Abstract

Pulsating aurora (PA) is characterized by the periodically changing emission amplitudes with on-off pulsations of less than 1 s to a few tens of seconds [*Røyrvik and Davis*, 1977; *Oguti et al.*, 1981; *Yamamoto*, 1988]. PA is also well-known as its patchy structure with the horizontal size of 10-200 km. A number of rockets and low-altitude satellites have provided observations of precipitating electrons, which generate PAs, and the characteristics such as 3-Hz modulations [*Bryant et al.*, 1971; *Sandahl et al.*, 1980; *Yau et al.*, 1981] and energy-time dispersions [*Sato et al.*, 2004; *Miyoshi et al.*, 2010]. The energy of precipitating electrons ranges from one to a few tens of keV. The electron precipitation that generates PA is thought to result from pitch angle scattering due to wave-particle interactions near the magnetic equator. In particular, the whistler mode waves are widely accepted as one of the drivers for PA on the basis of result from theoretical studies [*Johnstone*, 1983; *Davidson*, 1990], and it is suggested that whistler mode chorus wave taking into account non linear process plays an important role in the generation of PA [*Demekhov and Trakhtengerts*, 1994; *Trakhtengerts*, 1999].

Recently, *Nishimura et al.* [2010, 2011] found a one-to-one correspondence between the intensities of PA and amplitudes of whistler mode chorus near the equator. Similarly, electron cyclotron harmonics (ECH) with enough wave amplitudes to scatter electrons into a loss cone were observed synchronizing with switch-on and switch-off of PA [*Liang et al.*, 2010]. It is expected that ULF waves control the excitation of both the whistler mode chorus and ECH by the modulation of the local plasma density [*Liang et al.*, 2010; *Li et al.*, 2011]. However, an important problem, identifying which mechanism is the most dominant, remains unsolved. In addition, the observational evidence focusing on small-structures of PAs and their relationship among other properties of PAs such as the on-off periods and the rapid modulations has not been reported except for *Samara and Michell.* [2010]. Since PA has the distinctive properties in a variety of spatial and temporal scales, we should investigate such multi-scale properties statistically to further understandings of the generation mechanism of PA.

The purpose in this study is to reveal the precise spatial-temporal properties and a generation mechanism for the property of PA using two different approaches: micro-scale electron precipitations typically less than 1 second and identifications of source regions of the precipitating electrons obtained from the Reimei satellite, and further precise spatio-temporal properties in a two-dimensional plane using ground-based EMCCD camera with a wide field-of-view (FOV) and 100-Hz sampling rate. We will establish the generation mechanism for the properties of PA including unclear characteristics such as the small-scale structures (10-30 km) and rapid temporal variations (3-Hz modulations) based on observations and statistics.

We investigated the generation process of the electron precipitations and identified the source region of the electrons with applying the two TOF analysis models to 29 PA events. Reimei has a three-channel monochromatic auroral camera (MAC) with a narrow FOV and top-hat electrostatic electron and ion energy spectrum analyzers (ESA/ISA) with energy ranges from 10 eV/q to 12 keV/q. Time resolutions of the two instruments are 8 frames per second and 40 msec for a full scan of the energy range, respectively,

which make it possible to measure the micro-scale electron precipitations associate with PAs. The source region obtained from the standard TOF model (TOF-A) was distributed almost continuously in magnetic latitude ranges from -20 to 50°. On the other hand, the source region obtained from the new TOF model (TOF-B), which takes into account the interaction electron and whistler mode wave [*Miyoshi et al.*, 2010], ranged from the magnetic equator to low-latitudinal region ($\sim$ -11°). The source regions obtained from the TOF-B analysis generally corresponded to the regions in which whistler mode chorus waves are frequently observed in the previous studies, suggesting that the micro-scale precipitation of electrons caused by the cyclotron resonance with propagating whistler mode waves is a plausible mechanism for the production of PAs.

The result from the Reimei observation data and the TOF analyses implies that the micro-scale electron precipitation constitutes temporal variations of PA. For expanding our scope of the investigation on the property of PA, the ground-based optical observation was carried out during the period from November 2010 to March 2011 and from November 2011 to March 2012. We used an EMCCD camera with wide a FOV ($49 \times 49°$) and a high sampling rate of 100 frames/s. Firstly, we focused on meso- and small-scale PAs appeared at the early recovery phase of the substorm on March 4, 2011. Three independent pulsating patches (PA1-3) with different periods from 4 to 7 seconds were observed in the FOV of 100 $\times$100 km at the altitude of 110 km. The typical scale of the patch was estimated to be 2000 km in the magnetic equator, and it is comparable with the estimations based on recent in-situ observations. We examined the modulations of PAs in the frequency range higher than 1.0 Hz and their spatial distributions in detail. The results revealed that the modulation had a peak frequency around 1.5 Hz, with a narrow frequency width of 0.30 Hz. On the other hand, the adjacent PA2 and PA3 did not have dominant modulation and coherency at the frequency around 1.5 Hz. We also conducted the cross spectrum analysis and the result revealed that the modulations around 1.5 Hz inside PA1 were almost in phase. Moreover, it was found that the low frequency variations from 0.2 to 0.5 Hz inside PA1-3 propagated as a group of flows with consistent directions. The estimated fast flow velocities inside PA2 ranged from 50 to 120 km/s at the auroral altitude. They were corresponding to the horizontal velocities between 1800 and 2700 km/s at the magnetic equator, and almost equal to the Alfven speed at $L \sim 6$. The result suggests that compressional waves may drive control the growth rates of whistler mode waves, which can generate precipitation associated with PA, and drive the dynamics inside a patch.

Further, the PA observed on 1st December, 2011 also showed the typical cross-scale properties of PA in space and time. A southward propagating aurora patch exhibited the meso-scale structures composed of a few sub-structures. The temporal variations of the PA contained clear 3.0-Hz temporal modulations superimposed on on-off pulsations of the period of 8-10 seconds. While the large-spatial scale of the whole patch was estimated to be 1500 km mapped onto the magnetic equator, the spatial scale of the sub-structure was 800 km. Additionally, the strong 3.0-Hz modulations were excited only in the sub-structures. The minimum width of sub-structures was estimated to be 410 km at the magnetic equator. On the other hand local proton gyro radius was estimated to be smaller ($\approx$ 100 km) than the width, which suggests that the sub-structures would be mainly maintained by MHD forces. However, a kinetic effect, such as ion finite Larmor radius effects, may also contribute to form the complicated sub-structures [*Hiraki and Sakaguchi*, 2010], because the minimum scale was still close to local proton gyro radius.

Finally, the statistical study on the cross-scale properties were presented based on 53 events during the period from December 1st, 2011 to March 1st, 2012. The observed modulation frequency ranged from 1.5 to 3.3 Hz, and it is almost consistent with well-known 3 $\pm$ 1 Hz modulations in previous studies [*Røyrvik and Davis*, 1977]. The occurrence probability was slightly concentrated on the frequency range between 2.0 and 2.5 Hz. Although recent result with ground-based observations showed rapid variations in higher frequency range of 10-30 Hz, any strong modulations were not seen in frequency range higher than about 3 Hz in our study, which may suggest that the TOF of electron makes the time-smoothing effect on the rapid variations higher than 3 Hz. Moreover, the frequency of modulation showed relatively strong correlation to auroral intensity with the correlation coefficient of 0.52, and it can be explained with non linear wave growth theory suggesting that higher modulation frequency with larger wave amplitude of whistler mode chorus. In contrast to the rapid modulations, the on-off pulsations showed no significant correlations with any of other properties of PA. This result implies that the on-off periods may be determined by the balance of a variety of factor. In contrast to the rapid modulations, the on-off pulsations showed no significant correlations with any of other properties of PA. This results imply that the on-off periods may be determined by the balance of a variety of factor. In addition to the wave-particle interactions corresponding to loss rate of electrons in a flux tube, long-term variations of the cold plasma density caused by compressional mode waves would play more important role in control wave-particle interactions in the temporal scale of the on-off pulsation periods. The enhancement of rapid variations was seen inside sub-structures in many cases. However, no clear correlations between the modulation frequency and the spatial size of the whole and sub-structures were found statistically. The reason still remains an open question and should be addressed to investigate in near future.

As a conclusion of this study, we propose a possible generation mechanism of PAs that explains the spatial and temporal cross-scale properties presented in this study. A group of energetic electron with energy ranges from a few to a few tens of keV are supplied into a flux tube with a drift velocity. The electrons with sufficient anisotropy immediately excite whistler mode chorus element with a time scale less than 1 second based on non linear wave growth theory, and the electrons are almost simultaneously scattered into small pitch angles. The electrons scattered into a local loss cone result the micro-scale electron precipitation with a duration time of several hundreds of milli-seconds. As long as the supply of fresh electrons into the flux tube continues or the cyclotron resonance conditions are changed by temporal variations of cold plasma density due to compressional mode waves, both the chorus elements and the micro-scale precipitations of electrons are generated repeatedly. Consequently, the on-phase of PA modulated at the frequency of a few-Hz can be observed with ground-based optical instruments. Expanding a scope of the property in equatorial plane, a compressional mode wave may drive the dynamics inside a patch, such as expansion-contraction and streaming, via modulation of the flux tube. Force balance between magnetic tension and plasma pressure triggers the development of complicated spatial patch structures governed by instabilities taking into account kinetic effects on a time scale longer than a few minutes.

This model for the generation process gives us comprehensive understandings of the cross-scale properties of PA in space and time. Quantitative evaluation of the model combined with simultaneous ground-based and in-situ observations would be an essential, and the visualization of wave-particle interactions and related instabilities with a high-speed imaging technique is quite useful for further understandings of microscopic space plasma physics including PAs.