論文の内容の要旨

Study of ion upflows in the low-altitude ionosphere and their effects on supply of terrestrial heavy ions to the magnetosphere

（低高度電離圏におけるイオン上昇流とそれらが磁気圏への地球起源重イオン供給に与える影響の研究）

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The space around the Earth is under the influence of the geomagnetic field and the region is called as the magnetosphere. The magnetospheric plasma originate from two source regions: the solar wind, which is the plasma flow from the Sun, and the terrestrial ionosphere, which corresponds to the layer of the ionized atmosphere ranging at the altitude from ~80 km to ~1000 km. It is important to understand the supply processes for each ion species from these regions into magnetosphere. In particular, molecular ions ($O_2^+/NO^+/N_2^+$) in the magnetosphere have been observed during the magnetic storms [Klecker et al., 1986; Seki et al., 2019] as well as atomic oxygen ions (O^+) [Daglis et al., 1999; Nosé et al., 2005; Keika et al., 2013]. These molecular ions are supplied from the terrestrial ionosphere. The source of the molecular ions is low-altitude ionosphere (< 300 km) whereas O^+ is dominant in high-altitude ionosphere (> 400 km). These ions are transported upward in the ionosphere (ion upflow) before outflowing into the magnetosphere. Thus, understanding of properties of the ion upflows is important to reveal the supply processes of terrestrial heavy ions from the ionosphere to the magnetosphere.

The generation mechanisms of ion upflows is one of the important properties. Candidate mechanisms such as the ion frictional heating, particle precipitation, and small or large scale instabilities have been proposed and investigated for O^+ ion upflows in the high-altitude ionosphere. However, those mechanisms could not provide molecular ions with enough energy to escape overcoming the loss due to the dissociative recombination [Peterson et al., 1994] (Question 1). The dependence of the properties of ion upflows on the magnetic storms is also important. Ogawa et al. [2019] found that they have different dependences on CIR- and CME-driven magnetic storms at each magnetic local time and latitude in the polar high-altitude ionosphere. However, such dependences of ion upflows in the low-altitude ionosphere are still unknown even though many differences between low- and high-altitude ionosphere are considerable [e.g., Yamazaki et al., 2017] (Question 2). In this study, the author aim at comprehensive understanding of the ion upflows in the low-altitude ionosphere and their effects on supply of terrestrial heavy ions to the magnetosphere by solving those two outstanding questions via an event study for Question 1 and a statistical study for Question 2.

In the event study, the author analyzed an ion upflow event observed by the EISCAT radar at Tromsø on September 8, 2017 during a magnetic storm (Dst minimum ~ -100 nT). The magnetic storm started on September 7, 2017 and the Arase satellite continuously observed molecular ions in the inner magnetosphere. It means that there was a continuous supply of molecular ions during the magnetic storms. During the storm event, EISCAT observed the ion upflow in the low-altitude ionosphere. The upflow occurred with the ion velocity of more than 100 m/s and the enhancement of ion temperature and electric fields. A detailed estimation of dominant force in the transportation processes and remaining flux at higher altitude (~350 km) suggested that the ion frictional heating contributed to the rapid ion upflow, by which molecular ions could be supplied overcoming the dissociative recombination.

In the statistical study, the author investigated the effects of CIR- and CME-driven magnetic storms on ion upflows in the low-altitude ionosphere by using the long-term observational data obtained by the EISCAT radars at Tromsø and Svalbard from 1996 to 2015. The results show that ion upflows mainly occurred in dawn and nightsides during both CIR- and CME-driven magnetic storms. Also, the author inferred the generation mechanisms by evaluating the enhancements of ion and electron temperatures. The results indicate that the frictional heating mainly caused upflows during CME-driven magnetic storms at both locations and possibly in dawnside during small CIR-driven storms at Svalbard and the particle precipitations mainly caused upflows during CIR-driven magnetic storms at both locations and possibly in nightside during small CME-driven storms at Tromsø.

By comparing the results from the statistical study with the previous study by Ogawa et al. [2019], this study shows the comprehensive understanding about ion upflows in the polar ionosphere during magnetic storms. In particular, the characteristics of the low-altitude ionospheric upflows leads to understandings about supply processes of molecular ions to the magnetosphere. It is concluded that the particle precipitation such as the electron precipitation with the energy of more than ~1 keV from the inner magnetosphere frequently contribute to the ion upflows around the nightside auroral oval during magnetic storms and the large magnetic storms resulted in the additional supply of molecular ions along with the enhancement of Joule heating (the frictional heating) caused by the developed convection electric fields. Even during small storms, molecular ions can be supplied from dawnside by the frictional heating and from nightside by the precipitation. These results suggest that the magnetic storms are effective drivers of the ion escape from the collisional low-altitude ionosphere to space.