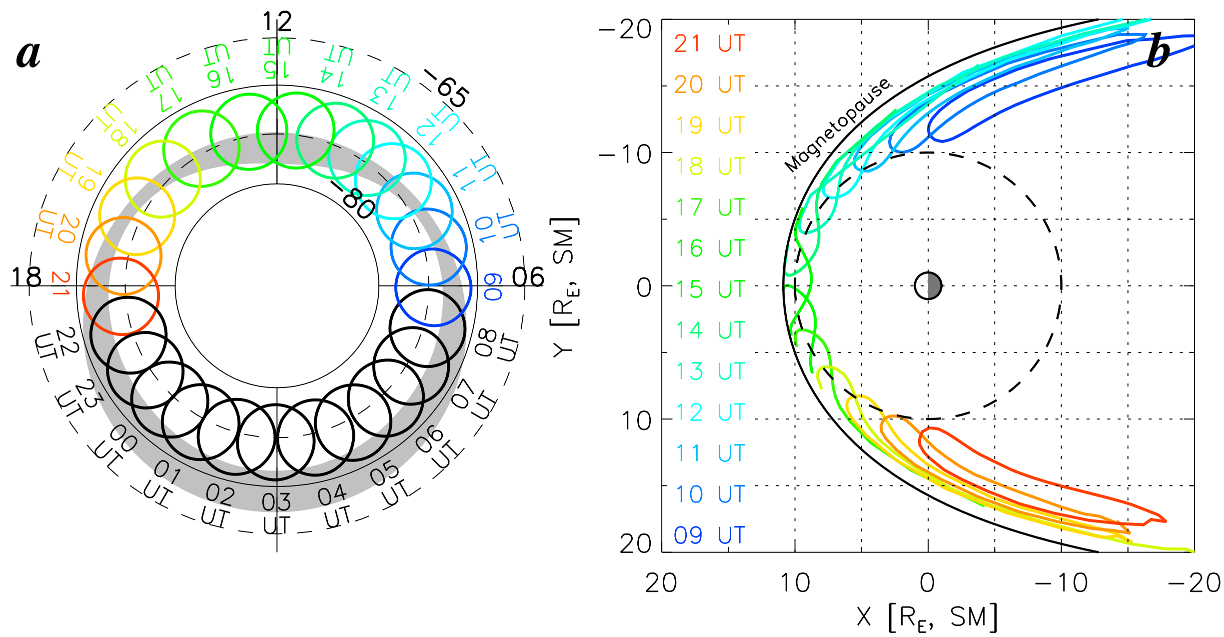

Figure 1. (a) South Pole all-sky field of view indicated at hourly intervals and in an MLAT-MLT coordinate system. The Feldstein model auroral oval for $Q = 1$ (quiet condition) is shaded in gray for reference. (b) Projection of the dayside fields of view onto the equatorial plane ($Z_{SM} = 0$) of the magnetosphere predicted by the T96 model. The magnetopause position (solid curve) given by the *Shue et al.* [1998] model and a radial distance of 10 R_E (dashed circle) are also shown.

precipitating auroral electrons, as well as of the magnetospheric regions. We also used magnetic field data from a colocated search coil magnetometer (0.1 s sampling), recording all three components of magnetic field, B_x (north-south component in geomagnetic coordinates), B_y (east-west component), and B_z (down component), in order to quantify the temporal variations in the ground magnetic field and to compare them with optical variations.

SPA—at which the magnetic local time (MLT) is 3.5 h behind universal time (UT)—is a unique, advantageous site in terms of dayside auroral observations from the ground because (1) it can continuously monitor optical aurora on the dayside including midday hours throughout ~4 months of austral winter season and (2) cloud cover is rarely a problem. Another geographical uniqueness of SPA can be seen in the dayside location relative to the auroral oval and the magnetospheric mapping. Figure 1a shows the spatial coverage of the all-sky field of view at SPA indicated at hourly intervals. Superimposed on Figure 1a is the Feldstein's auroral oval under a geomagnetically quiet condition ($Q = 1$) [*Feldstein and Starkov*, 1967]. It is found that the statistical auroral oval on the dayside mostly lies in the field of view at SPA. During geomagnetically quiet periods, therefore, the probability of observing the main part of the dayside auroral oval at SPA is expected to be relatively high.

Figure 1b presents the magnetospheric mappings of the dayside fields of view, as predicted by the Tsyganenko 1996 (T96) magnetic field model [*Tsyganenko and Stern*, 1996] with the following fixed input parameters: interplanetary magnetic field (IMF) $B_z = 7.5$, $P_{sw} = 1.5$ nPa, IMF $B_y = 0.0$, and $Dst = 0.0$ nT. One important point to keep in mind is that the dayside closed magnetic field lines around SPA are mapped mostly to a region in the outer magnetosphere ($L > 10$) under a geomagnetically quiet condition. The magnetospheric mapping result implies the possibility that the generation of dayside auroral pulsations at SPA, at least in part, is linked to a variety of electromagnetic waves in the outer magnetosphere that responds sensitively to external sources, including processes in the upstream solar wind or at the magnetopause boundary.

This paper presents daytime Pc3 auroral pulsations observed at SPA on 17 May 2012. The solar wind parameters and geomagnetic indices (AU/AL and SYM-H) on 17 May 2012 are summarized in Figure 2. The gray shading for 13:30–17:30 UT is the interval of interest, corresponding to the local daytime period (10:00–14:00 MLT) of SPA. Throughout this day both solar wind driving and geomagnetic substorm activity were considerably weak, as characterized by large and steady northward interplanetary magnetic field (IMF, ~5–10 nT) conditions and $|AL| << 100$ nT. For the first half of this day, on the other hand, it is found from

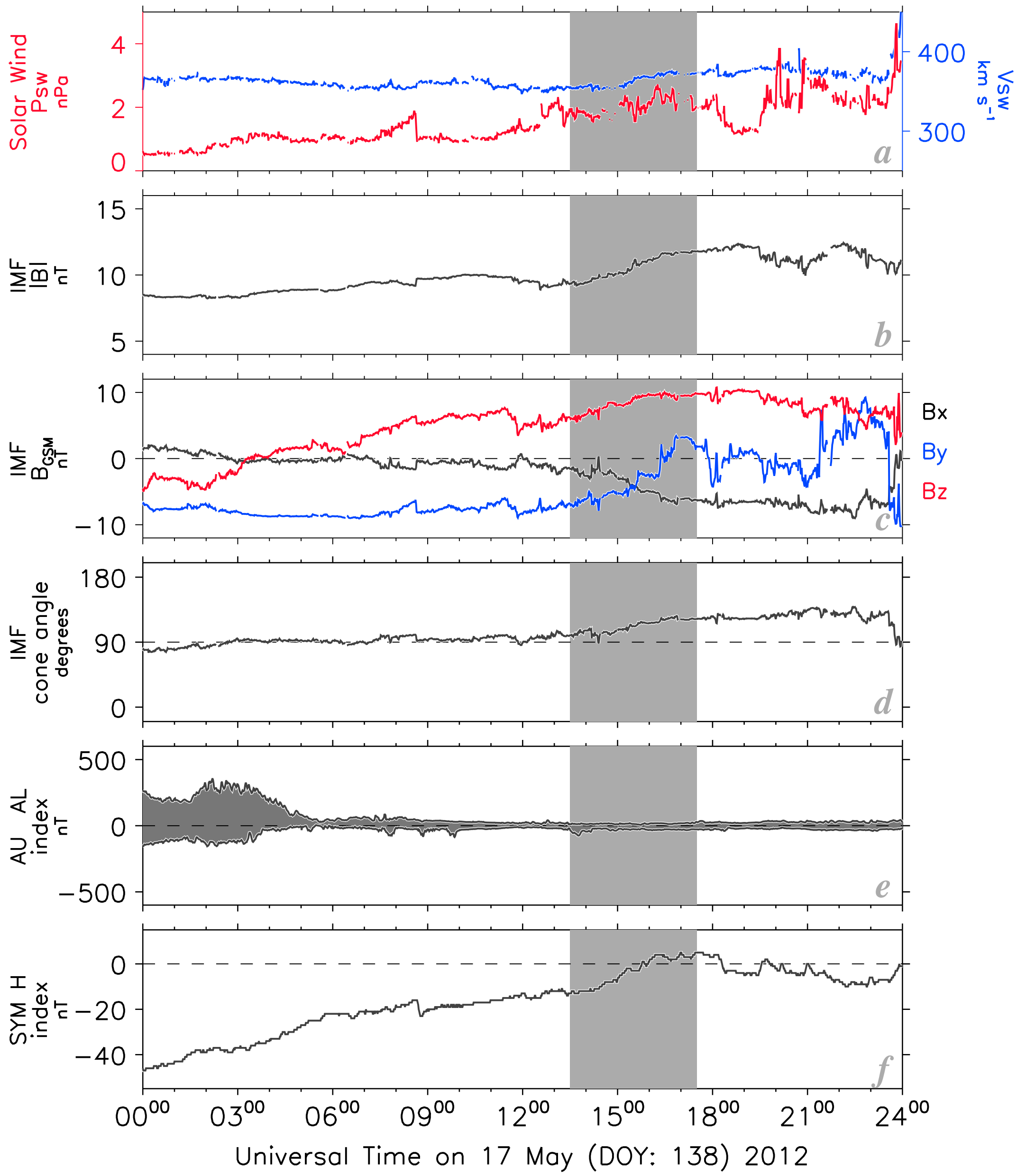

Figure 2. Solar wind and geomagnetic activity conditions on 17 May 2012. (a) Solar wind dynamic pressure (red) and velocity (blue). (b) The magnitude of the IMF. (c) Three components (B_x, B_y, and B_z) of the IMF. (d) The IMF cone angle ($\theta_{xB} = \mathrm{ACOS}(B_x / |B|)$). (e) AU and AL indices. (f) SYM-H index. The gray shading area is the daytime interval, covering $\pm$2 h of magnetic local noon at SPA.

the SYM-H index that the magnetosphere was in the recovery phase of a moderate storm which began on 16 May 2012. The recovery phase was about to end around the daytime period on 17 May 2012.

Figure 3 displays 1 day summary plots of optical and magnetic field observations at SPA on 17 May 2012. The orange and blue vertical lines indicate the magnetic local noon (15:30 UT) and midnight (03:30 UT), respectively. Figure 3a illustrates a wavelet power spectrum of the optical intensity time series at the zenith, extracted from the ASC image data. The spectrogram indicates strong Pc3-range enhancements in optical wave power within approximately $\pm$2 h either side of magnetic local noon.

Figures 3b and 3c show a 557.7 nm (630.0 nm) keogram derived from the magnetic north to south cross section of the ASI image data. Figure 3d shows the intensity ratios between red-line ($I_{630.0}$) and green-line

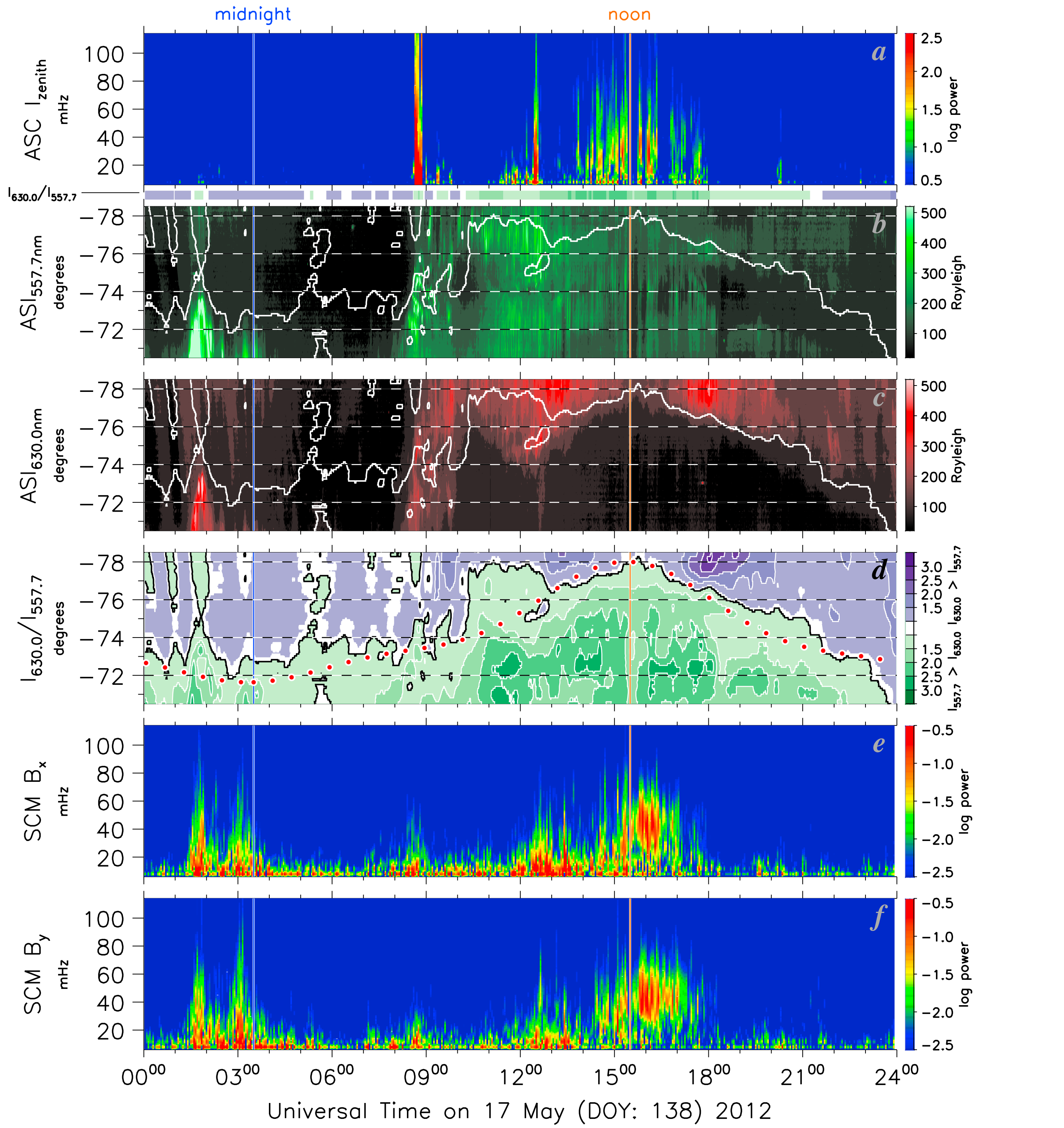

Figure 3. 1 day summary plots of multi-instrument observations from SPA on 17 May 2012. (a) Dynamic spectrum of panchromatic ASC auroral intensity at the zenith. (b and c) Keograms of the ASI 557.7 nm and 630.0 nm emissions. (d) Optical intensity ratio. (e and f) Dynamic spectra of the B_x and B_y components of the search coil magnetometer. Overplotted on Figures 3b–3d is $I_{630.0}/I_{557.7} = 1$, outlined with white (black) contours in Figures 3b–3d. Superimposed only on Figure 3d is the poleward edge of the Feldstein's auroral oval (red dots) for $Q = 1$ (see Figure 1a).

($I_{557.7}$) emissions in the same format as the keogram. The optical intensity ratios, coded by purple ($I_{630.0} > I_{557.7}$) and green ($I_{557.7} > I_{630.0}$), are an indicator of the hardness of precipitating electrons (i.e., higher or lower energy than 1 keV) or of the magnetospheric origins (i.e., open field lines or not). For instance, the green (purple)-coded region is speculated to be dominated by the precipitation of hard (soft) electrons, likely originating from the central/boundary plasma sheet (cusp or magnetosheath). Overplotted on Figures 3b–3d is the $I_{630.0}/I_{557.7} = 1$ boundary, outlined with white (black) contour in Figures 3b–3d. For comparison, the poleward edge of the Feldstein's auroral oval (red dots) for $Q = 1$ (see Figure 1a) is overplotted only in Figure 3d. It is found from Figure 3d that the diurnal variation of $I_{630.0}/I_{557.7} = 1$ on 17 May 2012 roughly follows the poleward edge of the Feldstein's auroral oval, in particular with a better agreement for the daytime interval. Thus, this indicates that at least the daytime $I_{630.0}/I_{557.7} = 1$ boundary can serve as a reliable proxy of the dayside polar cap boundary and open/closed field line boundary [e.g., *Lorentzen et al*., 1996; *Johnsen and Lorentzen*, 2012].

In Figure 3b some sequence of green-line auroral pulsations was identified as periodic vertical stripes for the daytime hours. The active auroral pulsations occurred in the green-dominated auroral region lying between −72° and −76°, a few degrees equatorward of the $I_{630.0}/I_{557.7} = 1$ boundary. This provides optical evidence that the daytime Pc3 auroral pulsations were produced by the precipitation of hard electrons within a closed field line region well inside the dayside magnetopause.

Figures 3e and 3f present the wavelet power spectra of the B_x and B_y components of the colocated search coil magnetometer, respectively. Both dynamic spectra reveal that strong Pc3 magnetic pulsations were active during the interval when the Pc3 auroral pulsations were active at the SPA zenith near magnetic noon. Most of the power in the daytime Pc3 magnetic and auroral pulsations appeared to share a common frequency band. These common features, as seen in the optical and magnetic field power spectra, suggest that the daytime Pc3 auroral and magnetic pulsations are intimately related to each other.

Figure 4 shows representative examples of the daytime Pc3 activity in order to take a closer look at the correspondence relationship between the auroral and magnetic pulsations. Here we selected two 10 min intervals during which the auroral pulsations were relatively active: one is the prenoon interval of 14:25–14:35 UT (Figure 4, left column), and the other is the postnoon interval of 16:00–16:10 UT (Figure 4, right column). Figure 4a shows the ASC keogram, and Figure 4b shows 22–100 mHz band-pass-filtered time series of the optical intensity at zenith and of the magnetic B_x and B_y components. Figures 4c–4e display the wavelet dynamic power spectra for optical intensity at zenith, B_x, and B_y, together with white contours of greater than 90% confidence level which outlines regions of the wavelet transform which enclose intensities above 90% of the time series data [cf. *Torrence and Compo*, 1998].

Daytime auroral pulsations are identified as a sequence of stripes in the keogram and of corresponding successive peaks in the optical intensity time series. The intense Pc3-range auroral pulsation activity as selected with 90% confidence level is noticeable for the following three periods: (i) 14:26:30–14:28:30 UT, (ii) 14:30:00–14:32:00 UT, and (iii) 16:03:30–16:06:30 UT. During periods (i) and (iii) the Pc3 auroral pulsations had three or more regular oscillation cycles. The corresponding Pc3 magnetic pulsations with $>$90% confidence level were observed in B_y during period (i) and in B_x during period (iii). Unlike periods (i) and (iii), the Pc3 auroral pulsations during period (ii) were more irregular waveforms and not accompanied by the corresponding Pc3 magnetic pulsations.

It is interesting to note that the daytime auroral and magnetic pulsations had a poor relationship for 16:00–16:03 UT; whereas intense Pc3 activity with a monochromatic frequency of 30–60 mHz was observed in both B_x and B_y, no corresponding auroral pulsations were seen. This implies that ground magnetic pulsations are not a necessary or sufficient factor for the generation of daytime auroral pulsations. One possible reason for such a poor correlation is that the magnetospheric Pc3 waves do not act as a direct driver for precipitating keV electrons responsible for auroral pulsations. Another possible explanation is due to differing fields of view of the instruments used to detect the auroral and magnetic pulsations. Whereas the ground-based magnetometer observes the magnetic pulsations as the integrated effect of ionospheric electric currents in a wide field of view, the auroral luminosity extracted only from a particular pixel (in this instance, the magnetic zenith) of the ASC would respond to the precipitation of keV electrons in a localized area. It is thus quite possible that the Pc3 waves affected electron flux modulations on field lines beyond the zenith. If this is the case, then the location of high correlation is expected to be somewhere at off zenith.

Hereafter our main focus of the optical data analysis is only on periods (i) and (iii), where clear daytime Pc3 auroral pulsations were observed with the corresponding ground magnetic field variations (correlation coefficients $>$ 0.8 and time shifts $\leq$ 1 s); thus, the conclusions are only relevant to these selected portions of daytime Pc3 auroral pulsations observed on 17 May 2012.

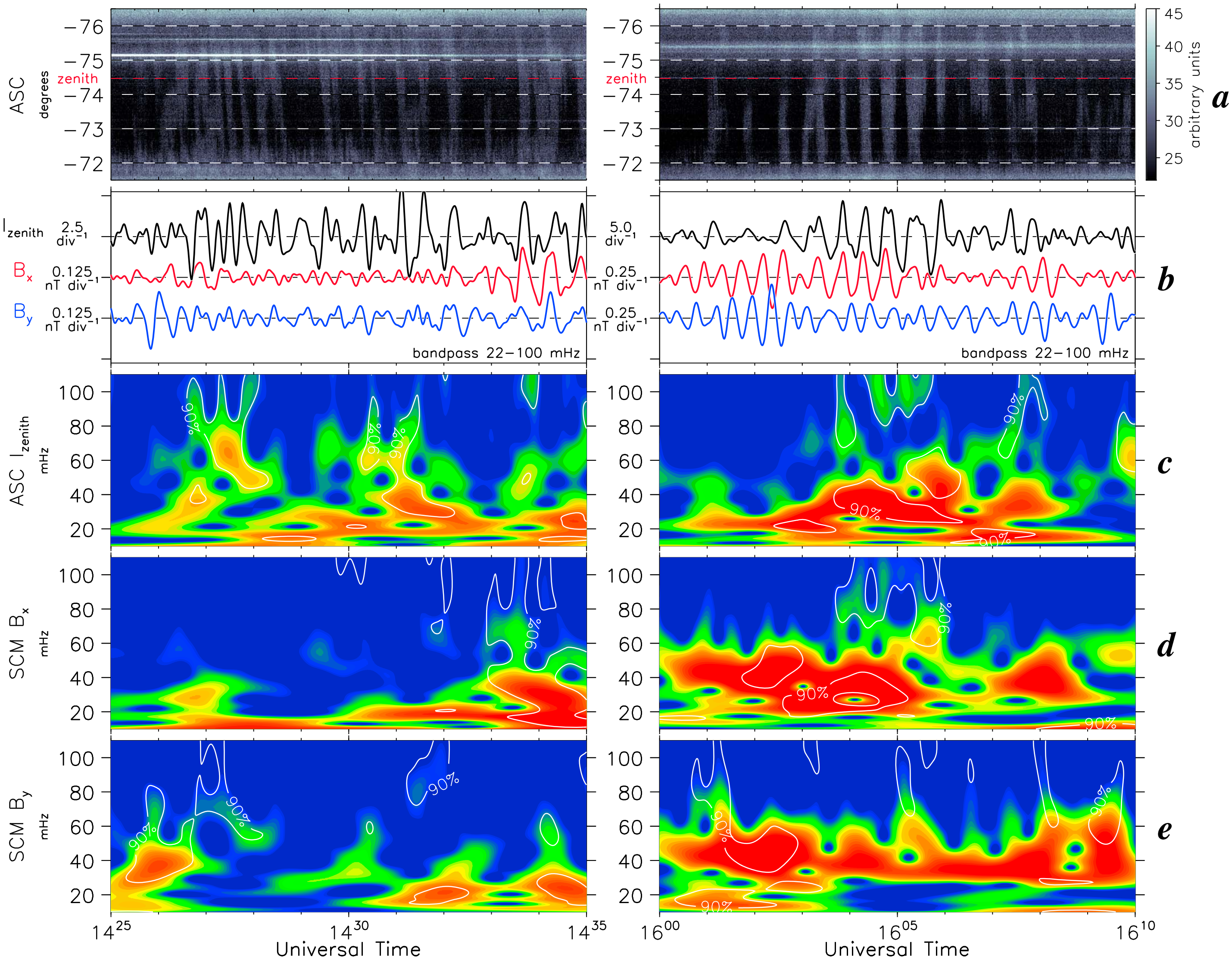

Figure 4. Comparisons between daytime auroral and magnetic pulsations observed for 14:25–14:35 UT (left) and 16:00–16:10 UT (right). (a) Keogram from the ASC images. (b) Band-pass-filtered time series of optical intensity at the zenith (black), B_x (red), and B_y (blue). (c–e) Wavelet spectra. The white contour superimposed on each of the dynamic power spectra encloses regions of greater than 90% confidence level.

Figure 5a shows the same keogram as Figure 4a but zoomed in at 14:27–14:28 UT of period (i). In this keogram the Pc3 auroral pulsations are characterized as a regular pattern of stripes of higher and lower luminosity between −72° and −76°. It is also found that the auroral stripes well coincided with the B_y oscillations in Figure 5b. Each auroral stripe has a negative slope (i.e., |MLAT| of the bright region decreases with time) as a result of the equatorward propagation nature of an auroral structure. The equatorward propagation speed was estimated to be in the range of 20–25 km s^{-1} based on the negative slope. To confirm what caused the auroral stripes in Figure 5a, Figures 5c–5j display sequential two-dimensional (2-D) images from 14:27:24.24 to 14:27:38.22 UT surrounding the middle of the time range of Figure 5a. The images at 2 s intervals were converted to a geographical coordinate system with an assumed emission altitude of 110 km and rotated to a local magnetic coordinate system; the top and right of each image are the geomagnetic poleward and eastward directions, respectively. The image sequence revealed the presence of an equatorward propagating, diffuse auroral patch with a horizontal scale of about 100 km, as traced by red arrows. It is interesting to note that no on-off changes with the Pc3 periodicity were seen in the auroral patch luminosity, although an ~3 Hz or faster modulation—undetectable in the ASC data that were used in this study—might be embedded. Thus, the repeated formation and rapid equatorward propagation of such diffuse

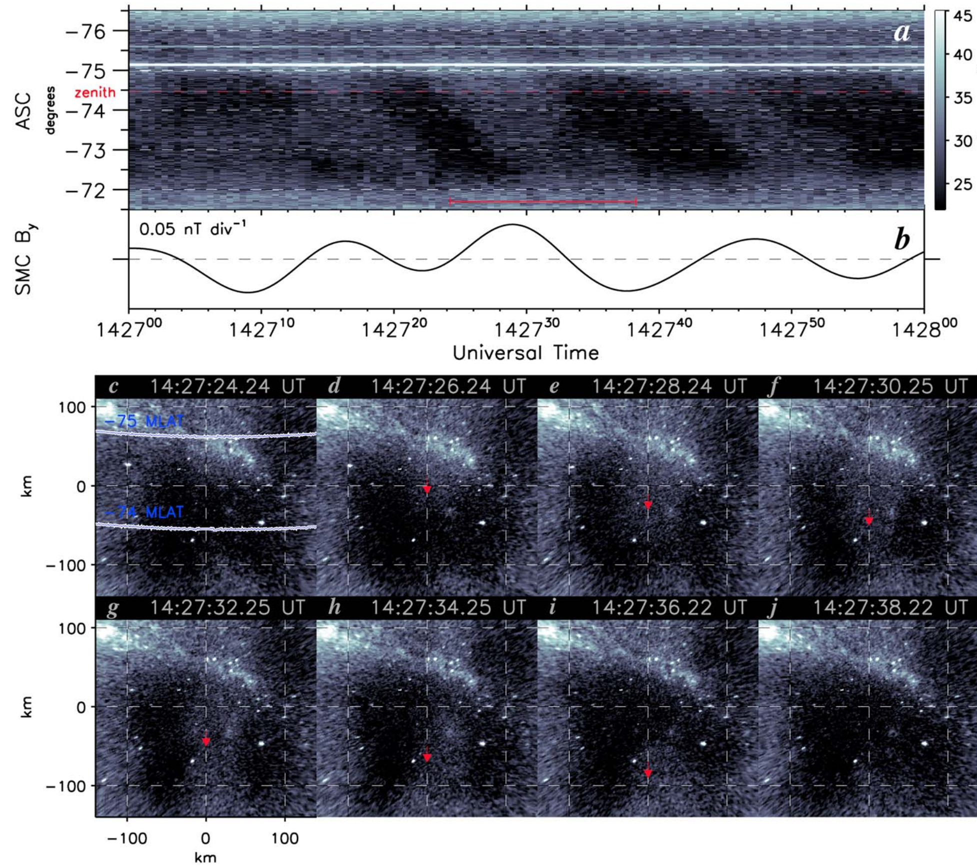

Figure 5. (a) Zoomed-in keogram at 14:27–14:28 UT. (b) 22–100 mHz band-pass-filtered time series of B_y. (c–j) Sequence of projected auroral images every 2 s for characterizing the 2-D structure and motion of a diffuse patch from 14:27:24.24 UT to 14:27:38.22 UT. The top and right of each image are magnetic poleward and eastward directions, respectively. Red arrows are for guiding our eye to see the temporal evolution of the patch, i.e., throughout the time interval the localized patch is appearing around zenith, moving equatorward, and eventually merging with its surrounding diffuse aurora. Brighter and tilted emission structure just poleward of zenith is the Milky Way.

auroral patches over the SPA zenith result in the daytime Pc3 auroral pulsations at a given point around the zenith, as seen in the keogram and optical intensity time series for period (i). A more detailed sequence of the fast-moving auroral patches for 14:27–14:28 UT can be seen in Movie S1 in the supporting information.

Similar to the prenoon case, a clear correspondence can be seen for the postnoon Pc3 auroral and magnetic pulsations in Figures 6a and 6b, showing the keogram and magnetogram, respectively, for 16:04–16:05 UT of period (iii). Figures 6c–6j show the sequential 2-D images at 1 s interval from 16:04:36.18 to 16:04:43.19 UT. Consistent with the prenoon auroral pulsations, the postnoon auroral pulsations are also found to result from repeated equatorward motion of diffuse auroral patches through the zenith (see Movie S2 for more details), although there are minor differences in the periodicity, propagation speed, and spatial scale of the patches. It is interesting to note that for only the postnoon case the surrounding background diffuse aurora dynamically changed in concert with the repeated equatorward motion of the patches.

Whereas the auroral pulsations at the magnetic zenith for both periods (i) and (iii) were strongly correlated with the magnetic pulsations with no significant time lag, it may be worthwhile to note that the area of high correlation was also found at off zenith allowing for a time shift of a few seconds up to several seconds (see Figures S1 and S2 in the supporting information).

In order to estimate the drift velocities of the equatorward-propagating diffuse auroral patches in a more quantitative way, a minimum mean square error (MMSE) analysis was applied to the 2-D auroral image data. This is the same method as that already used in *Ebihara et al.* [2007]. Figure 7a shows a representative example of the calculated drift velocities superimposed on the image at 14:27:27.24 UT (corresponding to

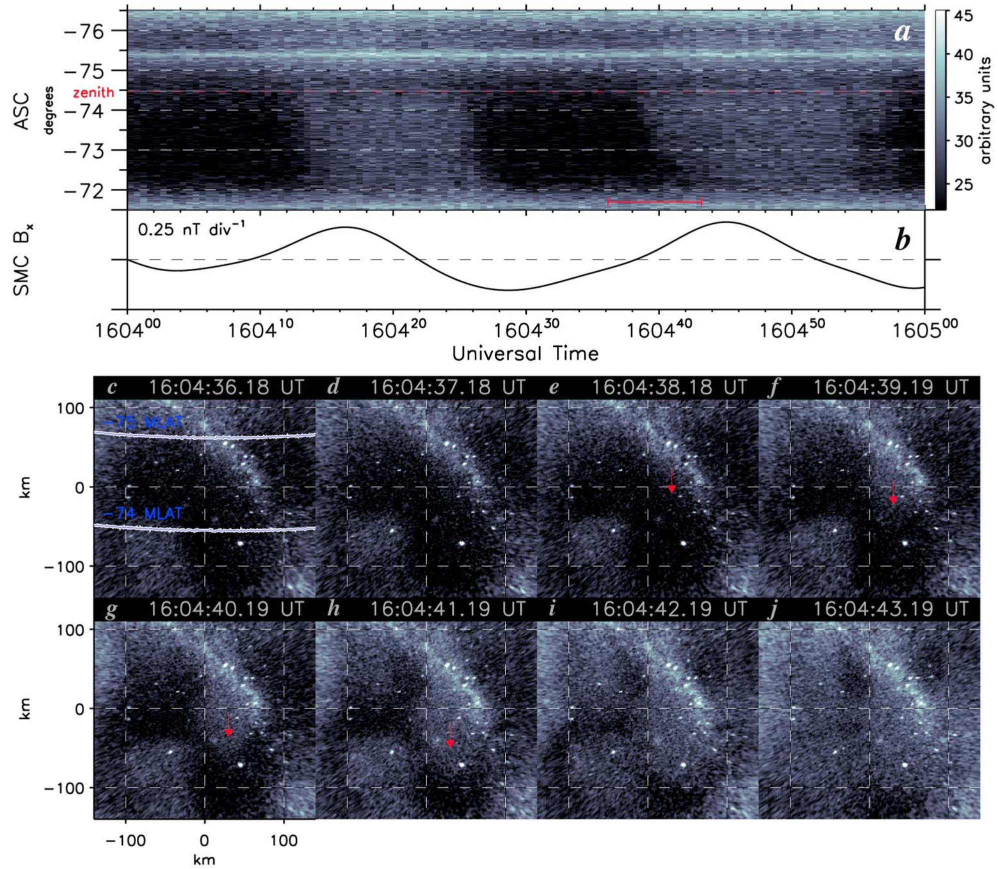

Figure 6. The same format as Figure 5, although for postnoon auroral pulsations for 16:04–16:05 UT of period (iii).

a time between Figures 5d and 5e) for period (i). Figure 7b illustrates a contour plot of the 2-D auroral patch structures, outlined with gray contours at 14:27:26.24 UT and with red contours at 14:27:27.24 UT, respectively. The drift velocities were calculated from two images at 14:27:26.24 and 14:27:27.24 UT with the MMSE analysis. The scanning area and the kernel area for the MMSE [see *Ebihara et al.*, 2007, Figure 3] were

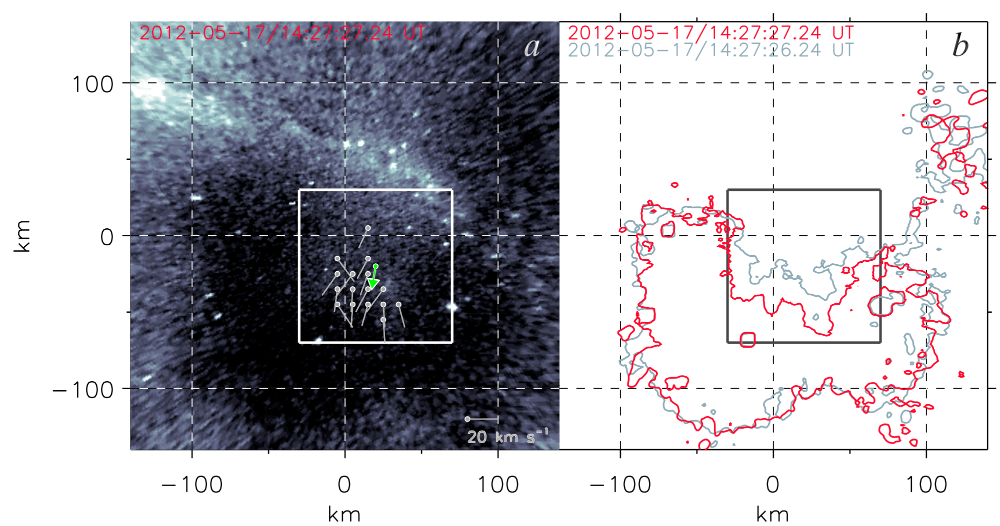

Figure 7. (a) An example of optical flow analysis at 14:27:27.24 UT, performed on the square area in which a diffuse auroral patch mainly moved equatorward. The average flow velocity is shown by a green arrow. (b) 2-D auroral patch structures, outlined with gray contours at 14:27:26.24 UT and with red contours at 14:27:27.24 UT, respectively.

set to 100 km × 100 km (marked by a white square) and 10 km × 10 km, respectively. The calculated equatorward drift velocities around the leading edge of the patch are ~20 km s^{-1}, consistent with those deduced from the auroral stripes in Figure 5a. The average velocity (green arrow) appears to be ~15 km s^{-1}.

3. Discussion and Conclusion

We have examined simultaneous optical and magnetic field data from SPA in order to investigate the spatiotemporal characteristics of Pc3 auroral pulsation activity observed near magnetic local noon on 17 May 2012. We found that the daytime Pc3 auroral pulsation activity, characterized as periodic oscillations of faint diffuse auroral luminosity when viewing a time series at a fixed point, occurred in a closed field line region ($I_{557.7} >> I_{630.0}$) a few degrees equatorward of the dayside polar cap boundary. This suggests that the daytime Pc3 auroral pulsations are caused by the diffuse precipitation of keV electrons, probably originating from the central plasma sheet extended to the dayside outer magnetosphere.

It has widely been accepted that the diffuse precipitation of keV electrons is caused by pitch angle scattering due to plasma waves. Upper band chorus and electrostatic electron cyclotron harmonic (ECH) waves effectively precipitate lower energy electrons (below a few keV), while lower band chorus waves are important for relatively high-energy electrons (more than a few keV). Whereas ECH waves have a high occurrence rate at $L > 5$ on the night-dawn side [*Ni et al.*, 2011], the occurrence rate of chorus waves tends to be strong at $L > 7$ on the dayside (prenoon) [*Li et al.*, 2009]. In particular, dayside chorus is moderately active even during geomagnetically quiet periods (AE < 100 nT). Considering such MLT-*L* occurrence distributions of ECH and chorus waves and their dependences on the level of geomagnetic activity, it could be reasonable to say that chorus waves are a viable candidate contributing to keV electron precipitation responsible for the observed Pc3 auroral pulsations, rather than ECH waves. This suggestion is consistent with results from simultaneous conjugate ground-space observations of dayside diffuse aurora and whistler mode waves [*Nishimura et al.*, 2013; *Ni et al.*, 2014].

Two striking features to be noted have been revealed from the 2-D spatiotemporal behavior of the daytime Pc3 auroral pulsations. First, the auroral pulsations are the result of repeated development of faint, nonpulsating diffuse auroral patches. Second, the individual patches propagate equatorward with speeds of 15 km s^{-1} up to 20–25 km s^{-1} one after another. In addition, it should be stressed that the daytime Pc3 auroral pulsations occurred in a prolonged nonsubstorm interval during which |AL| < 50 nT. The abovementioned features differ significantly from the well-known features of PsA observed frequently in the postmidnight to morning sector: they result from periodic luminosity on-off changes in a particular auroral patch; the PsA patch drifts in accordance with the convection electric field in the magnetosphere [e.g., *Nakamura and Oguti*, 1987; *Yang et al.*, 2015]; and they occur in association with substorm processes (preferentially in the aftermath of a substorm). These differences suggest that this particular daytime Pc3 auroral pulsation event has a different source and generation mechanism.

The simplest scenario to explain our observations could be that the observed daytime auroral pulsations (patches) may be caused by a combination of compressional Pc3 waves, keV electrons of a magnetospheric origin, and chorus waves in the dayside outer magnetosphere. In that case, compressional Pc3 waves are suggested to act as a primary driver in modulating the growth rate of ambient whistler mode chorus waves that scatter and precipitate keV electrons. This scenario is based on the theory of *Coroniti and Kennel* [1970], who proposed that the compressional component of ULF waves leads to the modulation of a pre-existing chorus source in the magnetosphere. In light of individual extensive ground-based and space-based observations of compressional mode Pc3 and whistler mode chorus waves that are often active in the dayside outer magnetosphere ($L > 7$) [e.g., *Cao et al.*, 1994; *Li et al.*, 2009; *Spasojevic and Inan*, 2010; *Agapitov et al.*, 2010], it is highly likely that both waves are simultaneously responsible for the generation of daytime Pc3 auroral pulsations.

Dynamical features of the observed auroral patches would also provide supporting evidence for the presence of compressional Pc3 waves. In fact, the auroral patches propagate equatorward with speeds of 15 km s^{-1} up to 20–25 km s^{-1}, exceeding the typical convection speed substantially. Mapping of this ionospheric structure to the magnetospheric equatorial plane along the T96 model field lines says that the projected patches would have an extent of ~0.5 R_E at a radial distance of ~10–11 R_E inside the dayside magnetopause and move radially earthward. The radial propagation speed is estimated to be about 350–600 km s^{-1}. This speed is about half the propagation speed (~1100 km s^{-1}) of a compressional Pc3 wave estimated from the Geotail observation in the dayside outer magnetosphere [*Takahashi et al.*, 1994] but on the order of the speed expected from the empirical model of *Moore et al.* [1987]. Thus, we suggest that the fast-moving diffuse auroral patches are a 2-D visual manifestation of compressional Pc3 waves, being launched and propagating earthward in the dayside outer magnetosphere.

Upstream waves, as excited in the ion foreshock region, are believed to be the primary source energy of compressional Pc3 waves in the dayside magnetosphere [*Troitskaya et al.*, 1971; *Chi et al.*, 1994]. Specifically, a low IMF cone angle is suggested to be a preferable condition for upstream wave generation and its penetration into the dayside magnetosphere. Contrary to this expectation, during this particular event the IMF cone angle θ_{xB}, i.e., the angle between the IMF direction and the Sun-Earth line, was on average 90° or larger (see Figure 2d). Such a large IMF cone angle agrees with the statistical result of *Vorbjev et al.* [1999], who demonstrated that the occurrence rate of daytime auroral pulsations is much higher for IMF $\theta_{xB} > 30°$ than IMF $\theta_{xB} < 30°$ (the occurrence rate peaks at θ_{xB} ~60–70°). Additionally, it is important to note that the observed Pc3 frequency, which generally ranges in 30–60 mHz, is lower than the expected dominant frequency (~60–66 mHz) of upstream waves, depending on the magnitude of the IMF according to the empirical relation, f (mHz) ~6 × IMF $|B|$ (nT) [*Gul'elmi*, 1974]. Similar IMF variations were also recorded by the ARTEMIS and Cluster spacecraft that were closer to the Earth (not shown). As for the mismatch between the cone angle and magnitude of the IMF and the occurrence and frequency of the Pc3 waves, there are at least two possibilities. One is that IMF-related upstream waves were not the source of the observed Pc3 oscillations. The other, as discussed in *Bier et al.* [2014], is that upstream waves were the source, but the available upstream monitors did not accurately represent the IMF conditions that actually impacted Earth during this event because they were located in the negative y coordinate in GSM.

Buffeting of the magnetopause by solar wind dynamic pressure (density) fluctuations, on the other hand, could be an alternative driver of dayside compressional Pc3 waves [e.g., *Heilig et al.*, 2010]. As seen in Figure 2a, the solar wind dynamic pressure gradually increased at ~12:00 UT from ~1.0 to ~2.0 nPa (corresponding to the density increase from ~4.0 to ~8.0 cm^{-3}) and then remained at a high level of ~2.0 nPa until ~19:00 UT. This may imply that compression of the dayside magnetosphere under such a higher solar wind dynamic pressure causes an increase of the daytime Pc3 activity. However, no corresponding Pc3 oscillation component in the solar wind dynamic pressure was found in high-resolution ARTEMIS and Cluster data, as well as coarse resolution OMNI data. Of course, we cannot deny the possibility that the ARTEMIS and Cluster spacecraft missed such a Pc3-range dynamic pressure oscillation in the solar wind.

Although we have interpreted the observed daytime auroral pulsations in terms of compressional Pc3 pulsations and their related processes, we cannot completely rule out other potential mechanisms without ULF waves for the generation of daytime auroral pulsations. For example, if an external Pc3 source (produced either in the solar wind/magnetosheath or at the magnetopause/boundary layer) causes magnetosheath-origin low-energy electrons to penetrate into the dayside outer magnetospheric plasma sheet along an azimuthally narrow channel (corresponding to the auroral patch size), then they may be a possible candidate for the source population that leads to the density fluctuations in the magnetosphere and related modulations of whistler-mode intensities. Such modulations would potentially cause the precipitation of the ambient energetic electrons responsible for daytime diffuse auroral patches as presented here. If this were the case, then the observed ground Pc3 magnetic pulsations may be generated in the ionosphere as a result of auroral precipitation, perhaps in a manner similar to that proposed by *Oguti et al.* [1984] as applied to PsA-related irregular magnetic pulsations which occur in the midnight-to-dawn auroral zone.

This case study has presented a new aspect of daytime Pc3 auroral pulsations apparently arising from the 2-D optical signature at ~2 Hz sampling. The 2-D morphological signatures, that is, fast-moving auroral patches, appear to be a visible manifestation of compressional Pc3 waves in the dayside outer magnetosphere. However, we cannot conclude whether the 2-D optical signature as identified in this study is rarely or commonly seen for daytime auroral pulsations because this is the only event. A statistical approach with more data is needed to obtain a more complete and reliable picture of the daytime auroral pulsations and to address a missing piece of the physical link between daytime Pc3/chorus waves and auroral pulsations.

Also, lack of in situ data in the outer magnetosphere has left our interpretation somewhat speculative. More comprehensive analysis in collaboration with simultaneous in situ observations, such as the THEMIS and Magnetospheric Multiscale (MMS) spacecraft of which the orbits often traverse the dayside outer magnetosphere, is also needed for determining the generation mechanism.

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