Direct comparison of pulsating aurora observed simultaneously by the FAST satellite and from the ground at Syowa

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[1] We have made a direct comparison of a pulsating aurora observed simultaneously from the ground at Syowa in Antarctica and onboard the FAST satellite (~3100 km altitude). The auroral form appeared as east-west-aligned bands consisting of two different types: a poleward moving pulsation and a standing mode pulsation, each with a period of ~5 sec. The aurora occurs within the region of an inverted-V structure of lower energy (0.1 – 1 keV) electron precipitation. The two different types of pulsating aurora are separated in space by a narrow gap in the inverted-V potential structure. Spatial and temporal variations of the down-going high-energy (>5 keV) electron flux show a one-to-one correspondence with the optical pulsating aurora. The down-going high-energy (1 – 10 keV) ion flux modulation is out of phase (anti-correlated) with the high-energy electron flux modulation. These features suggest that the precipitating high-energy electrons, which produce the pulsating aurora, are modulated by the oscillation of the field-aligned electric field located above FAST. *INDEX TERMS:* 2407 Ionosphere: Auroral ionosphere (2704); 2431 Ionosphere: Ionosphere/magnetosphere interactions (2736); 2455 Ionosphere: Particle precipitation; 2716 Magnetospheric Physics: Energetic particles, precipitating. **Citation:** Sato, N., D. M. Wright, Y. Ebihara, M. Sato, Y. Murata, H. Doi, T. Saemundsson, S. E. Milan, M. Lester, and C. W. Carlson, Direct comparison of pulsating aurora observed simultaneously by the FAST satellite and from the ground at Syowa, *Geophys. Res. Lett.*, *29*(21), 2041, doi:10.1029/2002GL015615, 2002.

1. Introduction

[2] Pulsating auroras are common phenomena, which are observed universally during the recovery phase of substorm in the auroral and sub-auroral zones. They exhibit typical periods of a few seconds to a few tens of seconds and scale sizes of 10 – 200 km [*Harang*, 1951; *Oguti*, 1978; *Yamamoto*, 1988]. Rocket measurements have demonstrated that modulated electron fluxes from as low as 2 – 3 keV to 100 keV are responsible for these phenomena [*Sandahl et al.*, 1980; *McEwen et al.*, 1981]. The most widely held view of pulsating aurora generation is a type of relaxation oscillator involving trapped electrons and VLF wave-producing instabilities in the equatorial region of the magnetosphere [*Trakhtengerts et al.*, 1986; *Demekov and Trakhtengerts*, 1994]. A recent observational and theoretical review is given by *Nemzek et al.* [1995].

[3] On the other hand, *Stenbaek-Nielsen* [1980] has proposed that active ionospheric processes probably play an important role in causing or modifying pulsating auroras. Recently, *Sato et al.* [1998] showed some supporting evidence for the active role of the ionosphere based on the non-conjugate features of pulsating auroras relating to their shapes and periodicities. *Tagirov et al.* [1999] discussed a new approach including the effects of relaxation characteristics of the ionosphere on previous theory. They suggested that the relaxation time of the ionosphere should be reflected in the pulsation periods. However, even today, certain basic characteristics of pulsating auroras, such as the generation region, periodicity, and shapes, are still open to debate.

[4] In order to investigate the generation region and modulation mechanism for pulsating aurora, simultaneous observations of optical aurora at conjugate-pair stations on the ground together with rockets and/or satellites are very informative and important. For such aims, simultaneous rocket-ground campaigns have been undertaken several times, mostly in the interval 1970 – 1990. However, direct temporal and spatial comparisons between satellite measurements and optical pulsating aurora have not, as yet, been reported. As a result of the complex shapes, rapid movements, and periodicities exhibited by pulsating auroras, spacecraft observations of these phenomena often cannot distinguish between their spatial and temporal ambiguities.

[5] The Fast Auroral SnapshoT (FAST) satellite was specifically designed to investigate the plasma physics of auroral phenomena at very high resolution in time and space within the acceleration region [e.g. *Carlson et al.*, 1998]. Our study centers on the direct comparison of pulsating aurora observed simultaneously from the FAST satellite and from the ground at Syowa Station (66.2°S, 71.6°E in geomagnetic coordinates, and MLT = UT + 0.15 hour) in Antarctica. The essential conclusion of this study is that the east-west-aligned multi-band pulsating aurora could have been generated by the oscillation of field-aligned electric fields.

2. Observation

[6] At Syowa Station in Antarctica a white-light all-sky TV camera recording at 30-frames/sec and a digital white-light all-sky camera (ASC) recording at 20-sec/frame with a

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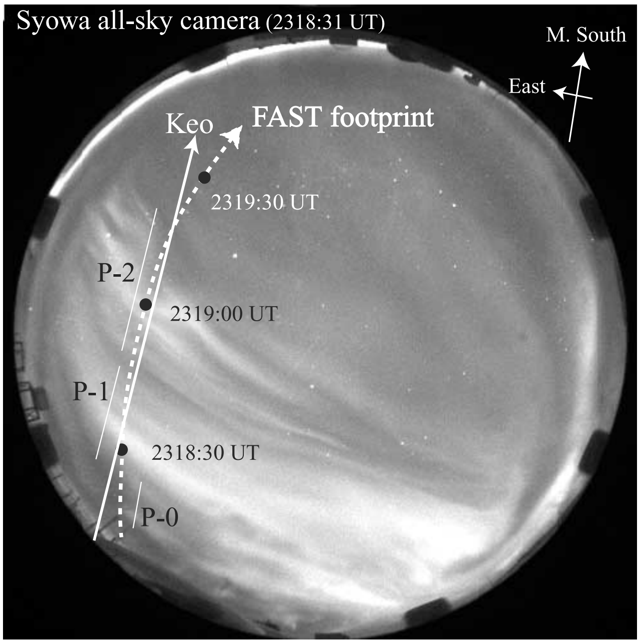

Figure 1. Snapshot images obtained by a panchromatic all-sky camera at 2318:31 UT with an exposure time of 2 sec. The footprint of the FAST satellite mapped to 100-km altitude and the Keogram position are marked on this image.

2-sec exposure time were in operation on 30 September 2000 during the Iceland-Syowa conjugate auroral campaign. An active pulsating aurora started to appear from ~2315 UT at the conjugate-pair of observatories during the recovery phase of a substorm. The FAST satellite passed over the Syowa all-sky camera field of view from ~2318 UT to ~2321 UT when the pulsating aurora was observed. The altitude of FAST was ~3100 km.

[7] Figure 1 shows an ASC snapshot image at 2318:31 UT. The footprint of FAST mapped to 100-km altitude and a Keogram time slice are marked in this ASC image. We shall begin by discussing some distinctive features of the optical pulsating aurora that appear in the ASC image and the Keogram. The Keogram, which is shown in Figure 2, was generated from the all-sky TV camera data. The ASC image shows that the pulsating aurora consists of multiple east-west-aligned bands. Furthermore, there are two different types of pulsating aurora (pulsation-1, P-1 and pulsation-2, P-2) as seen from the Keogram. Pulsation-1 is the poleward moving form located at lower-latitudes and pulsation-2 is the standing form located at higher-latitudes than pulsation-1. The recurrence period is ~5 sec for both types of pulsation. Emission intensity of pulsation-1 is relatively higher than that of pulsation-2. It is worth noting that another type of east-west aligned pulsation bands (pulsation-0) is seen at lower-latitudes than pulsaton-1. Pulsation-0 is elongated from the north-west horizon eastwards. The FAST satellite traversed over the faint pulsation-0 region just before entering the pulsaton-1 region.

[8] The upper panel of Figure 2 shows the Keogram and approximate FAST footprint. The Keogram departs slightly from the FAST footprint in the east-west direction, as seen in Figure 1. The energy spectrum of down-going electrons is illustrated in the bottom panel of Figure 2. The FAST footprint and Keogram indicate that FAST entered the region of pulsation-1 at ~2318:28 UT and exited from the region of pulsation-2 at ~2319:08 UT. The pulsating features observed prior to 'A' (~2318:28 UT) indicate that FAST was located at the region of pulsation-0. The energy spectrum demonstrates that accelerated electron flux enhancements forming inverted-V structures (marked as black dotted lines) are observed at the energy range of ~0.1–1 keV during the interval from 'A' to 'F'. Brief, spatially narrow 'gaps' in the inverted-V structure are found during the intervals 'B–C' and 'D–E'. It is worth noting that the east-west-aligned pulsating aurora occurs just within the region of the inverted-V structure. Furthermore, the occurrence regions of pulsation-1 and pulsation-2 are clearly separated by the gap 'B–C'. It is also noteworthy that a higher energy flux modulation is observed for electron energies of more than a few keV (marked by a white, dotted line on the energy spectrum), and that this is well correlated with the temporal and spatial variations of the optical pulsating aurora. However, the lower energy (0.1–1 keV) flux modulation, which is forming the inverted-V structure, does not show such a clear relationship with the optical pulsating aurora. This dependence of the observed optical intensity on the energy range of the precipitating electrons was confirmed by our calculation of the 427.8 nm emission rate by means of the model proposed by *Rees and Jones* [1973] with the incident electron fluxes obtained by FAST (bottom panel of Figure 2).

[9] The middle panel of Figure 2 shows the total energy flux of down-going electrons for >5 keV (black solid line) and the total energy flux of down-going ions in the energy range of 1–10 keV (red dotted line). It can clearly be seen that the optical pulsation 'ON-OFF' cycle shows a one-to-one correlation with the high-energy electron flux variations. For example, the FAST satellite is traversing through 'ON' regions of the poleward moving aurora (pulsation-1) during the intervals ~2318:28-2318:32 UT and ~2318:34-2318:40 UT and through 'OFF' regions in the intervals of ~2318:32-2318:34 UT and ~2318:40–2318:43 UT respectively. A similar relationship is found in the realm of pulsation-2. In other words, such temporal and spatial behavior indicates that in the pulsation-1 region the waves are overtaking the spacecraft and the behavior is dominated by the spatial structures of the wave as it moves across the spacecraft. In the pulsation-2 region FAST is above a pulsating arc and is sampling the temporal variability. Note that the position of the electron flux enhancement at ~2319:01 UT corresponds to a narrow auroral arc. It is also found that the temporal and/or spatial behavior of electron flux modulation between the intervals of ON and OFF for pulsation-1 are steep and step-like signatures, but those for pulsation-2 are rather gradual. As shown in Figure 3 these features suggest that pulsation-1 is caused by a step-like positive/negative potential structure which is moving poleward quasi-periodically, and that pulsation-2 results from a potential structure that is oscillating in intensity without spatial motion. The flux modulation rate between the ON and OFF for pulsation-1 is about 30–40%, which is consistent with previous work [*Sandahl et al.*, 1980].

[10] The temporal and spatial features of the down-going ion flux (1–10 keV), as displayed in the middle panel of Figure 2, are very interesting. It is clear that the ion flux modulation is anti-correlated with the >5 keV electron flux

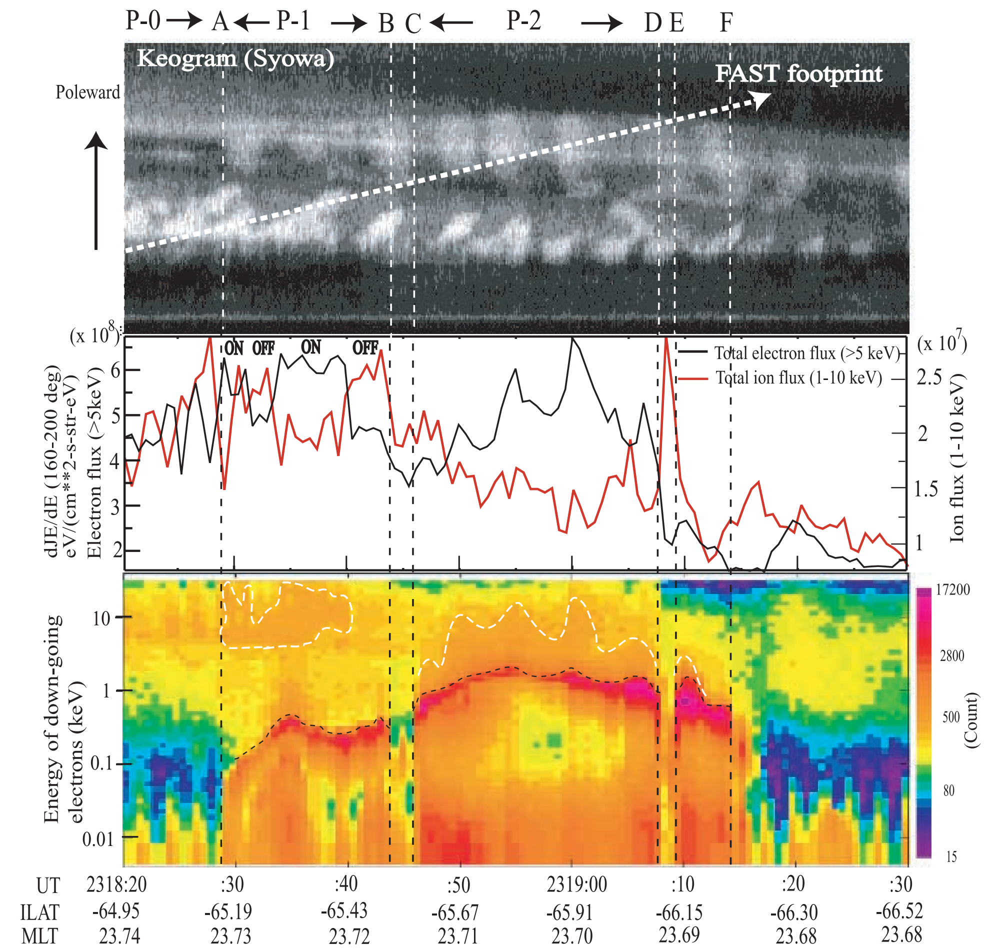

Figure 2. The upper panel shows the Keogram reproduced from the all-sky TV camera. The approximate FAST footprint is marked in this figure. The middle panel shows the total energy flux of down-going electrons for the energy range of >5 keV and the energy flux of down-going ions for the energy range of 1–10 keV. The energy spectrum for the down-going electrons is illustrated in the bottom panel, where ILAT and MLT stand for invariant latitude and magnetic local time, respectively.

modulation during the intervals of 2318:28–2318:43 UT in the pulsation-1 region and also during ~2318:20–2318:28 UT in the impulsive pulsation region (pulsation-0) located at the lower latitude side of pulsation-1. Such an out of phase feature is also found in the pulsation-2 region during the interval of 2319:05–2319:08 UT. A sharp ion-flux enhancement is found to coincide with the gap in the inverted-V structure at 'D–E'. These anti-correlated features suggest that the field-aligned electric field is located above the FAST spacecraft. Thus, optical pulsation ON occurs where the electric field is upwards aligned and, inversely, pulsation OFF occurs for downward electric fields. However, the field-aligned electric field intensity observed by FAST is rather weak and stable (from zero to less than minus 10 mV/m) in both the pulsation-1 and pulsation-2 regions, which suggests that the acceleration region might be located far from the FAST satellite altitude.

3. Summary and Discussion

[11] We have carried out a direct comparison between east-west-aligned multi-band pulsating aurora observed from the ground at Syowa in Antarctica and onboard the FAST satellite. The major findings in this study are that: 1) spatial and temporal variations of the down-going, high energy (>5 keV) electron flux shows a one-to-one correspondence with the optical pulsating aurora, 2) pulsating auroras occur within the region of the inverted-V structure of lower energy (0.1–1 keV) electron precipitation, 3) the occurrence regions of the two different types of pulsating aurora, pulsation-1 (poleward moving) and pulsation-2 (standing oscillation), are separated by the narrow gap in the inverted-V structure, 4) the down-going high-energy ion flux modulation is out of phase (anti-correlated) with the down-going high-energy electron flux modulation. Such features suggest that the quasi-periodic variation of the down-going high-energy electron flux producing the pulsating aurora is caused by a modulation of the field-aligned electric field located above FAST.

[12] The form of the east-west-aligned multi-band aurora reported in this study may be related to the inverted-V structure of the 0.1–1 keV down-going electrons. This signature is very similar to those of east-west-aligned discrete arcs, although the peak energy for a discrete arc

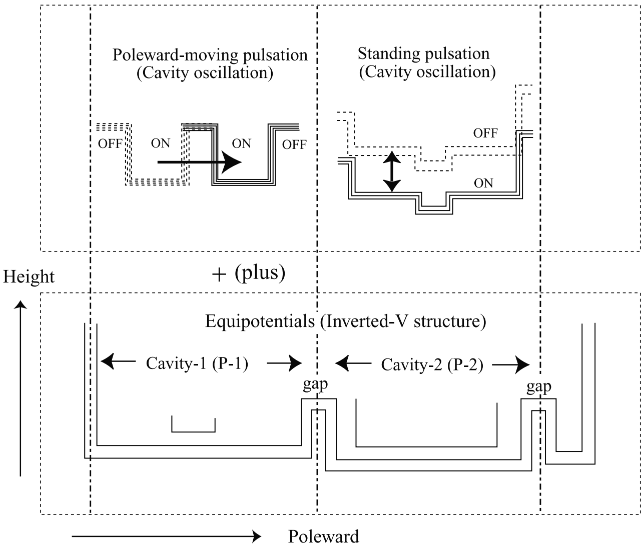

Figure 3. A schematic to explain the generation mechanism for the two different types of pulsating aurora. The different temporal and spatial oscillations of the potential structure may generate the two types of pulsating aurora. The quasi-static potential structure, which is generating the inverted-V structure in electron precipitation, may contribute to form the east-west-aligned band configuration.

is typically a few keV to 10 keV. Another interesting point drawn from this study is that there are two different types of pulsating aurora, which are clearly separated by the 'gap' in the inverted-V structure. We can infer that each type of pulsation may be caused by a resonance cavity oscillation between the potential boundaries. A poleward moving pulsating aurora may be the result of a cavity oscillation where an equipotential hole structure moves poleward without intensity variations, displaying only a spatial oscillation. On the other hand, a standing mode pulsation may be the result of a cavity oscillation where an equipotential hole changes its intensity with time without spatial movements. A schematic to explain this model is shown in Figure 3.

[13] Up to the present, almost all theoretical work [e.g., *Johnstone*, 1983; *Davidson*, 1990; *Demekov and Trakhtengerts*, 1994] attempting to explain pulsating aurora has been based on the assumption that the precipitating electrons are produced by pitch-angle scattering through wave-particle interactions in the equatorial region of the magnetosphere, and that aurora-producing particles precipitate symmetrically into both hemispheres along the geomagnetic field lines. However, these models cannot explain the most basic characteristics of pulsating aurora fully.

[14] The results presented here provide new insight into the mechanisms which generate pulsating aurora. The fundamental ON-OFF feature of the east-west-aligned pulsation is analogically the same as that of a patch-type pulsating aurora in terms of the period and the flux modulation ratio. However, the generation mechanisms are likely to be different in the two cases because the classical interpretations of the patch-type pulsating aurora can hardly account for the east-west-aligned pulsation that we observed. To clarify the generation mechanism, a similar conjunctional observation between FAST and a ground observatory for a patch-type pulsating aurora is needed, as well as a theoretical study of both kinds of pulsating aurorae.

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