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Role of the mirror force on the collision rate due to relativistic electron precipitation

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Introduction

Energetic electrons precipitating into the ionosphere collide with neutral gas and contribute to various ionospheric phenomena. Previous studies revealed the importance of energetic particle precipitation in the ionosphere- magnetosphere coupling system, but some of the processes have been treated through a simplified assumption. One of the processes is the role of the mirror force acting on the precipitating particles.

The collision process between precipitating electrons and neutral gas has been modeled by previous studies [e.g., Lummerzheim et al., 1989]. The effect of the mirror force, however, has not been fully included, because of the small change in the magnetic field strength in the altitude range of precipitation [Rees, 1963]. On the other hand, the effect of the mirror force should be significant for electrons having a larger pitch angle close to the loss cone, which often appear for the electron precipitation caused by the pitch angle scattering through wave-particle interaction in the magnetosphere. Marshall and Bortnik (2018) pointed out the significant effects of the mirror force on the backscatter of radiation belt electrons inside the bounce loss cone. The quantitative evaluation of the mirror force on the precipitating electrons is required.

This study numerically evaluates the effect of the mirror force on the collision rate due to the relativistic electron precipitation into the ionosphere.

Model

We compute the motion of energetic particles precipitating along a field line considering the mirror force acting on the particles. We use a cylindrical coordinate system (r,ϕ,z) aligned with the reference magnetic field, where z is defined along the magnetic field line, r is the distance from the axis z, and ϕ is the azimuthal angle from a chosen reference direction defined on the plane perpendicular to the magnetic field.

The background magnetic field is simplyfied by a nonuniform cylindrical magnetic field (B_r,B_ϕ,B_z). We assume that B_ϕ=0 and B_r is given by $B_r = -\frac{r}{2}\frac{\partial B_z}{\partial z}$ [cf. Katoh and Omura, 2006].

The motion of a charge particle is solved including relativistic effect.

We compute collisions between neutral gas and precipitating energetic electrons using a Monte Carlo method to derive the collision rate by the precipitating electrons [e.g., Solomon, 2001; Hiraki and Tao, 2008]. Only elastic collision and ionization cross-section are considered because these two processes are dominant in the energy range higher than 100 eV.

The probability of a collision between energetic electrons and neutral gas during the time interval Δt is given by [Caswell and Everett, 1959]

$$P_i = 1 - \exp\{-N(z_i)\sigma_{tot}(\varepsilon_i)v_i\Delta t\}$$

where $N(z_i)$ is the total atmospheric gas density at an altitude z_i of i-th electron, $\sigma_{tot}(\varepsilon_i)$ is the sum of the collision cross sections for the kinetic energy ε_i, and v_i is the velocity of i-th electron.

Elastic scattering cross-section and its pitch angle dependence are given by Lummerzheim (1987) and Lummerzheim et al. (1989), respectively.

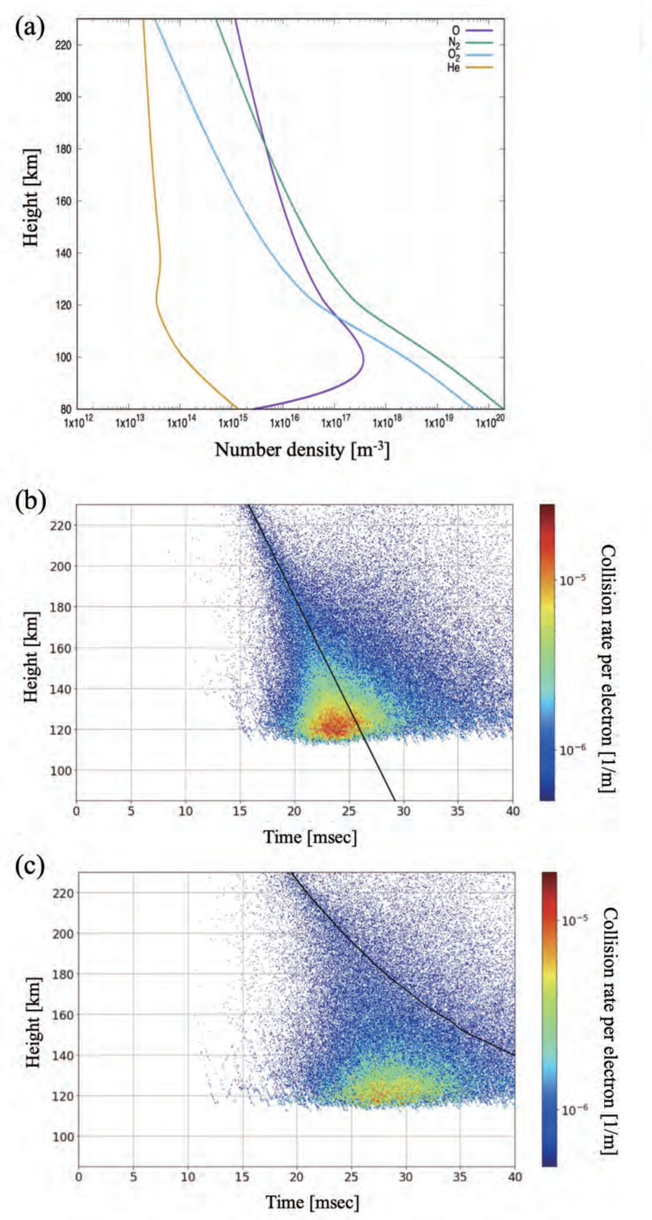

Figure 1. (a) Altitude profiles of neutral atoms and molecules at L=6.45. (b) Time history of the altitude profile of collision rate per electron obtained by the simulation without mirror force acting on electrons. (c) Simulation results with mirror force acting on electrons. 3 keV electrons whose initial pitch angle of 70 degrees at 400 km are assumed in both (b) and (c).

Results

We carry out simulations of mono-energetic precipitation of the different energy and pitch angle ranges with the mirror force. (Figure 2)

Simulation results demonstrate that larger kinetic energy lowers the altitude profiles of the collision rate, consistent with previous studies. The upward spread is caused by the backscattered electrons moving upward; these electrons underwent collisions during the precipitation but survived and bounced back from the mirror point. (Figure 3)

By integrating the evolution of the collision rate in time, we obtain the altitude profiles of the collision rate per electron. The upward motion of electrons bounced back from their mirror points results in the upward broadening of the altitude profile of the collision rate. (Figure 4)

Electrons above 100 keV close to the loss cone cause the formation of the secondary peak, and one order of the magnitude smaller collision rate. (Figure 5)

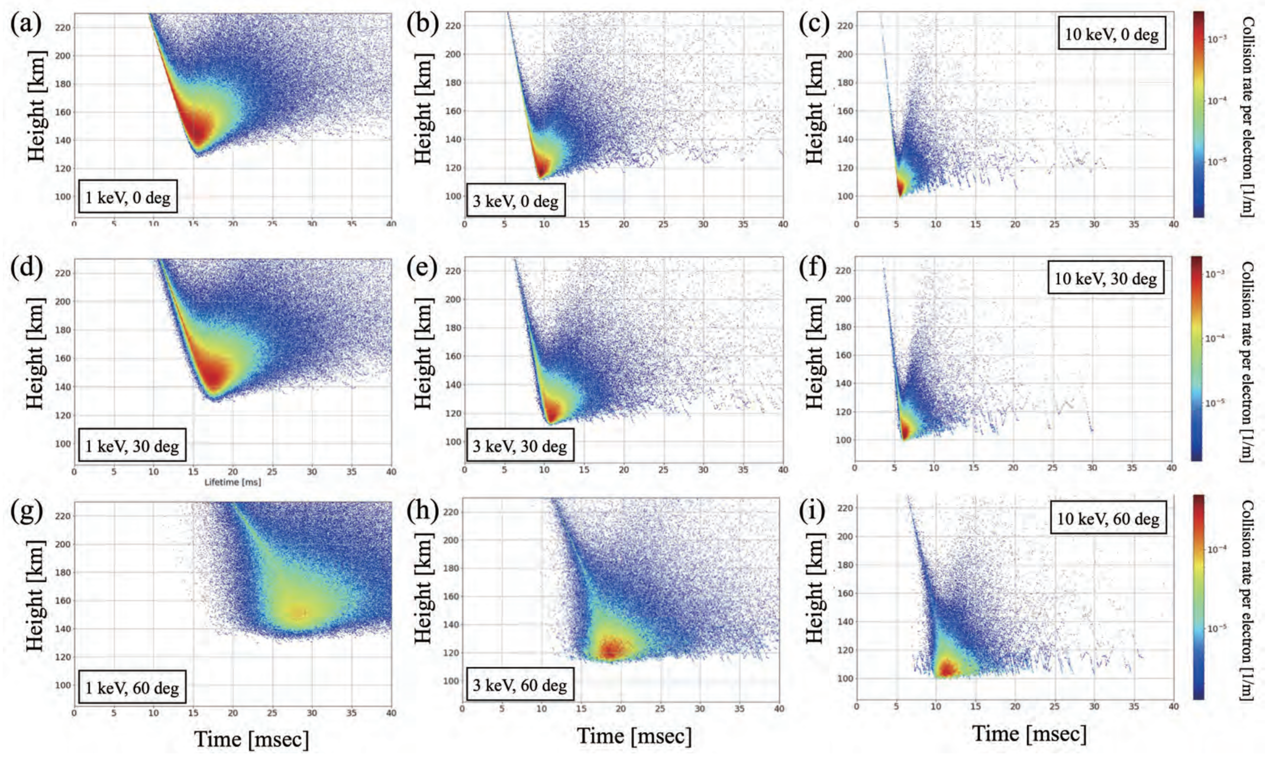

Figure 2. Time histories of the altitude profiles of the collision rate per electron obtained by a series of simulations with mirror force. The initial kinetic energy of (a,d,g) 1 keV, (b,e,h) 3 keV, and (c,f,i) 10 keV and the initial pitch angle of (a-c) 0 degree, (d-f) 30 degree, and (g-i) 60 degree are assumed at 400 km.

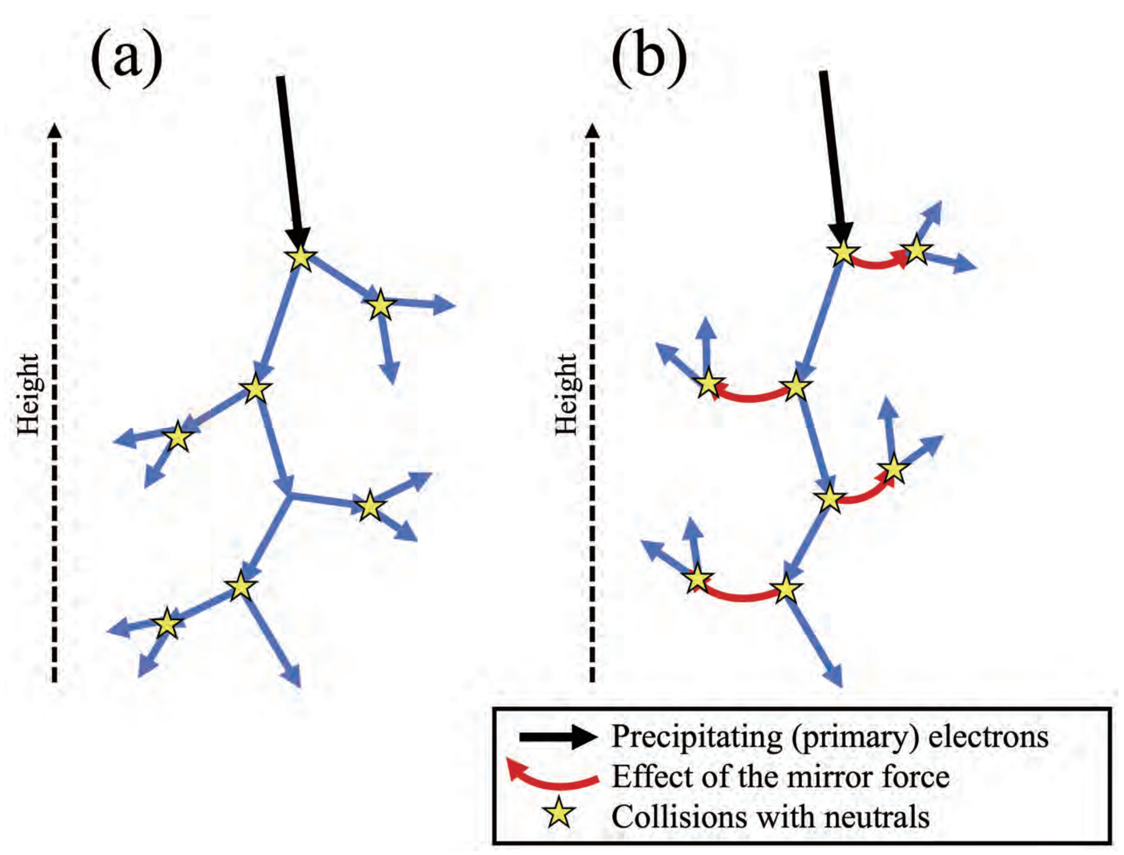

Figure 3. Illustration showing the relation between precipitating electrons, mirror force, and collisions with neutrals. The cases (a) without and (b) with mirror force are shown.

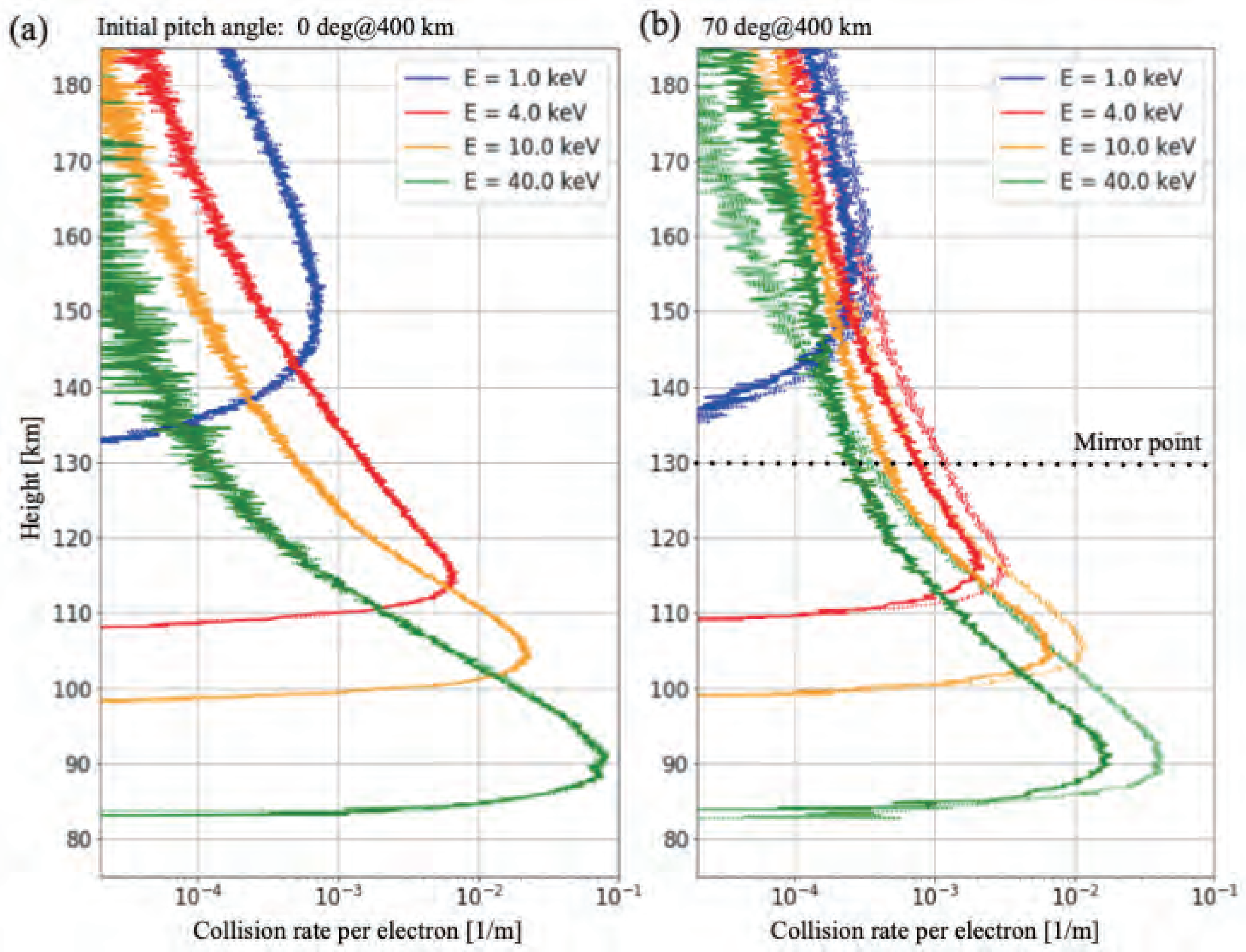

Figure 4. Altitude profiles of the collision rate per electron for the cases of mono-energetic precipitation of 1, 4, 10, and 40 keV electrons, whose initial pitch angle is (a) 0 and (b) 70 degrees, at an altitude of 400 km. Solid and dotted lines show the simulation results with and without mirror force, respectively.

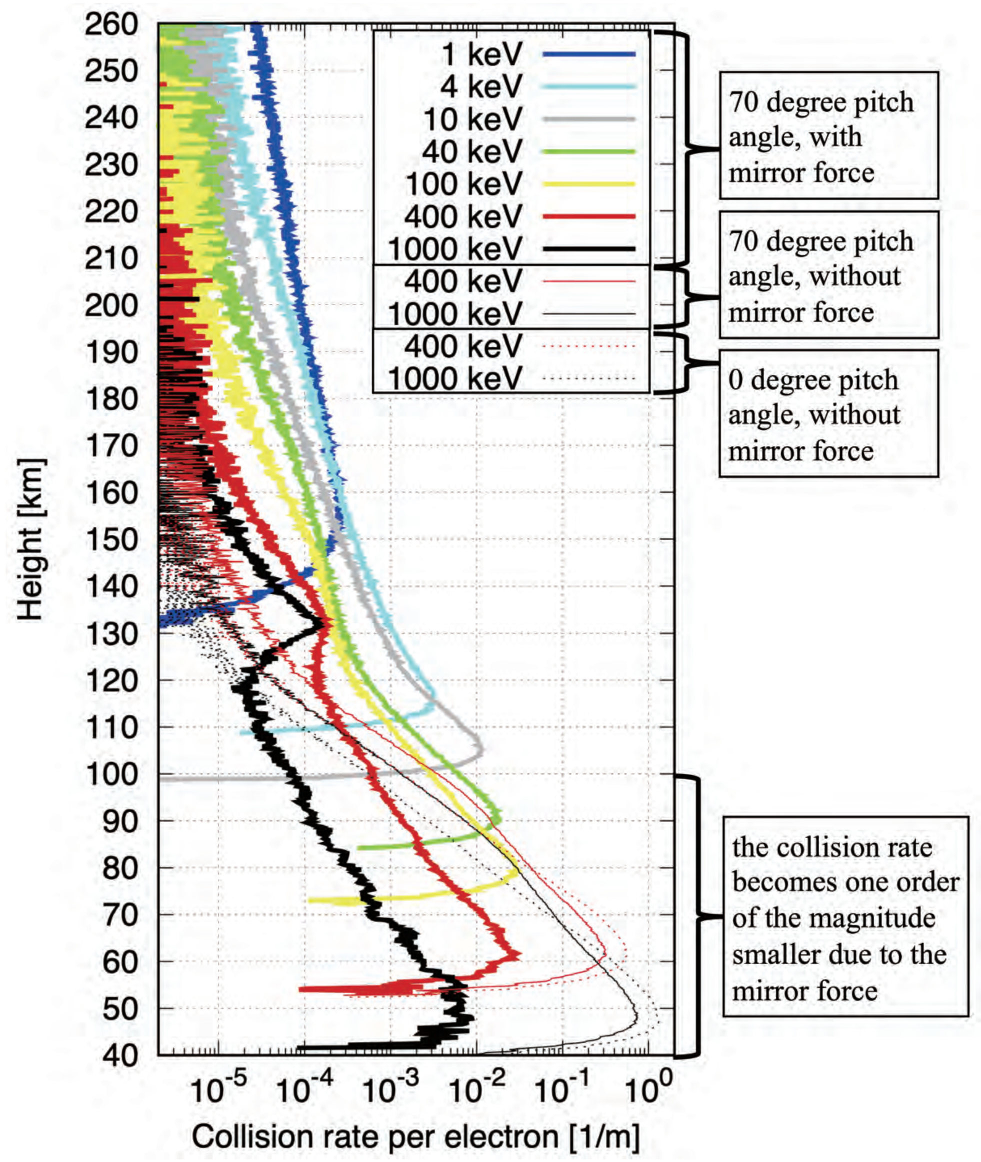

Figure 5. Altitude profiles of the collision rate per electron for the cases of mono-energetic precipitation of 1, 4, 10, 40, 100, 400, and 1000 keV electrons, whose initial pitch angle is 70 degrees at an altitude of 400 km, obtained by the simulations with mirror force.

CubeSat project PCUBE

We started a JSPS KAKENHI project PCUBE (Probing, Controlling, and Understanding of radiation Belt Environments)

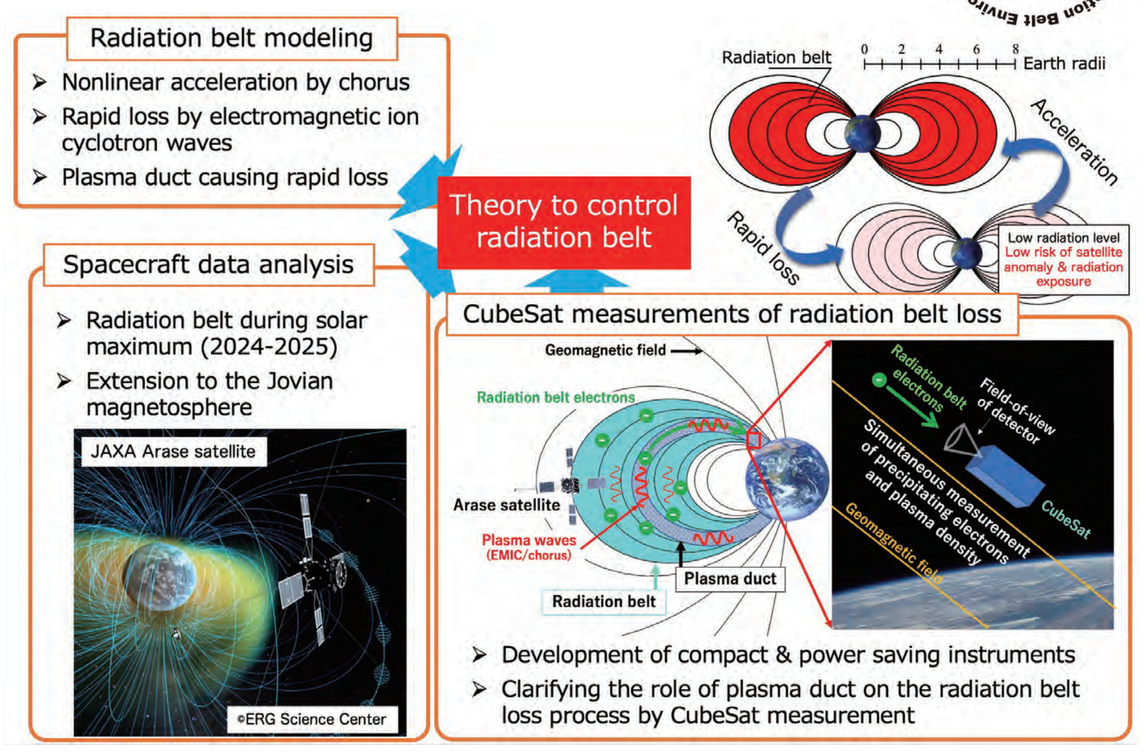

Figure 6. Schematic illustration of the PCUBE project

We develop a 3U CubeSat (to be lauched in 2026) to measure energetic/relativistic electron precipitation in plasma duct.

Payload: - LEXUS (keV - MeV electron detector)
- NEI (Impedance probe; plasma density)

Orbit: LEO (> 400 km)

The results presented in this poster are published in Katoh et al., *Earth Planets Space* (2023)

Summary

- We show that the upward motion of electrons bounced back from their mirror points results in the upward broadening of the altitude profile of the collision rate.
- Under the precipitation of electrons in the kinetic energy range larger than tens of keV with the pitch angle close to the loss cone, the maximum collision rate in the altitude range lower than 100 km becomes one order of the magnitude smaller.
- Electrons with kinetic energies above 100 keV form a secondary peak of the collision rate near the mirror point.
- The results of the present study suggest the importance of the mirror force for the precise modeling of ionospheric response due to the energetic electron precipitation caused by the pitch angle scattering through wave-particle interactions.

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