Generation mechanism of low-energy electron precipitation in pulsating aurora elucidated with Arase satellite, ground-based optical and radar observations, and computed tomography

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論　文　内　容　要　旨

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氏　　名	吹澤　瑞貴	提出年	令和　3　年
学位論文の 題　　　目	Generation Mechanism of Low-Energy Electron Precipitation in Pulsating Aurora Elucidated with Arase Satellite, Ground-Based Optical and Radar Observations, and Computed Tomography (あらせ衛星と地上光学・レーダー観測ならびにコンピュータ・トモグラフィによる 脈動オーロラ中の低エネルギー電子降下現象の解明)		

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論　文　要　旨

In the inner magnetosphere of the Earth, various plasma waves are excited by wave–particle interactions. Lower band chorus (LBC) waves scatter ~10 keV electrons into a loss cone by the cyclotron resonance, and cause pulsating auroras (PsAs). On the other hand, upper band chorus (UBC) waves cause stable precipitations at ~1 keV. Furthermore, electrostatic electron cyclotron harmonic (ECH) waves scatter a few hundred eV to a few keV electrons. In recent decades, observations and theories regarding LBC waves have been developed, and the relationship between LBC waves and PsAs has been almost revealed. However, there has been no observational evidence that ECH waves actually scatter electrons into a loss cone. In addition, the relationship between PsAs and low-energy (< a few keV) electron precipitation caused by UBC or ECH waves has not been fully understood.

In this study, we aim to understand the following subjects. (1) Observational evidence of the scattering of electrons into a loss cone by ECH waves. (2) Statistical analysis to examine the energy dependence and occurrence rate of pitch angle (PA) scattering by LBC, UBC, and ECH waves. (3) How often the *F* region electron density enhancement caused by soft electron precipitation occurs as associated with PsAs. (4) Reconstruction of three-dimensional (3-D) distribution of volume emission rate (VER) and horizontal distribution of precipitating electrons in a PsA patch. Results for each subject are summarized as follows.

(1) To verify whether ECH waves scatter electrons into a loss cone, we compared the ECH wave intensity with the electron flux inside the loss cone obtained with the Arase satellite. The cross-correlation coefficient between the ECH wave intensity and the loss cone electron flux at an energy of ~5 keV was statistically significant, while that with LBC wave intensity at the same energy was small. We calculated the PA diffusion coefficient of ECH waves, assuming that the wave normal angle is 87.0°, and the electron temperature is 1 eV. We found that the diffusion coefficient of 5-keV electrons is 10 times larger than that of other energies where cross-correlation coefficients were small. The linear growth rate of ECH waves is also large when the wave normal angle and electron temperature satisfy these conditions. We demonstrated that the electron flux correlated with the ECH wave intensity would cause the 557.7-nm auroral emissions, with an emission rate of 200 R according to a model calculation. As a result, we verified for the first time the observational evidence of PA scattering of electrons into a loss cone by ECH waves.

(2) From the statistical analysis of wave and electron data obtained with the Arase satellite from March 24, 2017 to August 31, 2020, we examined the characteristics of the strong electron scattering by LBC, UBC, and ECH waves, in the energy range from 0.1 to 20 keV. We revealed that the energy ranges where LBC, UBC, and ECH waves contribute to scatter electrons into loss cones are as follows. The regression line slopes for wave amplitudes versus loss cone filling ratios are positive, while correlation coefficients between them are statistically significant in the energy range greater than ~2 keV for LBC, of ~1–10 keV for UBC, and smaller than ~2 keV for ECH waves. In these energies, the occurrence rate of the strong PA scattering was also high for each wave. These energies are consistent with those predicted by the quasilinear theory, in the case that PA diffusion coefficients exceed the strong diffusion level. We clarified from the statistical analysis of the Arase data that a few keV electron precipitation scattered by

ECH waves was not common, while electrons with energy less than 1 keV were commonly scattered by ECH waves.

(3) We conducted two case studies to investigate the relationship between the electron density height profile and auroral type, such as discrete, diffuse, and pulsating aurora, using the data obtained with the EISCAT radar and an auroral all-sky imager at Tromsø on February 18, 2018 and October 27, 2019. We also carried out statistical studies on 14 events to clarify how often the F-region electron density enhancement occurs as associated with PsAs. We consequently found that 76% of electron density height profiles showed a local peak in the *F* region with an electron temperature enhancement. Compared with the model ionization profiles by electron precipitation, we suggest that 76% of these local peaks were caused by precipitating electrons in the energy range lower than 100 eV. The occurrence rate of these profiles exceeded 80% in the range of 22–3 magnetic local time. We suggest that the electron density enhancement in the *F* region would be caused by the low-energy electrons scattered by ECH waves in the magnetosphere.

(4) We reconstructed for the first time the 3-D VER and horizontal distribution of precipitating electrons in a PsA patch by Aurora Computed Tomography (ACT). All-sky images at 427.8-nm auroral emission obtained at Abisko, Kilpisjärvi, and Skibotn have been used. We improved the previous ACT used for discrete auroras to apply diffuse and dimmer PsAs in the following three points: first, the subtraction of background diffuse aurora from auroral images before conducting ACT, secondly, the estimation of the relative sensitivity between all-sky cameras, and third, the determination of hyperparameters of the regularization term. As a result, we succeeded to reconstruct the 3-D VER and horizontal distribution of precipitating electrons in the PsA patch. The characteristic energy of the reconstructed precipitating electron flux ranges from 6 to 23 keV, while the peak altitude of the reconstructed VER ranges from 90 to 104 km, consistently with previous studies. We found that the horizontal distribution of precipitating electron's characteristic energy was neither uniform nor stable in the PsA patch during the pulsation. The observed spatial and temporal variations of PsAs are important to understand the background magnetic and plasma conditions that would cause changes in the cyclotron resonance energy of LBC waves in the magnetospheric source region. Our reconstruction results are a great advantage of multiple ground-based data, since such 3-D distributions cannot be obtained by rockets and satellites. We quantitively evaluated the reconstruction results using a model PsA patch with adding artificial noises, and compared with the ionospheric electron density observed by the EISCAT radar. Considering the time derivative term in the electron continuity equation, the electron density was reconstructed with sufficient accuracy even when the PsA intensity decreased from ~1 to ~0.1 kR. If the time derivative term is not considered, the electron density rapidly decreases as the PsA intensity decreases. This result suggests that the time derivative term should be considered when we derive the electron density associated with PsAs from the continuity equation.

別　紙

論文審査の結果の要旨

吹澤瑞貴さんの博士論文は、人工衛星と地上光学・レーダー観測ならびにコンピュータ・トモグラフィを駆使して、脈動オーロラ中の低エネルギー電子降下現象の解明に取り組んだものである。人工衛星と地上観測のデータならびに波動粒子相互作用理論を組み合わせて、静電電子サイクロトロン高調波（ECH)という静電波の低エネルギー電子降下への寄与を実証した。また、コンピュータ・トモグラフィを用いて、地上３地点に設置されたカメラによって取得されたオーロラ画像から脈動オーロラ発光の３次元分布や降下電子の水平分布の再構成することに世界で初めて成功した。この成果は博士論文にまとめられるとともに、これまで合計３編（博士課程期間中は２編）の査読論文として出版された。

吹澤瑞貴さんは、「あらせ」衛星により取得された内部磁気圏の最新の粒子・電磁場データに理論モデルを適用し、1970 年代から提案されていた脈動オーロラ発光メカニズムの一つである静電電子サイクロトロン高調波が磁気圏電子散乱する観測事実を世界で初めて示した。この成果を２編出版し、学会報告においては学生発表賞を受賞した。また、この特徴を定量的に明らかにするため、地上光学装置と非干渉散乱レーダーの４年間のデータの統計解析を行い、この結果について論文を１編出版した。その後、あらせ衛星データの統計解析を行い、その研究結果についての論文投稿済みで、現在査読中にある。また、医療診断の分野で用いられる逆問題解析手法を用いて脈動オーロラの立体構造を初めて明らかにし、降下電子エネルギー生成過程を調べた。その研究結果についての論文も投稿済みで、現在査読中にある。

以上の研究内容と実績は、吹澤瑞貴さんが、今後自立して研究活動を行うに必要な高度の研究能力と学識を有する事を示している。

したがって，吹澤瑞貴さん提出の博士論文は，博士（理学）の学位論文として合格と認める。