論 文 内 容 要 旨

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学位論文の 題　　目	Study of generation processes of diffuse aurora based on ground-based and spacecraft observations （地上―衛星観測に基づくディフューズオーロラ励起過程に関する研究）		

論　文　目　次

Abstract

It has been thought that the source of diffuse auroral emissions is scattered plasma sheet electrons into the loss cone by some wave-particle interactions [Fontaine and Blanc, 1983]. Both ECH waves [e.g., Kennel et al., 1970] and whistler-mode chorus [e.g., Johnstone et al., 1993] have been thought to be the contributors to the production of diffuse auroral electrons since they can resonate with ~ keV electrons. A recent study done by Thorne et al. [2010] reveals that whistler-mode chorus is dominantly responsible for the production of diffuse auroral electrons. While, there are some observational suggestions that ECH waves cause diffuse auroral electron precipitations [e.g., Liang et al., 2010].

Although many studies have been conducted to understand the generation mechanism(s) of diffuse auroras, discussions on the dominant wave mode do not converge and further theoretical and observational studies are required. Combining the ground-based and spacecraft observations, we investigated how precipitation loss of energetic electrons occurs via wave-particle interactions, that is to say, the generation mechanisms of diffuse aurora. We further investigated phenomena associated with the generation processes of diffuse auroras, and also characteristics and generation processes of plasma waves themselves.

Contribution of ECH waves to generation of diffuse aurora

The theoretical works showed that scattering by ECH waves was insufficient to cause the diffuse aurora compared with whistler-mode chorus [Thorne et al, 2010]. Using the plasma wave and electron data obtained from the THEMIS spacecraft, we examined whether ECH waves can contribute to electron scattering in the velocity space or not. Since contours of an electron velocity distribution function (VDF) follow the diffusion curves of whistler mode when whistler mode waves are active [Cully et al., 2011], the diffusion curve of whistler mode can be used as a“marker” to identify changes of VDFs due to wave-particle interactions. We compared the contours of VDF with the diffusion curves of whistler mode for the case when ECH waves were active following the inactivation of whistler-mode waves. It was found that the contours deviate from the diffusion curves in the pitch angle range below □ 20◦, which is consistent with the pitch angle range where effective pitch angle scattering by ECH waves is expected [e.g., Lyons, 1974; Ni et al., 2011b]. The

result is observational evidence of electron scattering driven by ECH waves and we therefore conclude that ECH waves can contribute to the generation of diffuse auroras.

Our analysis based on the THEMIS observations gives confidence that ECH waves can contribute to the generation of diffuse auroras. Multi-point observations along a magnetic field line using low altitude satellites and spacecraft around the magnetic equator are important to investigate the contributor to the generation of diffuse aurora since the energy spectra of diffuse auroral electrons depend on the wave mode that causes electron pitch angle scattering [Horne et al., 2003]. We, then, conducted a coordinate analysis of dayside diffuse auroras using the data obtained from FAST, GEOTAIL, and all sky imager at the South Pole. During the conjunction event, GEOTAIL observed enhancement of both ECH waves and whistler-mode waves in association with increase in the diffuse auroral intensity. FAST observations showed that electrons below 5 keV were strongly scattered into the loss cone and contributed to the generation of the diffuse aurora. Based on the frequency spectrum and plasma parameters observed by GEOTAIL, we evaluated the resonance energies of ECH waves and wshistler-mode waves. We found that the resonance energy of the whistler-mode waves was above 5 keV while that of the ECH waves was below 5 keV, indicating that only the ECH waves could contribute to the pitch angle scattering of electrons with energies below 5 keV. This result indicates that the precipitating electrons observed by FAST are the result of pitch angle scattering by the ECH waves. It is concluded that the ECH waves contribute to the generation of the diffuse aurora in this case.

Relativistic electron precipitations in association with diffuse aurora

It has been suggested that relativistic electron precipitations are caused by scattering by whistler-mode chorus [e.g, Lorentzen et al., 2001]. Referring to the previous studies, it is natural to expect that relativistic electrons precipitate into the atmosphere in association with diffuse aurora if whistler-mode waves contribute to generation of diffuse auroras. To examine this hypothesis, we investigated conjugate observations of SAMPEX and the all sky TV camera (ATV) at the Syowa station on the dawn side, where diffuse auroras are frequently observed. We found the cases in which relativistic electron (> 1 MeV) precipitations observed by SAMPEX are associated with the diffuse aurora observed by ATV at the Syowa station. Since diffuse auroras are generated by precipitating electrons with the energy of □ keV, the observations indicate that electrons in the energy range from a few keV to 1 MeV precipitate into the atmosphere simultaneously. Our results support the idea that relativistic electron precipitations are caused by pitch angle scattering by whistler-mode chorus. We suggest that relativistic electron precipitations associated with diffuse auroras are caused by pitch angle scattering by whistler-mode chorus propagating within whistler mode ducts.

Generation mechanism of whistler-mode chorus

Chorus is discrete and coherent whistler-mode waves with narrow frequency bandwidth and is characterized by its spectral fine structures consisting of rising and falling tones. It has been proposed that rising tone chorus is generated by nonlinear wave-particle interactions between whistler-mode waves and counter-streaming electrons at the magnetic equator [e.g., Nunn, 1974; Omura et al., 1991]. The generation mechanism of rising tone chorus has been well studied by theory and simulation [e.g., Omura et al., 2008; Hikishima et al., 2009] while there are a few studies to validate the generation mechanism based on the spacecraft observations [e.g., Cully et al., 2011]. We discovered rising tone chorus elements whose spectral shape is predicted by the nonlinear wave growth theory of Omura et al. [2009] in the THEMIS data set. We examined the properties of the rising tone chorus elements and found that the properties of the chorus elements well agree with theoretical predictions by Omura et al. [2008] and Omura and Nunn [2011]. it is observational evidence that rising tone chorus elements are generated by nonlinear wave-particle interactions between whistler-mode waves and energetic electrons.

The theories for falling tone chorus generations have also assumed the nonlinear-wave particle interactions between field-aligned whistler-mode waves and counter-streaming electrons around the magnetic equator. However, it has been pointed out that falling tone chorus has highly oblique wave normal angles [e.g., Li et al, 2011], which is inconsistent with the model assumption. For better understanding of generation mechanism of falling tone chorus, we statistically investigated propagation characteristics of falling tone chorus, especially its propagation direction. Our

statistical analysis showed that falling tone chorus propagates from the magnetic equator to higher latitudes, in the same way as rising tone chorus. It strongly suggests that the magnetic equator is the common source location of both rising and falling tone chorus. We also found that there was no falling tone chorus element which satisfies the model assumptions in the THEMIS data set. It is required to construct new generation models which consider the observed properties of falling tone chorus.

Although we show several key findings in this thesis, there are still remaining issues to be addressed; e.g., probability of ECH wave-driven diffuse auroras, underlying physical processes of relativistic electron precipitations associated with diffuse auroras, precise models for generation of whistler-mode chorus. This thesis proposes approaches and new spacecraft missions to solve these issues as Concluding remarks.

論文審査の結果の要旨

極域で光るオーロラには、大別すると、筋状或いはカーテン状といった、はっきりした形状が見えるタイプとそうでないタイプがあり、後者はディフューズオーロラ(以下 DA)と呼ばれる。DA が発光する原因は、オーロラ域の磁力線を磁気圏赤道域まで辿った領域(プラズマシート)にある電子が、その場に存在するプラズマ波動により粒子散乱(以下 PAS)を受け、磁力線沿いにオーロラ域に降り込んで超高層大気を励起し、発光させた結果と理解されている。従来、粒子散乱に関する理論的な考察により、ホイッスラーモード・コーラス(WMC 波)と呼ばれる波動が卓越して DA の生成に寄与すると解釈されてきたが、近年、静電的電子サイクロトロン高調波(ECH 波)と呼ばれる波動の寄与を示唆する観測報告もなされ、DA の生成に WMC 波や ECH 波がどのように関わっているのかについて観測的実証が必要になっている。本論文は、科学衛星によるプラズマ波動や粒子観測や地上からのオーロラ光観測に基づくデータ解析と、粒子と波動の相互作用に関わる理論考察を組合せて、DA 生成に関わるプラズマ波動の役割と波動特性の解明を行った研究である。

本論文は以下の 3 つのテーマについて研究を行い、顕著な成果を示した。

1)DA 生成に対する ECH 波の寄与の実証：磁力線を介してオーロラ域に繋がる磁気圏赤道域を周回する科学衛星 THEMIS の粒子と波動データの解析から、ECH 波のみ存在する赤道域でオーロラ域への電子降下を示唆する PAS が確かに発生していたことを示した。更に、米国南極点基地設置の全天カメラの視野域と、磁気圏赤道域を周回する科学衛星 Geotail、オーロラ域上空を通過する科学衛星 FAST が同一磁力線上に存在した機会のデータを精査し、南極点上空に DA が現れた際に磁気圏赤道域で ECH 波が出現し、DA 上空では 5KeV 付近の降下電子が卓越して出現した事象を見出した。理論計算から、この降下電子は ECH 波による PAS により生じたと解釈されることを明らかにし、ECH 波が確かに DA 生成に関わる直接的な証拠を初めて示した。

2)WMC 波による DA 発生域への高エネルギー電子降下の実証：従来、DA 発生に関わる WMC 波は MeV クラスの高エネルギー電子の降下にも関与するとする理論的な予想があった。本論文では、南極昭和基地の全天カメラの視野域と、オーロラ域上空を通過する高エネルギー粒子計測器搭載の科学衛星 SAMPEX が同一磁力線上に存在した機会のデータの精査を行い、DA 発生時に数 keV から MeV クラスの広いエネルギー範囲の電子降下が確かに発生する場合があることを初めて示した。更に理論計算から、磁力線沿いに長距離伝搬する WMC 波と相互作用する場合に DA 域に降下する広いエネルギー範囲の電子が生成され得ること、また、この条件として WMC 波がダクト伝搬すると考えると電子降下域の空間スケールも含めて説明し得ることを示した。

3)WMC 波の生成過程の検証：WMC 波は個々の継続時間が 1 秒以下で周波数ドリフトを示す狭帯域の電波バーストであり、グループとして出現する。その多くは時間と共に周波数が増加する rising-tone で、周波数が減少する falling-tone は少ない。これらの出現特性は、WMC 波が赤道域で磁力線上を運動するエネルギー電子との非線形波動粒子相互作用により生成されるためであるとする理論的な予想があった。本論文では、科学衛星 THEMIS の粒子と波動データの解析に基づき理論予想との照合を行い、rising-tone WMC 波の周波数ドリフト特性が理論予想と良く合致し、その生成は現行理論で説明され得ること、一方、falling-tone WMC 波は波動伝搬特性が現行理論とは合致せず、新たな生成過程の考案が必要であることを初めて観測的に示した。

本論文の主たる成果は、これまで国内外の学会・研究会で公表されるとともに、3 本の国際学術誌論文が公表済み、更に 2 本の論文が国際学術誌に投稿直前である。これらは論文提出者が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ことを示している。したがって、栗田 怜 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。