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Pulsating aurora beyond the ultra-low-frequency range

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[1] Pulsations, irregularly switching on and off in the brightness with typical durations of an order of 2 to 20 s, are a fundamental characteristic of post-midnight aurora. Although pulsating aurora is weak compared with those of quiet arcs or breakups, a cutting-edge sensitive high-speed camera is now capable of detecting the faint aurora with more than several hundred frames per second. Here we briefly report the fastest-ever-observed fluctuation superimposed on a pulsating aurora, which is more than an order of magnitude faster than well-known 3 ± 1 Hz modulation. The exact generation mechanism remains unknown, and we discuss two different possibilities of the modulation source at the equatorial magnetosphere and at the magnetosphere-ionosphere coupled region.

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1. Introduction

[2] The aurora is known to be caused by showers of charged particles, mostly electrons, in the upper atmosphere but there remain fundamental uncertainties in the pulsation, i.e., a quasiperiodic plasma loss mechanism of trapped energetic electrons in the closed magnetic mirror. Pulsating aurora shows irregularly switching on and off in the brightness with typical durations in the range 2–20 s [e.g., *Yamamoto*, 1988]. Quasiperiodic fluctuation at a frequency of 3 ± 1 Hz is sometimes superimposed on the pulsation [*Oguti*, 1976]. Pulsating aurora is weak compared with those of quiet arcs or breakups. The intensity at 427.8 nm is less than 10 kR compared with bright forms which reach 100 kR and is usually only just above the visual threshold of approximately 1 kR [*Johnstone*, 1978].

[3] A number of studies have suggested that pulsating aurora is caused by wave-particle interactions near the equatorial magnetosphere. For example, THEMIS observations showed that the pitch angle scattering is caused by the whistler mode chorus waves, and the 8 s periodicity of a pulsating aurora corresponds to the repetition periods of the chorus waves [*Nishimura et al.*, 2010]. On the other hand, FAST observations of a pulsating aurora with 6 s periodicity showed an anti-correlation of precipitation between ions and electrons, which is explained by the modulations of the field-aligned potential drop in the magnetosphere-ionosphere coupled region [*Sato et al.*, 2004]. From ground-based conjugate imaging observations in the northern and southern hemisphere, it was found that the shapes of pulsating aurora are not always the same and the periods are in many instances different in the two hemispheres [*Sato et al.*, 1998, 2004; *Watanabe et al.*, 2007], which may suggest that the modulation takes place close to the ionosphere of each hemisphere rather than at the equatorial magnetosphere.

[4] The purpose of this paper is to report the fastest-ever-observed fluctuation in pulsating aurora with more than an order of magnitude faster than the 3 ± 1 Hz modulation. We discuss two different possibilities of the modulation source at the equatorial magnetosphere and at the magnetosphere-ionosphere coupled region to interpret the new data.

2. Results

[5] An observational campaign was conducted as part of a challenge put forth as part of NHK's TV program "The Cosmic Shore." We used a Phantom V710 high-speed camera equipped with a Hamamatsu image intensifier and a 24 mm F1.4 lens. The field-of-view is 42 × 24 degrees, with an image format of 1280 × 720 pixels. The temporal resolution was set to 500 frames per second, which is an order of magnitude faster than that of standard electron multiplying CCDs. We applied a sharp cut SCHOTT RG665 filter to remove the oxygen green and red lines and to detect only prompt emissions of the nitrogen first positive band with wavelengths longer than 670 nm. The associated energy range of electron precipitation is a few tens of keV. We operated the camera system at Poker Flat Research Range of University of Alaska Fairbanks (65N, 147W). The magnetic latitude is 65.5 degrees, and magnetic midnight is at approximately 1130 UT. The magnetic zenith is inside of the field-of-view. The time interval examined in this study is 13 s from 11:40:45.5 UT on 1 November 2011 when we see a clear pulsating ON-OFF sequence with very fast fluctuations during a typical postmidnight pulsating aurora after an aurora breakup initiated at ~1100 UT.

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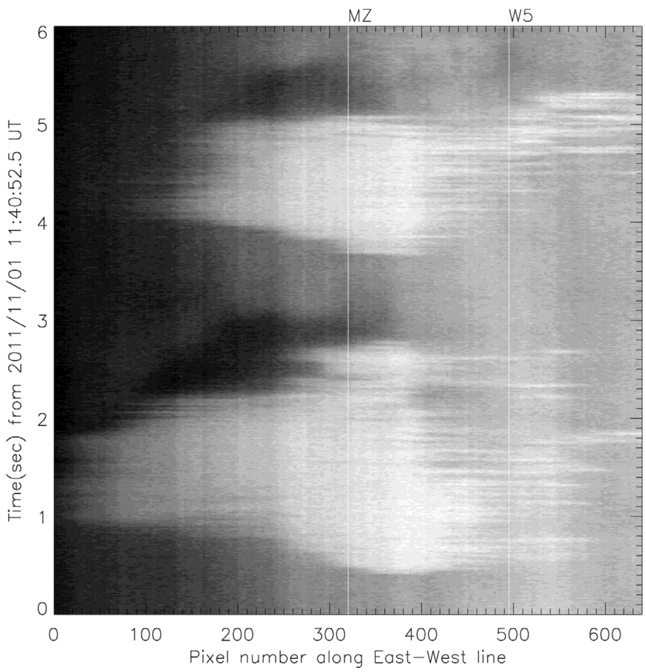

Figure 1. Position-time diagram of the pulsating intensity sliced along the east–west direction through magnetic zenith. Time is from bottom to top for the time interval of 6 s from 11:40:52.5 UT on 1 November 2011. The positions of magnetic zenith and 5 degrees to the west are marked by white vertical lines. The black to white color is linearly gray scaled from the intensity minimum to the maximum. There are pulsations of several different durations from a few seconds as appeared at magnetic zenith to only tens of ms at 5 degrees west.

[6] Movie S1 shows the ON-OFF pulsating sequence during the 6 s time interval.[1] A five-point running average in time was applied to each pixel in order to reduce random noise. The magnetic zenith (MZ) is to the left of the center, and the circle denotes a distance of 5 degrees from it. Magnetic north is approximately to the top and magnetic west is to the right. Assuming 100 km emission layer, 5 degrees distance from the zenith is about 9 km perpendicular to the magnetic field.

[7] Figure 1 shows the time variation of the horizontally sliced images along the east–west line over MZ and W5 in Movie S1. Time is from bottom to top, and west is to the right. It is clear that transient black auroras appear just after the ON signature and propagate from east to west. The pulsation at MZ shows what has typically been measured with the repetition interval of about 3 s, but the pulsation at W5 is showing ON-OFF periods much shorter than has been reported. The fast pulsation is located at the edge of ON signature of the typical pulsation, and the frequency of the outstanding modulation is 8–12 Hz as shown in Figure 2.

[8] Figure 2 shows the distribution map of Fourier spectral amplitude from 1 Hz to 50 Hz during the 1 s time interval from 11:40:52.5 UT on 1 November 2011. The time series averaged over each 10 × 10 pixels is Fourier transformed, and the spectral amplitude distribution of the Fourier transform at each frequency is linearly gray scaled from black to white to see the spatial coverage. The fastest part of repetition frequency is up to 35 Hz, which is an order of magnitude faster than 3 ± 1 Hz modulation. The well-known 3 Hz modulation cannot be found inside the main pulsation at MZ as shown in the panels of 2–5 Hz. Note that the images are not saturated.

[9] The patches of pulsating aurora rapidly change their spatial extent as shown in Movie S1. Such very fast changes in the shape of the patches correspond to the fast modulations in the emission intensity along the edge as shown in Figure 2. For example, the narrow shapes along the edge around W5 show the 8–12 Hz variation. The typical width of the narrow shapes is a few km at 100 km altitude. A rounded shape of about 5 km extension shows 18–22 Hz variation at around W5, while a localized spot of only a few km extension shows 33–35 Hz variation at similar location. These high-frequency variations are not a simple artifact of the Fourier analysis, and a series of 30 ms pulses actually exist in the time profiles.

[10] Figure 3 and Movie S2 shows evidence for the fastest fluctuation found during the observation time interval of the pulsating aurora. Magnetic zenith is approximately at the center, magnetic north is to the top, and magnetic west is to the right. The fastest part of repetition frequency is up to 54 Hz at about 12 degrees to the east from the magnetic zenith. As shown in Figure 3c, a series of 20 ms pulses actually exist in the time profiles at the signature X in Figures 3a and 3b. The FFT spectra in Figure 3d show the ensemble average of 16 pixels around the signatures X in Figures 3a and 3b. The dotted lines show the noise levels, where the average amplitude of more than 100 Hz is assumed as a white noise spectrum based on the fact that there is no structured spatial coverage of signals found in the distribution map of Fourier spectral amplitude beyond 100 Hz. As also shown in Figure 3d, the spectral amplitude is significant, exceeding the 3-sigma level at 54 Hz.

3. Discussion

[11] The interpretation of the fast modulation would be twofold. The first "near-equatorial" hypothesis assumes that the source region of the fast modulation is near the equatorial magnetosphere. *Trakhtengerts et al.* [2004] have reported short bursts of whistler mode chorus waves, with durations between 20 ms and 2.0 s, as measured by the Cluster spacecraft near the magnetic equator. The fastest part of these measurements is consistent with those of the fast pulsating aurora presented here. One-to-one relationship between the chorus elements and 20–30 ms pulses are expected if the electrons precipitated by the wave-particle interaction are mono-energetic, while the fastest modulation may be smoothed out by time-of-flight effect of the velocity dispersion if the energy range of electrons are broadband. The actual situation is in-between, and it raises an interesting problem for standard theories of chorus waves how to realize the wave-particle interaction to cause the electron precipitation in the narrow enough energy range with the duration of 20–30 ms. It would not be straightforward because the precipitating electrons of pulsating aurora have the energy

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[1] Auxiliary materials are available in the HTML. doi:10.1029/2012JA017987.

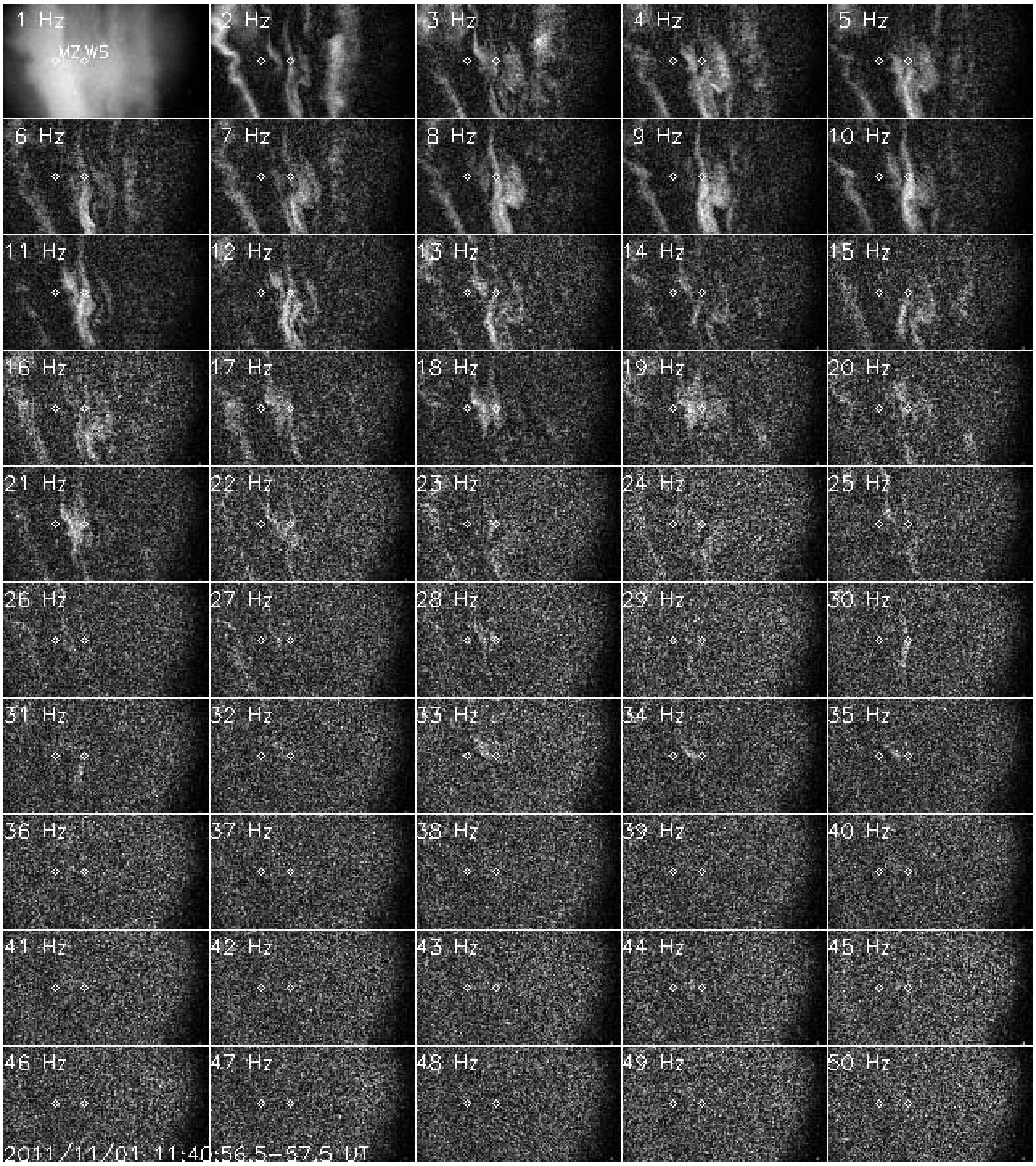

Figure 2. Distribution map of Fourier spectral amplitude from 1 Hz to 50 Hz during the 1 s time interval from 11:40:56.5 UT on 1 November 2011.

range from a few keV to 100 keV [*Sandahl et al.*, 1980; *Miyoshi et al.*, 2010].

[12] Usual rising-tone chorus elements have repetition periods of ~100 msec (~10 Hz) and are capable of creating 3 ± 1 Hz modulation. It would be important for future numerical simulations to relate the wave-particle interaction at near equatorial magnetosphere and the fast pulsations because the near-equatorial hypothesis may provide a unified hierarchical association of pulsating aurora with chorus waves extended to three orders of magnitude ranging from 20 ms to 20 s. If the near equatorial hypothesis was true, the spatial extent of the source of pulsating patches in the magnetosphere should change very quickly. Since the fast variations are mainly seen around the edge of typical pulsating patch, the wave-particle interaction by the chorus wave bursts with very fast repetitions must occur only in a localized area near the edge of pulsating aurora.

[13] The second “near-Earth” hypothesis assumes that the source region of the fast modulation is the magnetosphere-ionosphere coupled region of a half to a few Earth radii altitude. The 20–30 ms pulses may indicate a nearby source close to the ionosphere, in terms of minimizing the velocity dispersion. In contrast to the one-way association of the near-equatorial hypothesis, near-Earth hypothesis is more complex. However, note that any feedback processes via the ionospheric density are not likely the essential cause of the

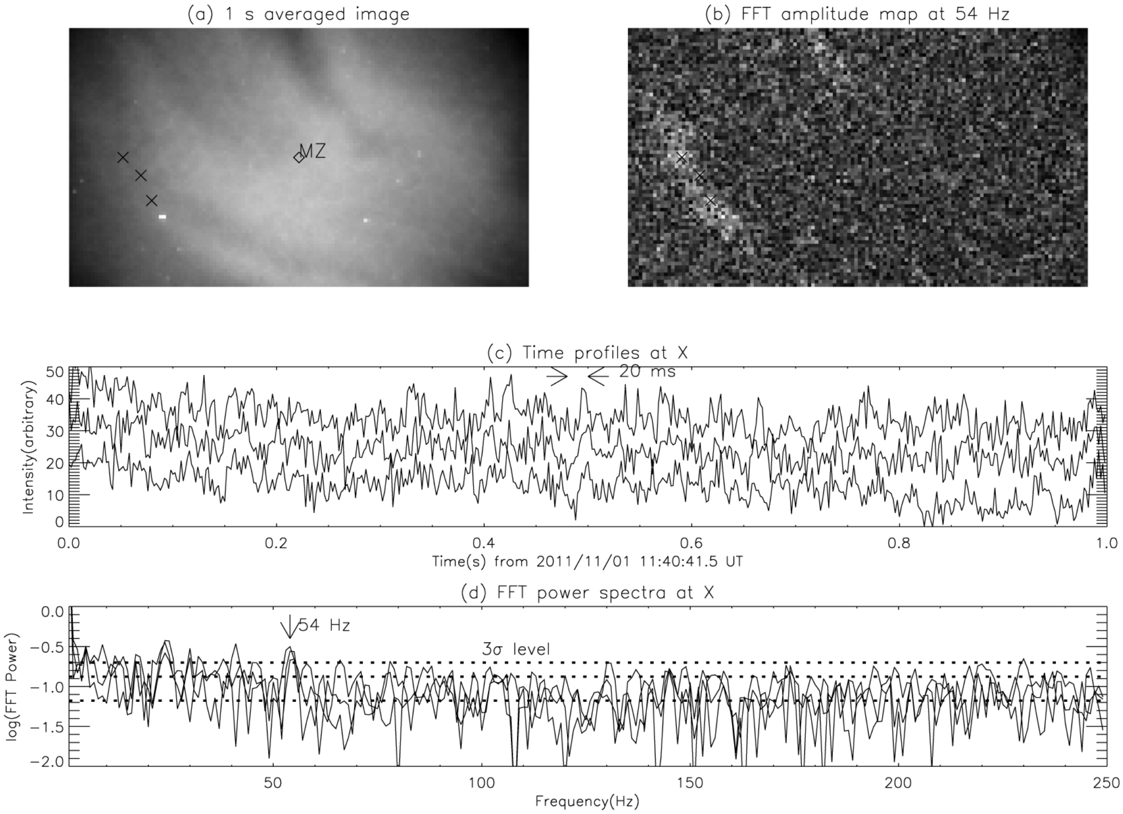

Figure 3. FFT spectral analysis for the 1 s time interval from 11:40:45.5 UT on 1 November 2011; (a) 1 s averaged image, (b) distribution map of Fourier spectral amplitude at 54 Hz, (c) time profiles at X points, (d) FFT power spectra at X points, where dotted lines show the white noise levels of 1, 2, and 3 times of the standard deviation.

fast modulation because the relaxation time scale due to the recombination is an order of 5 s at E region [*Tagirov et al.*, 1999], which is two orders of magnitude slower than the observed 20–30 ms pulses.

[14] In the magnetosphere-ionosphere coupled region, a different phenomenon called flickering aurora tends to develop within discrete arcs and exhibits oscillations of several Hz and higher [*Sakanoi et al.*, 2005; *Yaegashi et al.*, 2011]. The 20–30 ms pulses found in this study are, however, not likely representing a standard flickering aurora based on the morphology. Flickering aurora shows an interference-like pattern, and therefore the standard theory to explain it is the interference of electromagnetic ion cyclotron waves [*Temerin et al.*, 1986; *Sakanoi et al.*, 2005; *Kataoka et al.*, 2011]. The sinusoidal wave forms as expected from flickering aurora are very different from the appearance of 20–30 ms pulses. We may need to introduce a different type of transient excitation of dispersive and nonlinear properties of Alfven waves, such as Alfvenons [*Stasiewicz and Ekeberg*, 2008] and trains of solitons [*Strumik et al.*, 2011] to realize rapidly changing spatial extent near the edge of pulsation to support the near-Earth hypothesis.

[15] We cannot conclude that the fast fluctuation as identified in this study is a common feature for pulsations or not because this is the only one successful shot we found during the very limited campaign time interval of a few clear nights with significant aurora activity at magnetic zenith. Also, it is noteworthy that the pulsating aurora shown in this study did not coexist with the traditionally outstanding 3 ± 1 Hz modulation. Systematic search of the fast fluctuations of pulsating aurora around the magnetic zenith coordinated with in situ satellite observations would be very important in future to test the detailed physics behind the pulsation, i.e., a quasiperiodic plasma loss mechanism of trapped energetic electrons in the closed magnetic mirror.

4. Summary

[16] We found a series of 20–30 ms pulses in auroral electron precipitation during a pulsating aurora, although the source mechanism remains an open question. Until now it was impossible to capture the 20–30 ms pulses because of the Nyquist frequency of hundred Hz imaging observations, which is the fastest mode of electron-multiplying CCD cameras. We are in the beginning stage of the next generation of high-speed imaging of aurora. The auroral morphology has been explained in the ultra-low frequency range of less than 10 Hz. Understanding the rapid wave-particle interactions and magnetosphere-ionosphere coupled processes beyond the ULF range would not be restricted to pulsating auroras only, but could be of importance in all rapidly varying aurora as we are going to observe via high-speed imaging in near future.

[17] **Acknowledgments.** Robert Lysak thanks the reviewers for their assistance in evaluating this paper.

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