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Special Section:

Geospace multi-point observations in Van Allen Probes and Arase era

Key Points:

- Over-darkening of pulsating aurora (PsA) was observed during an interval of conjugate observation with the Arase satellite
- Corresponding over-decreasing of chorus wave intensity was not seen in the wave data from Arase
- Over-darkening is caused by a passage of dark region on the trailing edge of the PsA patch across the sensing area

Supporting Information:

Supporting Information may be found in the online version of this article.

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Over-Darkening of Pulsating Aurora

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Abstract Recent analyses of high-time resolution ground-based optical observations of pulsating aurora (PsA) have reported that the brightness of PsA sometimes decreases below the diffuse background level immediately after the ON phase of the main pulsation finishes. To date, however, the generation mechanism of such an “over-darkening PsA” is still unclarified. In this study, we investigated the characteristics of the over-darkening PsA by using simultaneous observations of PsA with an electron multiplying charge coupled device all-sky camera in Sodankylä, Finland and the Arase satellite. During one of the conjunction events in Scandinavia on March 29, 2017, almost all the PsA pulses showed clear over-darkening characteristics. By analyzing the 2D all-sky images at the times of over-darkening we discovered that over-darkening areas appeared in the trailing edge of PsA patches and moved in tandem with the poleward propagating patches. It was also found that similar over-decreasing characteristics were not seen in the chorus data from the wave instruments onboard Arase located at the magnetospheric counterpart of PsA. These results indicate that the over-darkening PsA is not caused by a temporal variation of chorus at a fixed point, but is produced by a propagation of over-darkening area with PsA patches. That is, the over-darkening PsA is a result of compounding effects of spatial structure and recurrent propagation of PsA. The mechanism creating the dark area is still unknown, but the existence of over-darkening PsA suggests that the temporal variation of PsA is not always a perfect copy of the modulation of lower-band chorus waves in the magnetosphere.

Plain Language Summary Pulsating auroras (PsAs) are characterized by quasi-periodic variations in the brightness whose period typically ranges from a few to a few tens of second. Coordinated ground/satellite observations in the last decade demonstrated that the main optical pulsation well correlates with the intensity modulation of electromagnetic wave called “chorus” in the magnetosphere. Recent optical observations of PsA using high-speed cameras have reported that the brightness of PsA often decreases below the diffuse background level immediately after the ON phase of the optical pulsation. In this study, we investigate the characteristics of such “over-darkening PsAs” by using simultaneous observations of PsA with an all-sky camera in Finland and the magnetospheric satellite Arase. By analyzing the 2D all-sky images of over-darkening PsA on March 29, 2017, we discovered that over-darkening areas appeared in the trailing edge of PsA patches and moved in tandem with the poleward propagating patches. Similar over-decreasing characteristics were not identified in the chorus data from Arase located at the magnetospheric counterpart of PsA. These results indicate that the over-darkening PsA is not a pure temporal variation of chorus at a fixed point, but a result of compounding effects of spatial structure and dynamical motion of PsA.

1. Introduction

Pulsating aurora (PsA) is one of the major types of aurora often seen at the equatorward part of the auroral region in the morning side. For the details of PsA, the readers may be interested in reading recent reviews by Hosokawa et al. (2015), Lessard (2012), and Nishimura et al. (2020). PsA is characterized by consecutive ON and OFF phases whose repetition period ranges from a few to a few tens of seconds (e.g., Yamamoto, 1988).

This primary beat of PsA has been termed as “main pulsation.” The main pulsation is sometimes a sinusoidal function showing relatively regular periodicity, but in most cases, its time-series behave more like a train of quasi-periodic peaks in the optical intensity (Røyrvik & Davis, 1977). It has also been known that much quicker luminosity fluctuations, whose repetition frequency is ~ 3 Hz, are embedded within the time-series of PsA during the ON phase of the main pulsation (e.g., Nishiyama et al., 2014). Such sub-second variations have been called “internal modulation” or “quasi 3 Hz modulation.” The mixture of these two distinct periodicity ranges compose the entire time-series of the luminosity variation of PsA (Hosokawa, Miyoshi, et al., 2020; Miyoshi, Saito, et al., 2015).

The luminosity variation of PsA has been considered as a consequence of periodic precipitation of energetic magnetospheric electrons scattered through the wave-particle interaction process (i.e., cyclotron resonance). In particular, as reviewed by Li et al. (2012), people believe that the whistler mode chorus waves, especially the LBC waves, occurring near the equatorial plane of the magnetosphere play a primary role in such resonance scattering process (e.g., Miyoshi et al., 2010; Miyoshi, Oyama, et al., 2015; Miyoshi, Saito, et al., 2015; Nishimura et al., 2010, 2011, 2018). Chorus waves are typically composed of two frequency bands: a LBC and upper-band chorus (UBC). These two frequency bands are divided by a gap at a half the gyro-frequency (Tsurutani & Smith, 1974). That is, the frequency of LBC (UBC) is less than (above) the half gyro-frequency. Recently, S. Kasahara et al. (2018) demonstrated, by using data from the Arase satellite (Miyoshi, Shinohara, et al., 2018), that the energetic electrons were intermittently scattered into the loss cone by the LBC waves during an interval of PsA. Later, Hosokawa, Miyoshi, et al. (2020) employed the wave data from Arase to show the complete one-to-one correspondence between the temporal variations of PsA and LBC. In particular, they identified two sets of good correspondence: (1) Between the main pulsation and chorus bursts, and (2) between the internal modulation and chorus elements, as predicted by Miyoshi, Saito, et al. (2015). These results made us believe that the temporal variation of magnetospheric chorus waves perfectly controls the periodic variation of PsA.

One of the non-trivial characteristics of the temporal variation of PsA is that, even during the OFF phase, the optical intensity generally does not decrease down to the complete dark level (e.g., Røyrvik & Davis, 1977). The existence of such a “diffuse background level” is consistent with past in-situ particle measurements showing weak drizzle precipitations of electrons at less than a few keV during the OFF phase of PsA (e.g., Evans et al., 1987; Sandahl et al., 1980; Yau et al., 1981). Miyoshi, Saito, et al. (2015) have explained the existence of the diffuse background by the stable precipitation of relatively lower-energy electrons (< 1 keV) by the UBC waves. The contribution of electron cyclotron harmonic (ECH) waves (e.g., Liang et al., 2010) can also be responsible for the diffuse background of PsA. However, the source of the drizzle electron precipitation (Miyoshi, Saito, et al., 2015) during the OFF phase is still controversial.

Recent ground-based optical observations with high-speed cameras demonstrated that the optical intensity sometimes decreases well below the diffuse background level in a limited time interval during the OFF phase. The most recent observations were made by Dahlgren et al. (2017) who showed, by using a narrow field-of-view (FOV) EMCCD (electron multiplying charge coupled device) camera, that the brightness reduces below the background diffuse level immediately after the end of ON phase (i.e., very beginning of the OFF phase). Dahlgren et al. (2017) also indicated that such an over-reduction of luminosity can also happen immediately before the start of the ON phase. Similar observations of such “over-darkening PsAs” were previously reported by Kataoka et al. (2012), who employed a high-speed camera with a narrow FOV that can take 500 frames per second. Figure 1 of Kataoka et al. (2012), which is a keogram along the east-west cross section of the narrow FOV of the camera, clearly demonstrated that the over-darkening took place immediately after the end of one single ON phase and continued for ~ 1 s.

As documented above, the temporal variation of the over-darkening signature of PsA has been investigated by a few recent studies. However, the optical instruments used in those studies (Dahlgren et al., 2017; Kataoka et al., 2012) are narrow FOV high-speed cameras observing a limited area near the magnetic zenith. This has not allowed them to visualize the two-dimensional (2D) evolution of the over-darkening feature of PsA. Thus, it has still been unclarified whether the over-darkening signature is purely a temporal variation or not. In addition, simultaneous satellite observations of chorus wave at the conjugate area in the magnetosphere have not been examined in the past studies of over-darkening PsA. Thus, the link between the over-darkening feature and the nature of the chorus waves is not yet understood.

Figure 1. Overview of an interval of PsA on March 29, 2017. (a) Keogram of all-sky camera data from Sodankylä, Finland during a 20 min interval from 00:00 to 00:20 UT. The raw count data along the south to north cross-section including the magnetic footprint of Arase are displayed. The horizontal green line marks the footprint of Arase on the cross-section. (b) 256 × 256 all-sky image at 00:04:18 UT. The two green circles respectively show the magnetic footprints of Arase at 00:00 and 00:20 UT calculated by the T04 model. The vertical green line gives the south to north cross-section used when making the keogram in (a). (c) Same optical data as b but mapped onto the geographic coordinate system by assuming the emission altitude of 110 km. PsA, pulsating aurora.

To overcome these limitations, we have employed optical data from an EMCCD all-sky imager (ASI) in Sodankylä, Finland obtained during the first coordinated observations of PsA with the Arase satellite which was conducted in March 2017. During a 20 min interval in the beginning of March 29, 2017, we captured successive appearances of PsA where many of the pulses clearly showed the over-darkening signature immediately after the ON phase of the main pulsation. In this study, we track the 2D spatial structure of the over-darkening signature by utilizing the FOV of the EMCCD ASI covering the entire spatial structure of PsA patches. At the same time, the wave data from Arase are used to investigate the origin of the over-darkening characteristics of PsA.

2. Observations

On March 29, 2017, we obtained an interval of conjugate observation of PsA with the Arase satellite (Miyoshi, Shinohara, et al., 2018) and a ground-based ASI in Sodankylä, Finland (Hosokawa, Oyama, et al., 2020). The ASI in Sodankylä was located at around 03 MLT during the interval of interest. This event was already studied by Hosokawa, Miyoshi, et al. (2020) for evaluating the chorus-PsA relationship. The ASI is equipped with a glass filter RG665 which enables us to observe prompt emissions only (i.e., the contribution of slower emissions like 557.7 and 630.0 nm were cut). The images were saved as 256 × 256 pixel images with a raw temporal resolution of 100 Hz. Detailed description of this 100 Hz ASI system is given in Hosokawa, Oyama, et al. (2020). In particular, Figure 2 of Hosokawa, Oyama, et al. (2020) shows the transmission characteristics of the RG665 filter which cuts the contributions from 557.7 and 630.0 nm emissions and is

Figure 2. (a) South to north keogram during a 5 min interval from 00:07 to 00:12 UT on March 29, 2017. The cross-section again includes the footprint of Arase whose position in the vertical Y axis in the all-sky image is marked by the horizontal green line. (b) Electric field wave data from PWE/OFA onboard Arase in a format of frequency-time diagram. 0.5 and 0.1 f_{ce} (gyro frequency) are indicated by the horizontal white lines. (c) Time-series of optical intensity at the footprint of Arase (red) and integrated lower band chorus (LBC) intensity (blue). (d) Zoom-in view of the two time-series in a 1 min interval from 00:09 to 00:10 UT. The optical intensity decreases below the diffuse background level indicated by the horizontal gray line. (e) Zoomed-in keogram showing the appearance of over-darkening signature immediately after the ON pulses of PsA. PsA, pulsating aurora.

sensitive to the so-called N21PG band extending from 650 to 700 nm that is one of the intense prompt auroral emissions. The bottom two panels of Figure 1 show snapshot images of PsA at 00:04:18 UT on March 29, 2017. In Figure 1c, the all-sky image has been mapped onto the geographic coordinate system assuming the emission height of 110 km. We have used a star map to calibrate the FOV of the ASI using the AIDA-toolbox (http://www.alis.irf.se/~bjorn/AIDA_tools/Documentation/). In both the 2D images (all-sky and mapped data), there exist a few distinct regions of PsA. The regions are indicated by the red arrows in Figure 1b.

The two green circles in the images give the magnetic footprints of Arase at 00:00 and 00:20 UT, respectively. These footprints of the satellite were estimated by using the T04 magnetic field model with upstream solar wind conditions (Tsyganenko & Sitnov, 2005). At the time of Figures 1b and 1c, a relatively large patch of PsA was observed close to the footprint of Arase which stayed near the eastern edge of the FOV ($X = 24$ and $Y = 124$ in the 256×256 image). Similar patches of PsA were continuously detected near the footprint during the 20 min interval from 00:00 to 00:20 UT, which is clearly seen in the south to north keogram in Figure 1a. Note that the data shown in this keogram have been smoothed with a running window of 1 s. This keogram has been made from the optical data along the south to north cross-section including the instantaneous footprint of Arase, which is depicted by the vertical green line in Figure 1b (the cut along the line of $X = 24$). The location of the footprint in the vertical Y axis is also indicated in the keogram by the horizontal green line (the line of $Y = 124$). In Figure 1a, there are a number of vertical stripes demonstrating almost continuous activity of PsA near the footprint of Arase.

Figure 2a again shows the same south to north keogram of optical data from Sodankylä, but for a 5 min interval from 00:07 to 00:12 UT (approximately the central part of Figure 1a). The original sampling rate of the EMCCD ASI is 100 Hz, but when making the keogram we smoothed the original data with a moving window of 100 ms duration to improve the signal-to-noise ratio. In this interval, there are more than 20 vertical stripes all of which are manifestations of the main pulses of PsA. Figure 2b shows the observation of LBC in the wave electric field data from the PWE/OFA (Plasma Wave Experiment/Onboard Frequency Analyzer) onboard Arase (Y. Kasahara et al., 2018; Matsuda et al., 2018). Repetitive enhancements of wave intensity are seen in the frequency slightly below 1 kHz, which are signatures of chorus bursts. It is clearly seen that all of the pulses in aurora (Figure 2a) have their counterparts in the chorus data (Figure 2b). Figure 2c plots both the data as time-series, where the auroral brightness at the footprint of Arase (red) and integrated wave intensity in the LBC band (blue) are displayed. This comparison again demonstrates an exact one-to-one correspondence between these two periodic phenomena, which has already been reported by Hosokawa, Miyoshi, et al. (2020).

Near the central period of this interval (00:09 to 00:10 UT, shaded by the gray box in Figure 2c), there are a few unique pulses showing clear signatures of over-darkening. Figures 2d and 2e respectively show zoom-in views of the data as time-series (Figure 2d) and keogram (Figure 2e). In the keogram, it can be seen that a slightly darker area appeared immediately after the end of the ON phase, which is most clearly recognized for the second pulse in this 1 min interval. The zoomed-in time-series data in Figure 2d indicate that the optical intensity (red line) decreased below the background diffuse emission level, which is traced by the horizontal gray line. The important point is that the over-darkening occurred for a short interval (less than a few sec) immediately after the ON phase and the luminosity recovered back to the diffuse background level in the remaining part of the OFF phase. This characteristic shape of the time-series is fairly identical to the over-darkening signature reported by Dahlgren et al. (2017).

First we check if corresponding over-decreasing signature was seen in the chorus data in the magnetosphere. Although the integrated LBC time-series is plotted (blue) in Figure 2d, the temporal resolution of the normal PWE/OFA observation is 1 s; thus, it would be difficult to look for an over-decreasing signature in chorus. To overcome this resolution problem, we made use of the high-time resolution (65 kHz) wave data from PWE/WFC (Plasma Wave Experiment/Waveform Capture) onboard Arase (Matsuda et al., 2018) which were obtained during a limited time interval during the conjunction. Figure 3b displays the optical data at the footprint of Arase during a 1 min interval from 00:09:08 to 00:10:08 UT, when the fine-scale waveform was captured by PWE/WFC. During this interval of burst mode chorus measurement, four complete main pulses of PsA were captured. The time-series of the optical intensity at the footprint of Arase (red line in Figure 3c) shows clear signatures of over-darkening especially for the second pulse. Figure 3a show the burst mode chorus data in which, four complete bursts of chorus were captured. However, the

Figure 3. (a) Frequency-time diagram of electric field wave data from PWE/WFC onboard Arase. Signatures of chorus bursts are indicated by the horizontal white bars. (b) South to north keogram during the same interval. (c) Time-series of the optical intensity (red) and integrated lower-band chorus (LBC) intensity in linear scale.

time-series of the integrated chorus intensity in the LBC frequency range (blue line in Figure 3c) does not show any signature of over-decreasing of the wave intensity. That is, the wave amplitude was almost zero in the entire interval of the OFF phase. Note that, here in Figure 3, we plot the integrated intensity of LBC in a linear scale rather than a logarithmic one. One of the reasons for using different scales (i.e., linear and logarithmic) in Figures 2d and 3c is that the optical intensity is plotted with a linear scale; thus, comparison should also be done by showing the wave data in the same linear scale. This absence of the corresponding over-decreasing in the LBC intensity implies that the over-darkening characteristics of PsA might have been produced by the contribution of other waves or other process. We will discuss such possible processes in detail in the discussion section.

Figure 4. (a) South to north keogram in a 3 min interval from 00:00 to 00:03 UT on March 29, 2017. (b) East to west keogram in the same interval. (c) Zoom-in of the data in (b). (d) Time-series of the raw count at $(X, Y) = (150, 180)$. The diffuse background level is traced by the horizontal gray line.

As mentioned in the Introduction, all of the previous observations of over-darkening PsA (Dahlgren et al., 2017; Kataoka et al., 2012) were achieved by using narrow FOV high-speed cameras; thus, it has been difficult to see their large-scale temporal evolution in 2D. Here, we try to visualize the temporal evolution of over-darkening PsA in a 2D fashion by using data from the high-speed ASI. The top two panels of Figure 4

respectively show the south to north and east to west keograms from a 3 min interval from 00:00 to 00:03 UT during the same interval. Prominent stripes of the main pulsation are again seen in both the keograms and, more importantly, dark areas, which are the signature of over-darkening, can be identified for most of the pulses. The other thing worth noting is that these PsA patches propagated poleward because the traces in the south to north keogram are not purely vertical but slightly slanted.

Figure 4c is a zoom-in of the central 1 min interval in the format of east to west keogram where the over-darkening signatures are obvious for all the pulses from A to F. The corresponding time-series data in Figure 4d, which are the optical intensity values at $(X, Y) = (150, 180)$, show much clearer over-darkening signatures than those in Figure 3. This is because here we sampled the data ignoring the location of the footprint of Arase. The interesting point is that the over-darkening can appear both before and after the ON phase (i.e., the ON pulse is sandwiched by two dark regions) as seen for pulses E and F. In addition, there are cases when only the over-darkening region was observed (i.e., without the ON phase) for example the dark area before the first ON pulse (denoted by “Z”). Hereafter we will look into the 2D temporal evolution of the pulse D in Figure 4c which was accompanied by one of the clearest over-darkening signatures in the entire interval.

Figures 5a–5c and 5h–5k compile a sequence of all-sky images at the time of the pulse D in Figures 4c and 4d. The all-sky images for 5 s from 00:01:36 until 00:01:41 UT are shown. At the time of Figure 5a, a patch of PsA appears in the central part of the FOV. The sequence of images demonstrates that this patch of PsA started propagating poleward right after the appearance. This poleward progression of the patch can be seen as slanted traces in the south to north keogram in Figure 4a. In the first three images (Figures 5a–5c) it might be difficult to identify the appearance of over-darkening area. However, at 00:01:39 UT (Figure 5h), an east-west elongating slightly dark area became recognizable on the trailing edge of the bright area. Subsequent images (Figures 5j and 5k) show that this region of over-darkening propagated poleward together with the bright area. The movie attached to the electronic version of this article more clearly demonstrates how the over-darkening part appeared and moved in tandem with the bright part of the patch.

The middle four panels of Figure 5 (Figures 5d–5g) respectively display the time-series of the optical intensities at four points 1–4 shown in Figure 5a. Here, we investigate how the optical intensities at these fixed points can change by the passage of a PsA patch accompanied by a dark region on its trailing edge. Due to the poleward propagation of the patch during the ON phase, there is a systematic time lag among the time-series at the four points. That is, the enhancement during the ON phase and subsequent over-darkening signature were observed earlier at point 1 than at the remaining three points. In particular, the signature of over-darkening was detected in the latest timing at point 4 due to the poleward propagation of the dark region. As will be discussed in detail in the Discussion part, the sequence of all-sky images indicates that the over-darkening part already appeared on the trailing edge right after the start of the ON phase. This fact infers that the over-darkening signature in the time-series, for example, the one shown in Figure 4d is not a pure temporal variation at a fixed point but a variation produced by a passage (or sweeping) of the dark region through the fixed sensing area.

3. Discussion

In the previous section, we demonstrated that the over-darkening region already appeared on the trailing edge of the patch at the start of the ON phase and the dark region propagated poleward together with the main (i.e., bright) part of the patch. Figure 6 is a simplified cartoon showing how the over-darkening signature in the optical intensity at a fixed point is produced by the passage of a PsA patch. The upper part of the cartoon indicates how the patch of PsA propagates poleward after its appearance at time A. Immediately after the appearance of the patch, a dark area emerges on the trailing edge of the patch (at Time B) and the entire patch propagates poleward (at Time C, D). During this course of poleward propagation, the bright area (white region in the cartoon) and the dark region (black part) pass through the red circles which is an imaginary observation point fixed in space. During the crossing of the dark area across the sensing point, the optical instrument should observe the over-darkening signature (at Time D). At Time E, the brightness of the patch decreases, which marks the end of one cycle of main pulsation. Until around that time, a new patch appears in the equatorward of the sensing area and a new cycle starts.

Figure 5. (a–c and h–k) A sequence of all-sky images every 1 s from 00:01:36 to 00:01:41 UT on March 29, 2017. (d–g) Time-series of the optical intensity at four points (1–4) shown in (a). The diffuse background level is traced by the horizontal gray line.

Figure 6. Schematic diagram showing how the over-darkening signature is created by the poleward propagation of a PsA patch accompanied by a dark region along its trailing edge. PsA, pulsating aurora.

The bottom part of the cartoon illustrates what should be observed if a patch of PsA with a dark area propagates through a fixed sensing point (red point in the upper part). Before the crossing of the patch (Time A and B), the diffuse background level (which is expressed the gray background color in the cartoon) is observed as the luminosity during the normal OFF phase. During the passage of the bright area across the red sensing point (Time C), the optical device should observe an enhancement of luminosity which corresponds to the ON phase of PsA. Subsequently, the dark area on the trailing edge sweeps the sensing point at Time D at which the optical intensity decreases down to the complete dark level. After the complete crossing of the patch (Time E), we again observe the diffuse background level during the normal OFF phase. This cartoon represents the actual observation shown in Figure 5 and indicates that the systematic passage of the combination of bright and dark areas across the sensing point can produce the characteristic over-darkening signature in the time-series of luminosity at a fixed point. This model implies that the over-darkening is not a pure temporal variation, but the signature is created by propagation of a spatial structure.

As shown in Figure 6, we probably understand why we observe the over-darkening feature in the time-series of the PsA luminosity. We still, however, do not know what process produces the dark area on the trailing edge of PsA patches. One possibility is an interplay of lower and upper band chorus (LBC and UBC) waves. Miyoshi, Saito, et al. (2015) suggested that LBC scatters energetic electrons directly causing the pulsating precipitation while UBC is generally more continuous and resonates with lower-energy electrons responsible for the background diffuse emission. This idea is able to associate the spatial structure of the over-darkening PsA with the LBC and UBC waves, which is schematically illustrated in the upper part of Figure 7 as Scenario A. In this diagram, the background diffuse emission (gray area) is associated only with UBC while both the LBC and UBC waves contribute to the main bright region of patch (white area). The point is that UBC is always distributed in the entire area (i.e., both inside and outside the patch); thus, the luminosity of aurora does not decrease to the complete dark level even outside the patch (and, of course, even during the OFF phase). Here we suggest that the dark area (i.e., the region of over-darkening) on the

Figure 7. Two possible physical mechanisms (scenarios) for the appearance of over-darkening area on the trailing edge of PsA patches. PsA, pulsating aurora.

trailing edge corresponds to a region without any chorus emissions in the magnetospheric counterpart. In such a case, no electrons are precipitated through the resonance with chorus; thus, the optical intensity should be ideally zero within the dark area.

It was impossible to prove this speculation by the conjugate observation with Arase because UBC was not detected because the satellite was located at the off-equatorial region to which UBC cannot propagated from its source near the magnetic equator (Meredith et al., 2012) due to stronger Landau damping at higher frequencies (Bortnik et al., 2007). ECH is also known as a candidate for regulating the temporal variation of PsA (Fukizawa et al., 2018). In particular, the temporal variation of ECH may explain the over-darkening structure of PsA in this time interval. Actually, Fukizawa et al. (2018) identified a good correlation between the amplitude of ECH and luminosity variation during the same interval of conjunction. However, the conjunction interval on March 29, 2017 was 2 h long (00–02 UT). Fukizawa et al. (2018) investigated the data

from the later stage of this interval (0130–0200 UT), which is ~ 1.5 h after the current interval. There was almost no activity of ECH when we observed the over-darkening signature; thus, at least during the current interval, the occurrence of over-darkening cannot be explained by the temporal variation of ECH.

The other possible mechanism creating the dark area along the trailing edge is based on the ionospheric feedback process caused by the enhancement of conductance in the ionospheric dynamo layer (Hosokawa et al., 2010). This idea is illustrated in the bottom part of Figure 7 as Scenario B. When a patch of PsA appears in the ionosphere, the electron precipitation during the ON phase enhances the conductance only within the patch of PsA. Due to such a localized enhancement of conductance, the ionospheric current gets intensified only within the patch. If we assume that the background electric field is directed westward, the Hall current, which is dominant during the ON phase of PsA (as indicated in Figure 2 of Hosokawa & Oga-
wa, 2010), flows poleward in the northern hemisphere. Due to a large gap in the conductance at the poleward and equatorward edges of PsA, we expect accumulation of polarization charges; positive (negative) charges along the poleward (equatorward) boundary. This additional negative potential and corresponding downward electric field on the trailing edge could suppress the electron precipitation causing auroral emission and make the trailing edge dark. This alternative explanation employing the ionospheric feedback process is apparently plausible. However, the actual background electric field in the morning side is mostly southward, especially in the region of PsA (Yang et al., 2015, 2017). In Figure 3 of Yang et al. (2017), for example, the ExB drift velocity of PsA patches is shown to be westward, corresponding electric field being southward. In such a case, the over-darkening region should appear in the eastern edge of the patch, which contradicts the current observations.

The reason for not showing the particle data from Arase is the lack of temporal resolution for resolving the evolution of the particle flux in the loss cone. The MEP instrument onboard Arase has a fine pitch-angle resolution for the study of PsA (e.g., S. Kasahara et al., 2018). However, the temporal resolution of such particle data covering full pitch angle distribution is 8 s, which is equal to the period of PsA and well longer than the duration of over-darkening (1–2 s). This did not allow us to use the corresponding particle data in this study.

Although the physical process is still unclear, we demonstrated that the over-darkening signature in the beginning of the OFF phase can be explained by propagation of a PsA patch accompanied by a dark area on its trailing edge. Dahlgren et al. (2017) indicated that the over-darkening signature is observed not only after the ON phase but also before the ON phase. Since Dahlgren et al. (2017) only showed the time-series of optical intensity sampled from a pixel in the narrow FOV high-speed camera, it was unclear if the over-darkening signature in their time-series was spatial or temporal variation. However, the similarity with the case introduced in the current study implies that the over-darkening before the ON phase in Dahlgren et al. (2017) is also the spatial variation. That is it corresponds to the over-darkening on the leading edge of a moving patch of PsA. We can explain such an inverse case by considering the dark area along the leading edge of propagating patch of PsA. The current observation also demonstrates that the over-darkening can be observed before and after the ON phase at the same time (patches E and F in Figure 4c). In such a situation, the over-darkening area should appear both at the leading and trailing edges, but more likely along the entire outline of the patch. Scenario B cannot account for such an exceptional case because the accumulation of negative charges cannot be expected at two opposite sides of patches. In addition, as shown in Figure 4c, we sometimes see only the over-darkening areas without any mother patches in their vicinity. The ionospheric feedback mechanism is not able to explain such a case either. These considerations may discard Scenario B as a physical mechanism for the generation of a dark region along the boundary of PsA patch. Scenario A does not have any inconsistency with the observational facts. However, this scenario still does not provide any ideas explaining the complete absence of chorus (LBC and UBC) in a limited region along the trailing edge of PsA patch, which should be answered in the future study.

Finally, we must discuss the relationship of the over-darkening signature with the previously studied “black aurora.” Black aurora is a region of no optical emission typically embedded within a region of diffuse aurora including PsA (Davis, 1978). Previous studies of over-darkening by Kataoka et al. (2012) and Dahlgren et al. (2017) discussed the origin of the over-darkening phenomena in connection with black aurora. Since any particle precipitation would not be expected in the region of over-darkening (though there was no overflight of a low altitude satellite equipped with an electron detector during the interval of interest) the region over-darkening can be recognized as one of the class of black aurora. However, the over-darkening

signatures are observed only during the ON phase of PsA in most cases; thus, the current over-darkening phenomenon may be called as “transient” black aurora. In addition, the scale size of black aurora tends to be much smaller (typically less than 10 km: e.g., Kimball & Hallinan, 1998) than that of the dark region corresponding the over-darkening. Especially, most of past observations of black aurora were archived by narrow FOV cameras (e.g., Trondsen & Cogger, 1997).

By investigating an event of black aurora with conjugate optical and the FAST satellite observations, Petcolas et al. (2002) suggested that both the ECH and chorus waves were responsible for the precipitation in the diffuse background and the appearance of black aurora is explained by localized suppression of pitch angle scattering at the magnetospheric side. Similar conclusion was drawn later by Sergienko et al. (2008) by using highly-sensitive ground-based auroral imagers and FAST electron measurements. In contrast, Fritz et al. (2015) investigated black aurora observed together with PsA and suggested an importance of active roles played by the ionosphere (i.e., ionospheric feedback process). Although the typical scale size of black aurora is smaller than that of over-darkening PsA, there should be similarities in the possible explanation for these two phenomena. Hence, in the future study, the generation process of the over-darkening PsA should be discussed in close connection with black aurora.

4. Summary and Conclusion

We introduced an interval of over-darkening PsA which is simultaneously observed by the Arase satellite and a high-speed EMCCD all-sky camera located near the footprint of the satellite in northern Scandinavia. During the interval of interest on March 29, 2017, the over-darkening signatures were identified for most of the pulses of the main pulsation of PsA. The signatures sometimes appeared before the ON phase and it was quite rare but the over-darkening signatures were seen both before and after the ON phase. Simultaneous wave data from Arase showed no corresponding over-decreasing characteristics in the amplitude of lower band chorus waves, which implies that the over-darkening of PsA is not directly associated with the temporal variation of lower band chorus at a fixed point. An analyses of 2D all-sky images of the over-darkening PsA, it was discovered that a dark region appeared on the trailing edge of a PsA patch and the patch with the dark area propagated poleward in tandem. This suggests that the over-darkening is not a pure temporal variation at a fixed point, but is actually produced by the passage of the dark area on the trailing edge across the sensing area. That is, the over-darkening PsA is a result of compounding effects of spatial structure and dynamical motion of PsA patches. The mechanism creating the dark area is still unknown, but an interplay of UBC and LBC may explain the formation process (Miyoshi, Saito, et al., 2015). Charge polarization along the boundary of PsA patches (Hosokawa et al., 2010) may provide an alternative explanation for the dark area along the trailing edge of patches. However, the location of the region of over-darkening in the vicinity of PsA patch is not consistent with the typical southward electric field in the morning side. In summary, the existence of over-darkening PsA indicates that the temporal variation of PsA is not always a perfect copy of the modulation of lower-band chorus waves. That is, to fully explain the temporal variation we need to take into account various factors such as contributions of multiple waves and dynamical propagation of the wave source region. We showed that the over-darkening signature is not a pure temporal variation at a fixed point but a variation produced by a passage (or sweeping) of the dark region through the fixed sensing area (i.e., mixture of spatial and temporal variations). Thus, it is also needed to observe the temporal evolution of the spatial distribution of electron precipitation (especially the energy of precipitating electrons). In that sense, 3D volumetric observation with a large incoherent scatter radar like planned EISCAT_3D would be a key instrument to further investigate the over-darkening structure.

Data Availability Statement

The Arase (ERG) satellite science data were obtained from the ERG Science Center (Miyoshi, Hori, et al., 2018) operated by the Institute of Space and Astronautical Science of the Japan Aerospace eXploration Agency and the Institute for Space-Earth Environmental Research of Nagoya University (<https://ergsc.isee.nagoya-u.ac.jp/index.shtml.en>). The data from the EMCCD camera at Sodankylä are available at <https://ergsc.isee.nagoya-u.ac.jp/psa-pwing/pub/raw/cam2/2017/03/>. The Arase satellite data are publicly available in the ERG Science Center. In the present study, we used level 2 OFA v02_01 data

(<https://doi.org/10.34515/DATA.ERG-08000>), level 2 WFC v00_01 data (<https://doi.org/10.34515/DATA.ERG-09002>), and level 2 definitive orbit v3 data (<https://doi.org/10.34515/DATA.ERG-12001>). The data of the EMCCD camera are available from the ERG Science Center.

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