# Turbulent microstructures and formation of folds in auroral breakup arc

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[1] We conducted a ground-based optical measurement pointing at local magnetic zenith with a narrow field of view of 9.3° by 9.3°, using a high-speed electron multiplier charge-coupled device camera at Poker Flat Research Range. We show evidence that auroral folds were periodically formed in a breakup arc and the luminosity is exponentially increased for about 10 s before an auroral breakup onset. The evolution of turbulent microstructures and the formation of folds may be interpreted by the nonlinear evolution of inertial Alfvén wave (IAW) turbulence in the thin current sheet. On the basis of these optical observations, we discuss a possible role of the ionosphere for modulating the triggering process of the onset via the self-organization of the IAW turbulence associated with Kelvin-Helmholtz and tearing instabilities of the thin current sheet.

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## 1. Introduction

[2] Auroral breakup is the greatest explosive plasma phenomenon occurring in the ionosphere and magnetosphere coupled system [*Akasofu*, 1964]. The triggering mechanism has been one of the longest-standing unsolved problems in the magnetospheric physics. Highly sensitive TV observations have shown three basic auroral forms, namely spirals, folds, and curls, which differ from each other in their sizes, vorticities, velocities [*Hallinan and Davis*, 1970]. Auroral spirals are large-scale vortex configurations with typical sizes from tens to hundreds of km. Folds are characterized by a scale size of about 20 km. A curl is a small-scale vortex configuration with typical size of less than ten kilometers. *Trondsen and Cogger* [1998] investigated the statistics of curls in detail.

[3] The numerical simulations by *Chmyrev et al.* [1992] demonstrate that within the framework of the nonlinear inertial Alfvén wave (IAW) model, one can describe all the observational stages of the development of folds, spirals, as well as the disintegration of folds and spirals into the vortex chain. Physically, the nonlinear mode couplings of the inertial Alfvén fluctuations self-organize into larger-scale structures, which eventually break into smaller size coherent vortex structures [*Stasiewicz et al.*, 2000]. Recently, *Chaston and Seki* [2010] showed that Kelvin-Helmholtz (KH) and tearing instabilities of a thin current sheet lead to vortices similar to folds and the eventual breakup of the planar arc into distorted fine-scale sheets and filamentary currents. The purpose of this paper is to briefly report for the first time the stepwise morphological evolution from the turbulent microstructures to finally form the folds in a breakup arc for a few minutes before an auroral breakup onset, which potentially suggests a possible role of the ionosphere for modulating the triggering process of the substorm onset via the self-organization of the IAW turbulence associated with KH and tearing instabilities of the thin current sheet.

## 2. Instrumentation

[4] We conducted a campaign observation of the high-speed auroral imaging at Poker Flat Research Range (PFRR) located at geographic latitude 65.1 N and longitude 147.4 W during a winter season from January to April 2010. An electron multiplier charge-coupled device (EMCCD) camera (Hamamatsu, C9100–13) was installed, directing toward the magnetic zenith with a 50 mm/F0.95 lens to form the narrow field of view (FOV) of 9.3 deg by 9.3 deg. The imaging part of the EMCCD has 512 × 512 pixels, which were binned equally into 128 × 128 pixels during the acquisition of the data to operate at a sampling rate of 110 Hz, yielding a spatial resolution of about 0.1 km at a 100 km altitude. The image integration time was 8 ms. The EMCCD camera is equipped with a narrow passband interference filter centered on 845.5 nm wavelength with a full-width half-maximum (FWHM) of 2.3 nm. This filter passes 844.6 nm prompt emission from Oxygen molecule, as a result of both direct excitation and dissociative excitation. Breakup aurora is known as "ray" aurora [*Sakaguchi et al.*, 2009a, 2009b],

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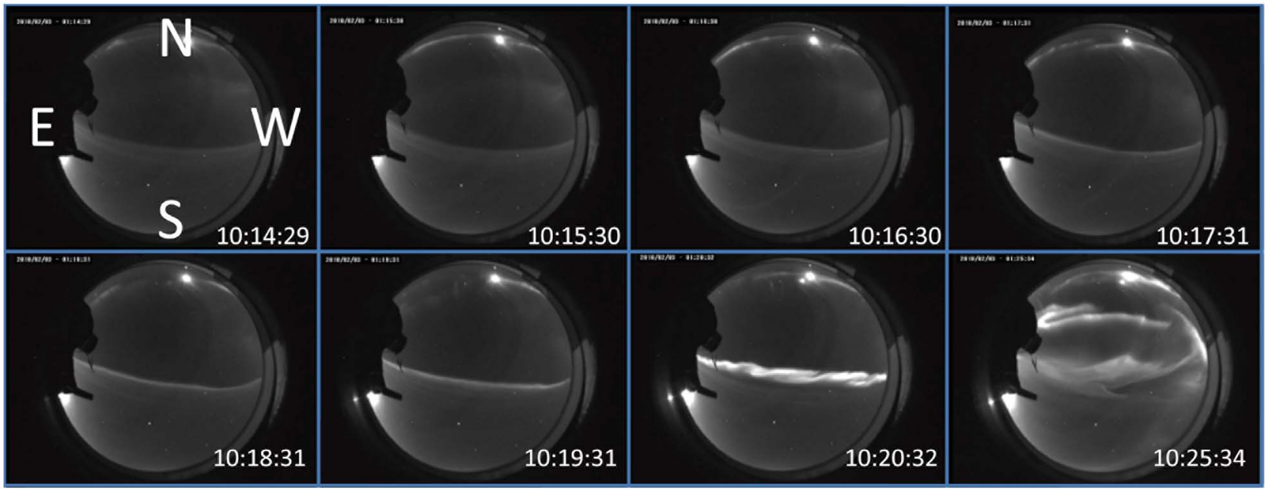


**Figure 1.** Auroral breakup event on 3 February 2010 as seen by panchromatic all-sky imager. The coordinate is top to the north and right to the west.

which has electron precipitation with the broadband energy range [*Mende et al.*, 2003]. The 844.6 nm is a prompt emission, capable of capturing the rapid variation of both hard and soft electrons associated with the auroral breakup.

## 3. The Auroral Breakup Event

[5] Figure 1 shows an overview of the auroral breakup event as obtained by a panchromatic all-sky imager (camera: WATEC WAT-120N+, lens: FUJINON 1.4 mm/F1.4 fisheye) installed at PFRR for the monitoring purpose. The faint and roughly east-west aligned diffuse arc existed covering the magnetic zenith at 1015:30 UT on 3 February 2010. The auroral breakup suddenly occurred in the 1020:32 UT frame, forming the bright auroral folds. The expanding complex auroral forms subsequently appeared over the FOV in the 1025:34 UT frame. Satellite conjugate observations (REIMEI, Cluster, THEMIS) are unfortunately not available.

## 4. Results

[6] An example of some EMCCD images of the breakup arc is shown in Figure 2. Since we do not see any significant variations faster than 10 Hz for the whole time interval, all the images shown in this study are averaged over 0.1 s to reduce the noise. The breakup arc emerged at the poleward edge of preexisting diffuse auroral arc in the first panel at 1015:48 UT. A turbulent microstructure is identified with possibly five curls periodically aligned in the east-west direction around 1015:55 UT as indicated by yellow arrows. As shown in middle two rows, the turbulent microstructure evolves into larger scale with typical wave number of three as indicated with yellow arrows, associated with brightening and poleward motion of the breakup arc. The bottom two rows show the formation of folds just before the auroral breakup onset. Note that the dominant scale of the fold structure seems to be larger than the FOV.

[7] Figure 3 summarizes the poleward motion and brightening of the east-west aligned breakup arc as obtained from the EMCCD images. Top panel shows the peak position of 1 s averaged brightness of the arc in the north-south meridian, and the bottom panel shows the 1 s averaged brightness of the arc at the peak position. The peak position is obtained by taking a north-south cross section and averaged over east-west direction of the images in Figure 2. The breakup arc emerged at ~1015:50 UT. The timing of auroral breakup onset can be determined at ~1019:50 UT, as identified by the rapid variation of the arc position and brightness. The position and brightness are correlated each other over the 5 min. Stepwise evolution is evident in the top panel; the first stage starts from ~1015:50 UT, and the second stage starts from ~1017:20 UT. The amplitude of the brightness variation is smaller for the first stage, and is larger for the second stage. Periodic and exponential growth of the brightness is identified associated with the formation of folds at the end of the second stage at 1019:35–1019:50 UT just before the breakup.

[8] Figure 4 shows the time variation of the east-west slices along the breakup arc, tracking the north-south arc position as shown in Figure 3. It is apparent that the eastward propagating features are getting faster and faster toward the breakup; for example, nearly vertical wavy structures at 1016:00–1017:00 UT in Figure 4 (second panel) and nearly horizontal wavy structures at 1019:40–1019:55 UT in Figure 4 (fifth panel). The typical speed is ranging from 0.5 km/s to 2.0 km/s in the first stage, and is ranging from 2.0 km/s to 6.0 km/s in the second stage, assuming the emission altitude of 100 km. It is also apparent that fine-scale structures are more evident in the first stage than in the second stage, as if the turbulent microstructures organized into subsequent larger-scale structures.

## 5. Discussions

[9] The evolution of turbulent microstructures and the formation of folds before the breakup onset are apparent, as summarized in Figure 4. Starting from the turbulent microstructures in the emerging narrow breakup arc, folds were periodically formed and showed exponential growth of brightening just before the onset (Figure 2). These results suggest that nonlinear IAW framework may be fundamental as suggested by the simulation of curls and folds [*Chmyrev*

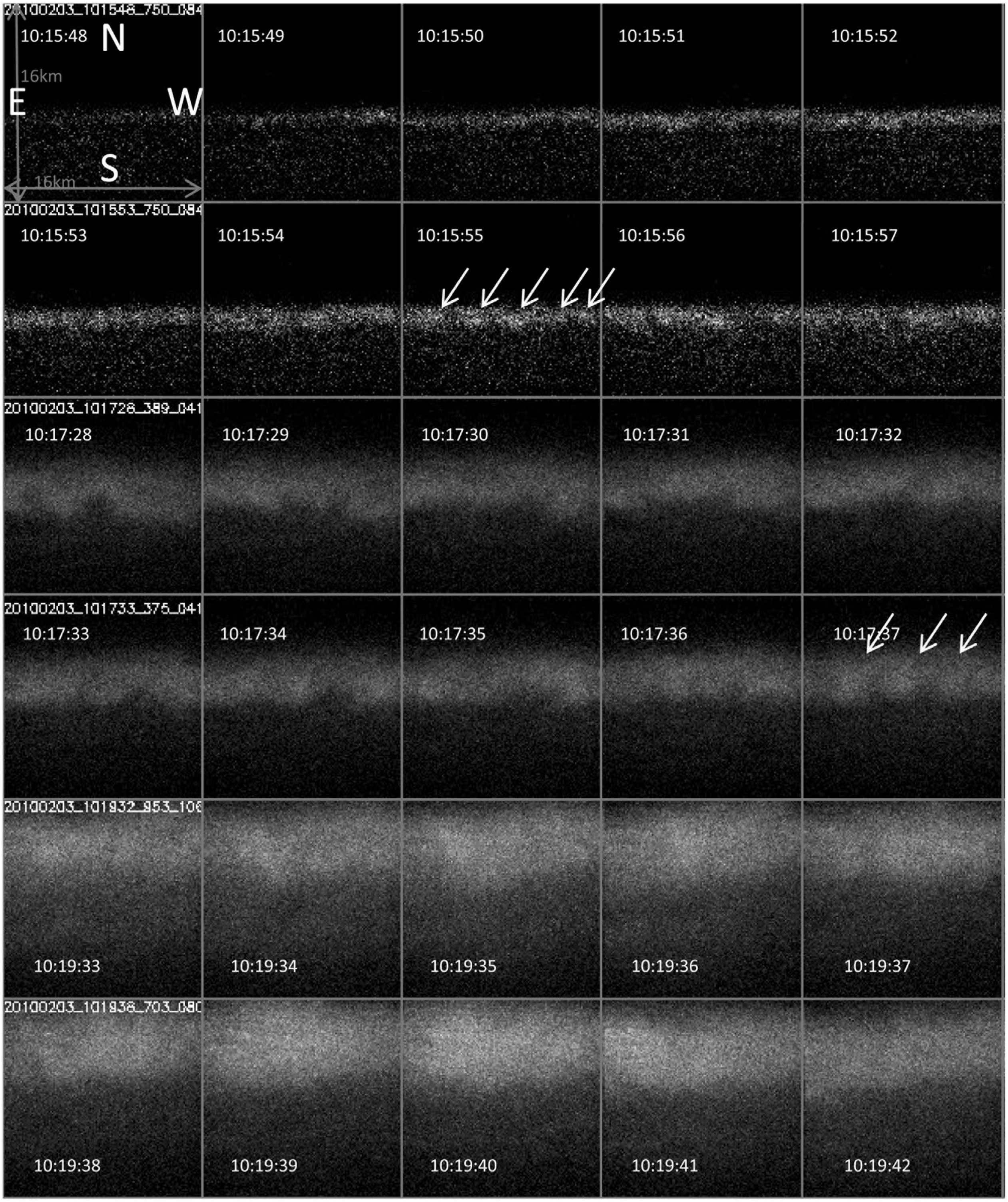


**Figure 2.** Breakup arc emergence and (top two rows) the birth of the curl system, (middle two rows) the evolution of the curl system, and (bottom two rows) the birth of folds as observed by the EMCCD camera. Each panel shows the running averaged image over 0.1 s. The image sequence is from left to right and top to bottom. The coordinate is top to the north and right to the west.

*et al.*, 1992]. Physically, the nonlinear mode couplings of the inertial Alfvén fluctuations self-organize into larger-scale structures, which eventually break into smaller size coherent vortex structures [*Stasiewicz et al.*, 2000]. Such a structural evolution into finer scales may be basically expected as shown by *Lysak and Song* [2008]. In fact, such a transient forward cascading can be seen everywhere in Figure 4, for example at 1018:40–1018:50 UT. Under typical plasma

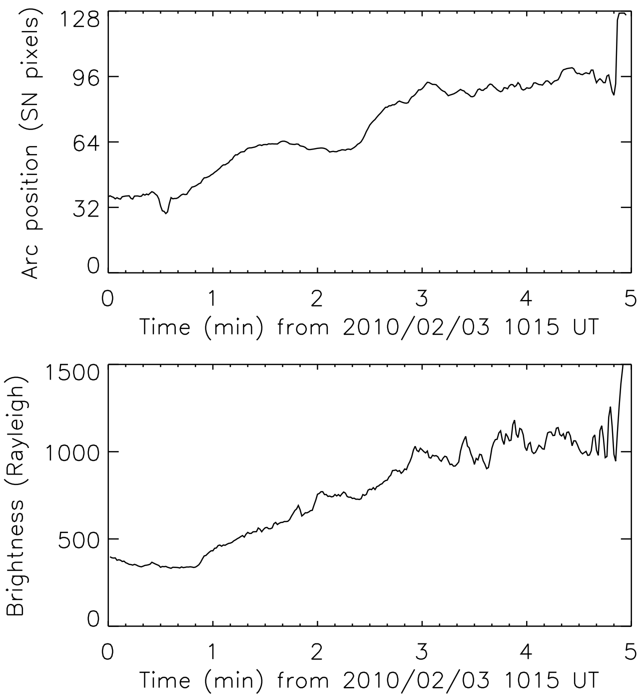


**Figure 3.** Evolution of the (top) position and (bottom) brightness of the breakup arc for the time interval from 1015 to 1020 UT on 3 February 2010. Stepwise poleward motion and correlated variation of the brightness can be identified.

density at thousands of km altitude, typical electron inertial scale is less than 1 km, and all of the observed apparent scales of auroral forms in this study are comparable with or larger than the electron inertial scale. Small-scale structures with such scales are to be significantly damped by collisional damping in the ionosphere [*Borovsky*, 1993].

[10] A necessary threshold criterion for linear excitation of Alfvén waves due to perpendicular ion velocity gradient is given by *Wu and Seyler* [2003] as $(\omega_s/\Omega_i)$ $(k_y/k_z) > 2$ where $\omega_s = \partial V_y/\partial x$ is the shear frequency, $\Omega_i$ the ion cyclotron frequency, and $k_z$ wave number along the geomagnetic field direction. The velocity gradient in the observed flow roughly provides $\omega_s/\Omega_i \sim 0.1$–$0.01$ considering typical $H^+$ and $O^+$ plasma, and consequently the flow may be unstable to IAWs with $k_y/k_z > 20$–$200$. These estimates are comparable with those of *Asamura et al.* [2009], and it is likely that IAWs of $k_y/k_z > 20$–$200$ generate by the shear instability. Also, about the time scales for nonlinear IAW interactions, *Chmyrev et al.* [1992] showed that the formation of a fold is within 2 s for the auroral parameters [*Stasiewicz et al.*, 2000].

[11] The structural evolution in larger scale can be visualized and confirmed in a different way. Figure 5 shows the time evolution of the spatial scale indicated as the east-west wave number, which is estimated by averaging the two dimensional FFT spectra of each image in the wave number domain. It is apparent that the higher wave number is dominant in the first stage at 1016–1017 UT, and lower wave number is dominant in the second stage at 1018–1020 UT.

[12] Why do folds periodically formed from turbulent microstructures, and why do they subsequently grow exponentially just before the breakup onset? The unstable growth of the magnetosphere-ionosphere coupled system such as ionospheric feedback instability (IFI) may be important, based on our observations of the final exponential growth of folds and the fact that the scale of the fold system is comparable to the prediction of *Lysak and Song* [2002]. It has been noted [*Lysak*, 1991] that the feedback instability can be greatly enhanced if reflections from the sharp gradient of the Alfvén speed above the auroral ionosphere occurred. The eigenmodes of this so-called ionospheric Alfvén resonator (IAR) have periods of a few seconds, as opposed to the field line resonance (FLR) that have periods of minutes. Thus the IFI operating in the IAR will evolve much more quickly than the instability based on FLR, and so the former may be called as a fast IFI while the FLR version is a slow IFI. There are theoretical predictions that auroral acceleration region–associated resonator (so-called RAAR) might be more effective than IAR [*Pilipenko et al.*, 2002].

[13] *Liang et al.* [2008] reported a few packets of aurora classified as “standing waves.” Before the full growth of the wave packet, there were several “valley-to-peak” variations with periods of ~6 s, which were interpreted as the IAR effect [*Lysak*, 1999]. The standing waves may be related to the folds shown in the present study. *Sakaguchi et al.* [2009b] showed the inverse cascading feature from the all-sky images and discussed the association with the possible importance of IFI/IAR, although the spatial scale and temporal scale is very different from the present study. One possible test here is to investigate the magnetometer data to identify the IAR resonance signatures, although ground based magnetic field measurement has a limitation to clearly detect the resonant signal above the ionosphere simply due to the obscured signal at ground. In fact, we did not find any particular responses in ground-based magnetic field data in the ULF/ELF range at PFRR associated with the evolution of the turbulent microstructures or fold formation before 1020 UT (not shown). Although it is not yet obvious how ground-based magnetic field variations look like when IFI is actively working, we did not observe any resonant-like signatures with specific frequencies in ground-based magnetic field variations as predicted from the theory of IAR.

[14] *Chaston and Seki* [2010] simulated a thin current sheet evolution in the domain of IAW with and without a resistive layer. They showed that without a resistive layer a combination of KH and tearing instabilities lead to vortices similar to folds and the eventual breakup of the planar arc into distorted fine-scale sheets and filamentary currents, while with a resistive layer KH instability dominates leading to the formation of auroral folds. Our observations may fit their prediction as follows: in the first stage, within a thin diffuse arc of a few km width, the flow shear across the arc is typically a few km/s, leading to a small linear KH growth rate of *Hallinan and Davis* [1970] of about 5 s at maximum. In the second stage, the arc is getting thicker and brighter, the flow shear is getting larger up to 10 km/s with a large linear KH growth rate of 0.5 s at maximum. If we assume that a resistive layer is absent in the first stage and is formed in the second stage as the field-aligned potential drop, all of the signatures may be understood in the framework where a combination of KH and tearing instability was active in the

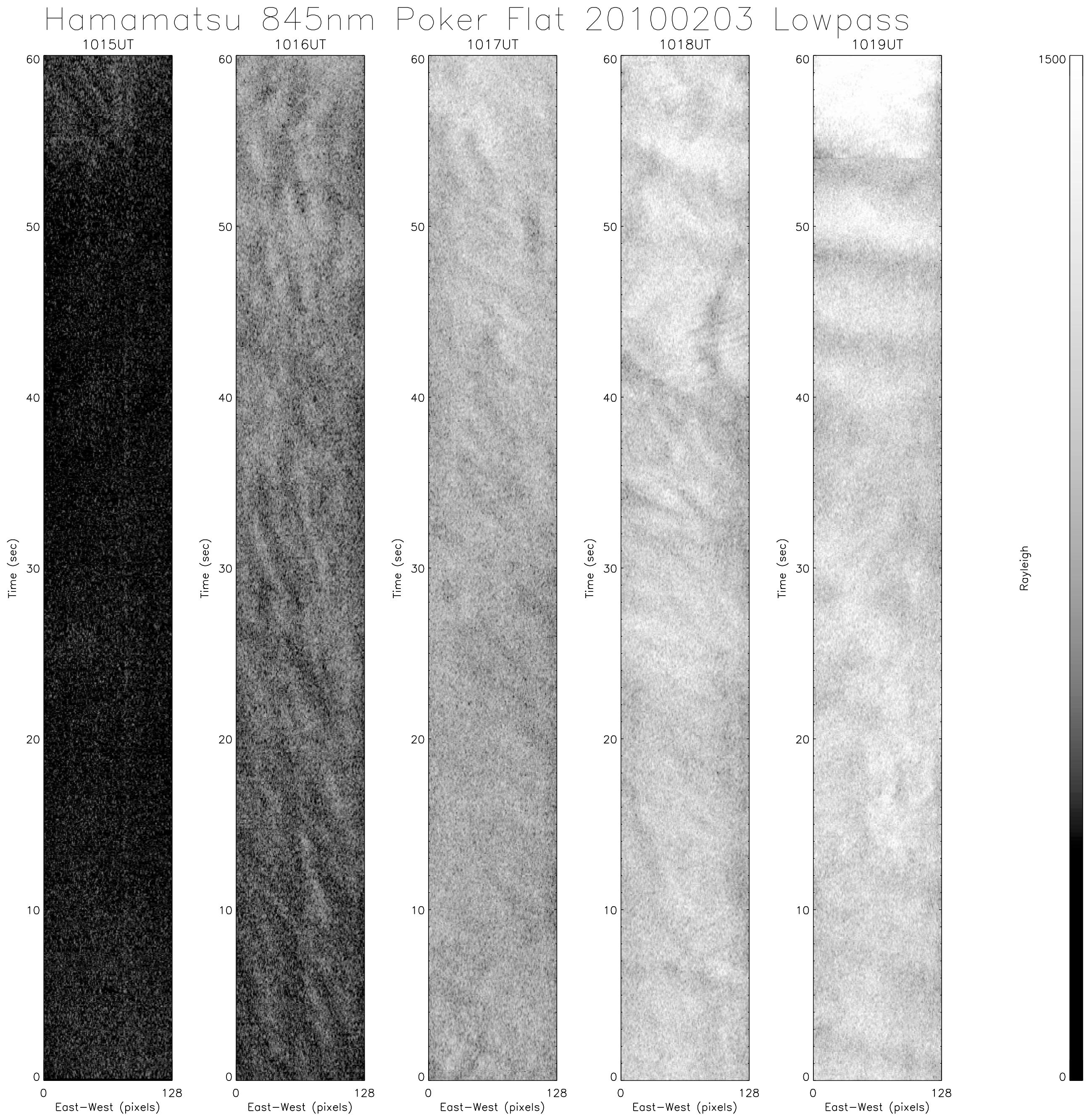


**Figure 4.** Time evolution of the east-west slices along the breakup arc for the time interval from 1015 to 1020 UT, along the south-north peak position of the arc intensity. Left side is to the east.

first stage and only KH instability dominates in the second stage.

[15] The morphological evolution is not smoothly developed, and a stepwise evolution is apparent as summarized in Figure 3. A simple hypothesis is that the position of arc is more related to the magnetosphere, and the evolution of turbulent microstructures is more related to the ionosphere. The ionospheric modulation as seen in the evolution of turbulent microstructures may be reflected back to the magnetosphere to exchange the information, causing stepwise features via the slow IFI. The temporal scale of slow IFI is an order of minutes and is consistent with the time scale of the observed multistep evolution. Based on the hypothesis, the whole auroral morphological evolution shown in this study may be interpreted in a unified picture as a result of self-organization of IAW turbulence with KH and tearing instabilities of the thin current sheet under fast and slow IFI conditions. The stepwise morphological evolution from the turbulent microstructures to finally form exponential growth of folds just before the auroral breakup onset may therefore suggest a possible important role of the ionosphere for modulating the triggering setup via the self-organization of the IAW turbulence in the IFI system. Such a definite conclusion, however, cannot be drawn from the

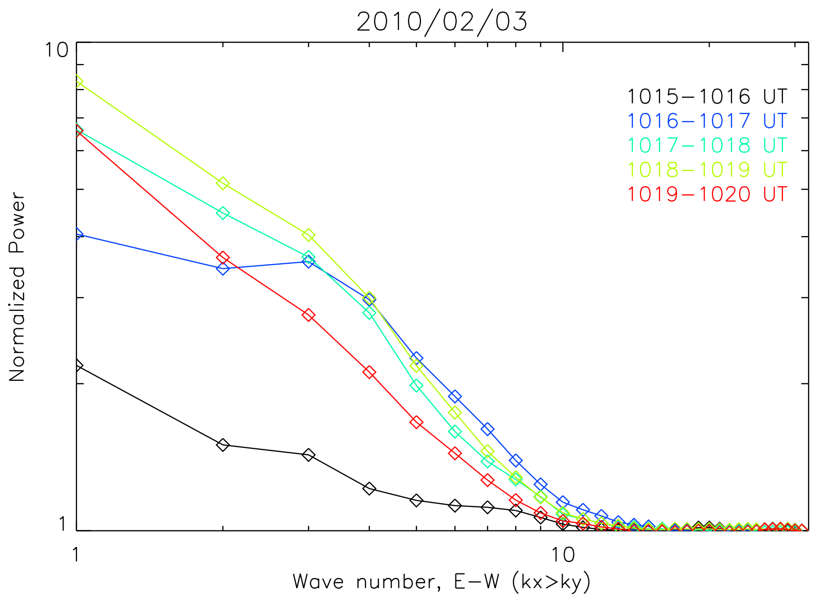


**Figure 5.** Evolution of dominant east-west spatial scale of breakup arc for the time interval from 1015 to 1020 UT on 3 February 2010, as estimated from 1 min temporal averages of two-dimensional FFT spectra of EMCCD images. The wave numbers 1 and 10 correspond to the scale sizes of 16 and 1.6 km, respectively.

single event analysis of this report. We are planning to continue the ground-based fine-scale EMCCD imaging observations, preparing to the oncoming active period during solar cycle 24.

## 6. Conclusions

[16] We found that the turbulent microstructures appeared in a breakup arc and evolved into larger scale to finally form folds periodically, and the folds subsequently showed exponential growth just before an auroral breakup onset. There are two stepwise stages in the evolution where the arc is darker at lower latitude with smaller flow shear and finer structures in the first stage, while the arc is blighter at higher latitude with faster flow shear and coarser structures in the second stage. The stepwise evolution may be explained in a unified picture of self-organization of nonlinear IAW turbulence with KH and tearing instabilities of the thin current sheet under the fast and slow IFI system.

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