"Physics of Auroral Phenomena", Proc. XLIV Annual Seminar, Apatity, pp. 126-129, 2021

Polar Geophysical Institute

DOI: 10.51981/2588-0039.2021.44.029

ON THE POSSIBLE ORIGIN OF INTERNAL (2-3 HZ) MODULATION OF PULSATING AURORAS

V. Safargaleev[1,2], T. Sergienko[3], K. Hosokawa[4], Y. Ogawa[5],
Y. Miyoshi[6], S.-I. Oyama[6,4], S. Kurita[7], R. Fujii[8]

[1]*Polar Geophysical Institute RAS, Apatity, Russia*
[2]*Institute of Terrestrial Magnetism, Ionosphere and Radio Wave Propagation RAS, St. Petersburg, Russia*
[3]*Swedish Institute of Space Physics, Kiruna, Sweden*
[4]*University of Electro-Communications, Tokyo, Japan*
[5]*National Institute of Polar Research, Tokyo, Japan*
[6]*Institute for Space-Earth Environmental Research, Nagoya University, Nagoya, Japan*
[7]*Research Institute for Sustainable Humanosphere, Kyoto University, Kyoto, Japan*
[8]*Research Organization of Information and Systems, Toranomon, Minato-ku, Tokyo, Japan*

Abstract. Data of three all-sky cameras in Kiruna and Tjautjas (Sweden) were used for estimation of altitude of pulsating arc-like forms and investigation of so-called internal modulation (2-3 Hz) during the ON-phase of a few second pulsations. It is found that for two closely spaced arcs, internal modulation took place only in the lowest arc. Based on this finding, an explanation is proposed due to the pulsations of anomalous resistance in the field-aligned current associated with a pulsating structure appart to the traditional mechanism of particle scattering by VLF waves.

1. Introduction

Pulsating aurora (PsA) is referred to as a kind of diffuse aurora that appears, in general, as irregular patches or more regular arc/segment structures with quasi-periodic on-off switching of its intensity. One of the types of PsA is characterized by a mixture of two distinct periodicities that coexist hierarchically. One periodicity is the "main pulsations" which is the primary periodicity component ranging from a few to a few tens of seconds. The other is the so-called "internal modulation" which is quicker luminosity scintillation (a few Hz) embedded in a single pulse of the main pulsations (Fig.1,b). *Royrvik and Davis* (1977) showed that internal modulation appears in more than 50% of all PsA events.

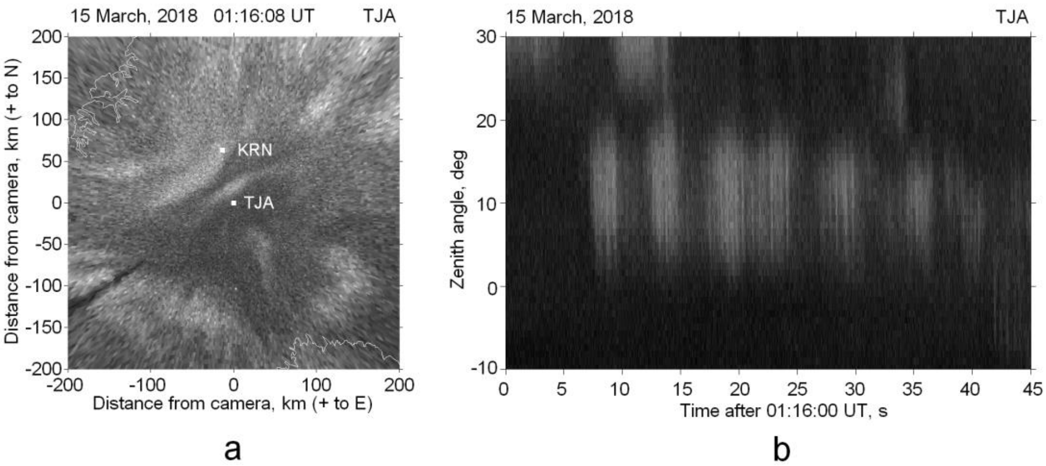

Figure 1. (a) Location of pulsating arc relatively Kiruna (KRN) and Tjautjas (TJA) observatories shown with white squares. (b) keogram showing the temporal variation in auroral brightness sampled along south to north cross section. Series of bright patches reveals the main pulsations, vertical strips inside the patches are the signature of internal modulation.

Pulsating aurora has been studied for decades (see review by *Lessard*, 2012), but its generation and modulation mechanisms are still open issues. The still-existing different approaches to the mechanism of pulsating aurora seem to be conditioned by a lack of *in-situ* observations. Indeed, the rocket and satellite studies represent a case study. Beside of this, it is noteworthy that in many studies there is no direct indication of exactly what auroral form is under consideration either the difference of pulsating forms is not emphasized. The morphology and nature of different pulsating forms may be different. In this study we focus on the measurements of internal pulsations in the arc-like structure as well as the estimation of the structure altitude with pair of closely-located cameras.

2. Instrumentation and some details of the methods used

The data of three all-sky-cameras were used in this study. The EMCCD all-sky camera in Tjautjas (TJA; 67.31°N, 20.73°E), Sweden, that was installed under the PsA research project and PWING project (e.g. Shiokawa et.al., 2017) gives 100 images per second that allow us to detect both the main pulsations and the internal modulation in PsA. Two identical sets of all-sky Watec Monochromatic Imagers (WMI) of National Institute of Polar Research, Japan, installed in Kiruna (KRN; 67.88°N, 20.42°E) and Tjautjas (see Fig.1a) with the north-south base distance ~ 60 km give the images with the time resolution 1s, and therefore pulsating aurora with a period of main pulsations can be targeted to study (*Ogawa et al.*, 2020).

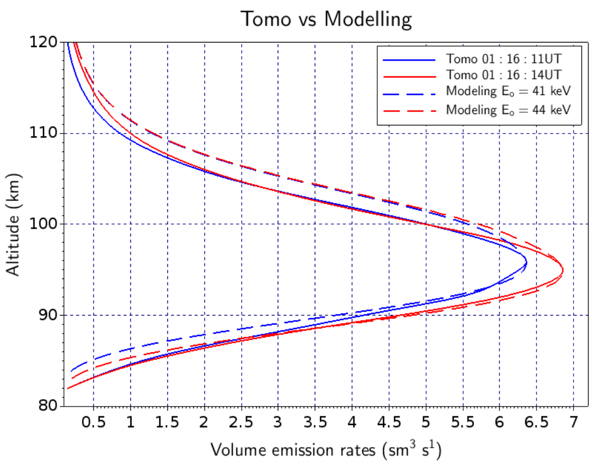

Figure 2. The reconstructed (solid line) and calculated (dashed line) 557.7 emission rate profiles.

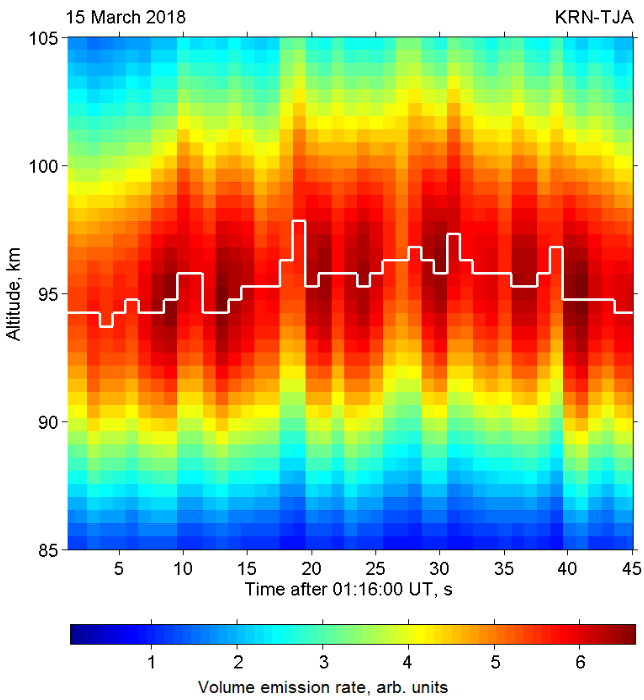

Figure 3. Altitude vs time diagram. White step-like line shows the time variation in the altitude of maximum luminosity.

The images taken with the WMI cameras were used for the reconstruction of the volume distribution of the auroral emissions. Unfortunately, the 557.7 and 670.0 images were oversaturated during the event. Following the results by *Partamies et al.* (2007), we used the green channel images of the color WMI camera for the tomography-like reconstruction of the volume distribution of the auroral emission and hereinafter we refer to this as the 557.7 nm emission distribution. The reconstruction was done with a tomography-like algorithm developed by *Gustavsson* (1998). Looking ahead, we note that for event considered there was no noticeable difference between luminosity altitude profiles inferred from green channel data by the method of tomography by *Gustavsson et al.* (1998) and calculated using the model of the auroral green line by *Ivanov et al.* (1993) (see Fig.2b).

When it was possible, we also performed the comparative analysis of a few Hz luminosity variations (internal modulation) in two neighboring pulsating arcs during the ON phase of the pulsations. For the high-speed camera images, the mean intensities of certain 3x3 pixel areas of the pulsating auroral structures were calculated.

3. Results of observations

The main results of investigations are the following:

(1) <u>Main pulsations and internal modulation represent the localized phenomenon attributed to the arcs.</u>

(2) <u>Altitude of the arc during the ON phases is less than that for OFF phases.</u> By regarding the examined arc as a homogeneous structure, we have found out the following feature of its behaviour (see Figure 3). The “arc altitude”, defined by us as the position of the maximum of luminosity, was less within the switch-on intervals than between them. The altitude changes by 1.5 – 3 km that is larger than the spatial resolution of the method of optical tomography (~ 500 m). To the authors’ knowledge, the earlier observations of PsA showed no indication of changes in height of the lower border during the lifetime of a single pulsation (e.g. *Brown et al.*, 1976). Probably,

this is due to the lower spatial resolution of the triangulation method, which is traditionally used in such investigations. The decrease of arc altitude means that the energy of precipitating particles increases.

(3) Of two closely spaced arcs, internal modulation of luminosity took place only in the lowest arc. The merit of optical tomography is an ability to distinguish the fine structure of auroral arc whereas on ordinary all-sky images it may be masked by neighboring structures. The more careful analysis showed that the structure considered consists actually of two thin arcs, at least, at the beginning of the interval. This allowed us to calculate the variation of luminosity in each arc separately (Fig. 4,b). The comparison with tomographic reconstructions showed that internal modulation appears in that arc of two which altitude is less during the ON phase. Earlier, *Whiter et al.* (2010) showed that the energy of flickering electron precipitation was higher than the energy of the non-flickering auroral electrons.

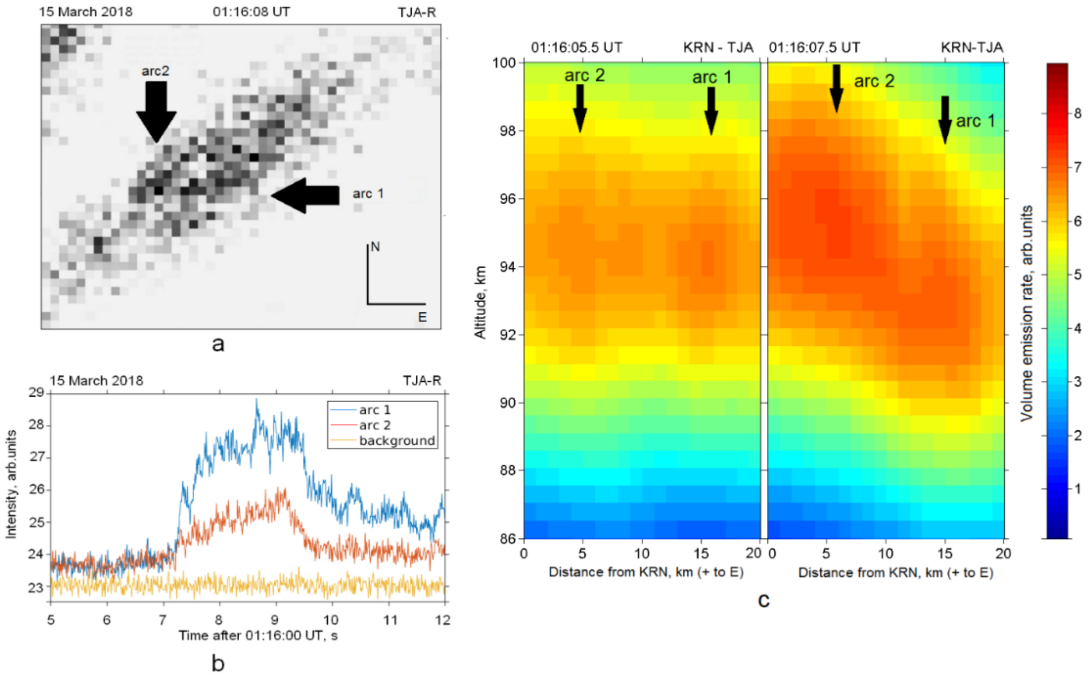

Figure 4. Internal modulation takes place in that arc of two, the altitude of which decreases with the luminosity increase. (a) Fine structure of pulsating arc; (b) luminosity variations in the arcs and background for switch-on interval; (c) altitude distribution of arc luminosity before (left panel) and during (right panel) the ON interval.

4. Interpretation of PsA features in the frame of traditional mechanism

The widely accepted a primary process for the PsA is the pitch angle scattering of electrons at the magnetosphere (e.g. *Lessard*, 2012). An other process without wave-particle interactions has been proposed by *Sato et al.* (2004) who showed that the time variations of the field-aligned potential drop may cause the pulsating aurora. In what follows, for brevity, we will refer to these approaches as scattering and accelerating approaches, respectively.

We have shown that the altitude of the emission is lower during the ON phases of PsA that means that the energy of precipitating electrons is higher at these moments. In the frame of scattering approach, the result can be explained by the model of *Miyoshi et al.* (2015). They demonstrated that PsA during the “on” phase is caused by scattering of electrons due to the lower/upper band chorus. The upper (lower) band resonates with lower (higher) energy electrons. Both the higher and lower energy electrons are detected during the “on” phase whereas only lower energy electron precipitations are seen during the OFF phase. Such a precipitation causes the higher altitude emission.

The internal modulation may be explained in the frame of scattering approach, too. *Hosokawa et al.* (2020) have demonstrated a direct association between the multiscale temporal variations in chorus wave power detected onboard Arase satellite and aurora luminosity inferred from the ground optical measurements. Namely, they showed correlation between chorus bursts and the main optical pulsations, as well as between discrete chorus elements embedded in a burst and internal modulation embedded in an impulse of main pulsations. *Hosokawa et al.* (2020) also noted that the energy of precipitating electrons ranges from a few to several tens keV.

Due to different time-of-flight from the magnetosphere to the ionosphere, significant spreading in time of the electron flux appears. In such a case, the sub-second modulation in chorus tends to be smeared out and ground-based optical instrument does not see the corresponding internal modulation in the PsA emission. If the resonance energy is higher (in our case this means that the corresponding arc is close to the Earth’s surface), the dispersion effect would be smaller and sub-second (internal) modulation is able to survive in the optical data.

5. Periodic acceleration as a possible mechanism for internal modulation

By using the Swarm satellite, *Gillies et al.* (2015) identified upward field-aligned current (FAC) throughout the interior of the PsA (pulsating patches). It is widely assumed that the aurora brightening is due to the increase of the flux of precipitating particles that may mean the increase of FAC. In the course of its increase, the FAC can exceed the threshold of electrostatic ion-cyclotron instability (EIC-instability) due to which the anomalous resistivity appears and yields the field-aligned potential drop (e.g. *Papadopoulos*, 1977). The potential drop accelerates the precipitating electrons along the magnetic field line due to which the altitude of the corresponding arc decrease during the ON phase. The signatures of electron acceleration were found in FAST satellite data by *Sato et al.* (2004).

Safargaleev (1996) showed that the value of the EIC-instability threshold inside the area where the anomalous resistivity is appearing decreases due to the change of some plasma parameters in the course of instability development. After resistivity appearance, FAC should decrease following Ohm's law. When FAC becomes less than the new threshold, then the anomalous resistivity and potential drop turn off, FAC starts to increase again and the on/off process becomes quasi-periodic. The absence of internal modulation in the upper arc (arc 2 in Figs. 5,6) may simply mean that the arc-related field-aligned current for some reasons does not achieve the threshold value.

In many papers related to pulsating auroras, there is no direct indication of exactly what auroral form is under consideration although the generation mechanisms for pulsating patches and pulsating arcs may be different. In accordance with *Sato et al.* (2015) the applying the field-aligned electric field modulation model to elongated pulsating arcs may be more reasonable than the pitch-angle scattering approach if one takes into account the analogy to ordinary auroral arcs. Ordinary arcs are enhanced via field-aligned electric field accelerations, as is widely accepted due to *in-situ* observations.

Acknowledgments. The work of Japanese co-authors has been supported by JSPS KAKENHI JP 15H05747 and 16H06286. The operation of the EMCCD camera at Tjautjas has been supported by Swedish Institute of Space Physics.

References

1. Gillies D.M., Knudsen D., Spanswick E. *et.al.*: Swarm observations of field-aligned currents associated with pulsating auroral patches, J. Geophys. Res. Space Physics, 120, 9484–9499, doi:10.1002/2015JA021416, 2015.
2. Gustavsson B.: Tomographic inversion for ALIS noise and resolution, J. Geophys. Res., 103 (A11), 26,621-26,632, doi:10.1029/98JA00678, 1998.
3. Hosokawa K., Miyoshi Y., Ozaki M. *et al.*: Multiple time-scale beats in aurora: precise orchestration via magnetospheric chorus waves, Sci. Rep., 10, 3380, https://doi.org/10.1038/s41598-020-59642-8, 2020.
4. Ivanov V.E., Kirillov A. S., Sergienko T., Steen A.: Modelling of the altitude distribution of green line (λ5577A) luminosity in aurora, SPIE, 105–113, https://doi.org/10.1117/12.164815, 1993.
5. Lessard M.R.: A review of Pulsating Aurora. Auroral Phenomenology and Magnetospheric Processes: Earth and Other Planets, Geophys. Monogr. Ser., vol. 197, pp. 55-68, https://doi.org/10.1029/2011GM001187, 2012.
6. Miyoshi Y., Saito S., Seki K., *et al.*: Relation between fine structure of energy spectra for pulsating aurora electrons and frequency spectra of whistler mode chorus waves, J. Geophys. Res. Space Physics, 120, 7728-7736, doi:10.1002/2015JA02156, 2015.
7. Ogawa Y., Tanaka Y., Kadokura A., *et.al.*: Development of low-cost multi-wavelength imager system for studies of aurora and airglow, Polar Science, 23, 100501, https://doi.org/10.1016/j.polar.2019.100501, 2020.
8. Papadopoulos K.: A review of an anomalous resistivity for the ionosphere, Rev. Geophys. Space Phys., 15, 113-127, doi:10.1029/RG015i001p00113, 1977.
9. Partamies N., Syrjäsuo M., Donovan E.: Using colour in auroral imaging, Canadian Journal of Physics, 85(2), 101–109, doi:10.1139/p06-090, 2007.
10. Royrvik O., Davis T.N.: Pulsating aurora: local and global morphology, J. Geophys. Res., 82 (29), 4720-4740, https://doi.org/10.1029/JA082i029p04720, 1977.
11. Safargaleev V.: Disturbances in the magnetosphere-ionosphere system, PhD thesis, Saint-Petersburg State University, 12 p, 1996.
12. Sato N., Wright D.M., Carlson C.W., *et al.*: Generation region of pulsating aurora obtained simultaneously by the FAST satellite and a Syowa-Iceland conjugate pair of observatories, J. Geophys. Res., 109, A10201, doi:10.1029/2004JA010419, 2004.
14. Sato N., Kadokura A., Tanaka Y., *et al.*: Omega band pulsating auroras observed onboard THEMIS spacecraft and on the ground, J. Geophys. Res., 120 (A7), 5524-5544, doi: 10.1002/2015JA021382, 2015.
14. Shiokawa K., Katoh Y., Hamaguchi Y.: Ground-based instruments of the PWING project to investigate dynamics of the inner magnetosphere at subauroral latitudes as a part of the ERG-ground coordinated observation network, Earth Planets Space, 69, 160, https://doi.org/10.1186/s40623-017-0745-9, 2017.
15. Whiter D.K., Lanchester B.S., Gustavsson B., *et al.*: Using multispectral optical observations to identify the acceleration mechanism responsible for flickering aurora, J. Geophys. Res., 115, A12315, https://doi.org/10.1029/2010JA015805, 2010.