Study of generation processes of diffuse aurora based on ground-based and spacecraft observations

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 $\sim$ 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 $\sim 20°$, 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 the 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 $\sim$ 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.