Abstract

We focus on the molecular ion upflow in the topside ionosphere using a ground-based optical remote sensing. Ion upflow is important since it is considered to be a source of ion outflow which contributes planetary atmospheric escape and controls magnetospheric dynamics. The heavier ions including molecular ions (N_2^+, NO^+, O_2^+) have been observed in the magnetosphere [*Klecker et al.*, 1986] in spite of their existence in the lower ionosphere (E-region) originally. The mechanism of ion upflow in the ionosphere for molecular ions is uncertain because it is rather difficult for heavy ions to move upward overcoming the gravitational force. Furthermore, N_2^+ ion production mechanism in the topside ionosphere in the sunlit region in relevance to N_2^+ ion upflow is not understood well. Thus, we examined the unresolved mechanisms for N_2^+ ion production and N_2^+ ion upflow using ground-optical instruments combined with radar and satellite data.

We investigated the data obtained with the Auroral Spectrograph (ASG) located in Longyearbyen (78.15°N, 16.04°E) during the period of 2004 - 2016 to measure the N_2^+ resonant scattering light (427.8 nm) in the topside ionosphere associated with N_2^+ ion upflow and/or caused by locally generated N_2^+ ion. We found totally 13 events of N_2^+ resonant scattering light in the topside ionosphere out of 75 analysis days selected from the data obtained at one month before and after the winter solstice. The MLT range of the events was 9 - 18 MLT in the dayside sector. In this study, we selected the observation events for a single auroral arc by using ASG and All-sky Color Digital Camera (CDC). We assumed that the observed emissions of N_2^+ 427.8 nm, O 557.7 nm and 630.0 nm are along a single geomagnetic field line, and calculated the auroral emission heights converting elevation angle to altitude.

On the 22nd January, 2012 case, we carried out the coordinated observation of ASG and the European Incoherent Scatter (EISCAT) Svalbard Radar (ESR). The aurora associated with N_2^+ resonant scattering light was observed with ASG and ESR at the magnetic zenith around 15:30 UT. The intensity of 427.8 nm emission kept high (>100 R) up to $\sim$ 400 km altitude, and the intensity of 630.0 nm emission was relatively high ($\sim$ 10 kR). The ion upflow was not measured at this time. When we assume that heavier N_2^+ ion upflow does not occur either, this result demonstrates that N_2^+ resonant scattering light is caused by locally generated N_2^+ ion.

On the 21st December, 2015 case, we examined the ASG data in conjunction with the Defense Meteorological Satellite Program (DMSP) satellite. During the period of 7:00 - 8:34 UT, a stable aurora was observed in the southward of the field of view for ASG at Longyearbyen with relatively high intensity at 630.0 nm aurora ($\sim$ 10 kR). The maximum intensity of 427.8 nm emission during 7:00 - 8:34 UT was recorded at 8:34 UT, and was $\sim$ 650 R at an altitude of 350 km. The intensity above $\sim$ 600 km kept higher than 100 R up to 1,000 km, and the inclination above the peak of 427.8 nm emission was relatively steeper than 557.7 nm and 630.0 nm

emission above $\sim$ 450 km. In addition, we investigated the time variation of the N_2^+ resonant scattering light in the F-region and topside ionosphere during the period of 7:00 - 8:20 UT when there was no clouds in the southward of the field of view for ASG. The time variation of N_2^+ emission in the F-region (400 km) and in the topside ionosphere (800 km) were different. The intensity at an altitude of 400 km varied in the range of 150 - 500 R, while at an altitude of 800 km, gradually increases throughout this period ($\sim$ 100 R to $\sim$ 300 R). The DMSP data of electron and ion energy flux showed Low Latitude Boundary Layer (LLBL/cleft) signature in conjunction with the aurora at 7:36:40 UT (66.89° MLAT, 10.04 MLT), and the ion horizontal velocity measured by the drift meter was very large ($\sim$ 4 km/s) at the poleward edge of the aurora. The estimated electric field perpendicular to the geomagnetic field was $\sim$ 90 mV/m, and ion velocities perpendicular and parallel to the geomagnetic field were 2,350 m/s and 2,830 m/s. This large ion upward velocity was also reported in the preceding study [*Shen et al.*, 2016]. Next, we evaluated the N_2^+ emission with the GLOW model and compared with the ASG data. We evaluated the N_2^+ emission with the GLOW model and compared with the ASG data. When we increased the atmospheric scale height above 200 km, the calculated 630.0 nm emission peak is consistent with observed emission and the inclination of calculated 557.7 nm emission above 200 km was similar to the observed emission. For 427.8 nm emission, both of the emission peaks at 300 km were relatively the same, and the inclinations below 450 km altitude were similar. Then, we estimated the O^+ ion density which is important for N_2^+ ion production due to the charge exchange reaction between N_2 and O^+, assuming that the N_2^+ emission is caused by the local generation. The estimated O^+ ion density around 500 km was $\sim 10^5$ cm^{-3} (or 10^{11} m^{-3}) which is in the same as that reported in the previous statistical study with ESR [*Bjoland et al.*, 2016].

Furthermore, the observed N_2^+ emissions are dependent on Kp index. As Kp index increased, the intensity of N_2^+ resonant scattering light in the F-region increased. When the Kp index were 3 and 7-, the intensities at 350 km altitude were $\sim$ 100 - 200 R and more than 600 R. In addition, the higher Kp index was, the higher altitude the emission distributed. When the Kp index was 7-, the altitude which the intensity was less than 200 R was higher than 1,000 km. This demonstrates that the intensity of N_2^+ emission in the F-region is high and the emission distributes to higher altitude when the auroral activity is high.

From the results obtained in this study, we suggest that N_2^+ ion upflow starts from F-region or above the F-region, not the E-region, and N_2^+ ion in the topside polar ionosphere in the dayside sector is dominantly produced by the charge exchange reaction between N_2 and O^+. Our results demonstrate that the existence of soft electrons precipitation is well correlated with N_2^+ ion upflow due to the strong ambipolar electric field and N_2^+ ion production in the topside ionosphere which implies that the enhancement of O^+ generated by the precipitating soft electrons. The effect of N_2^+ ion upflow and outflow on the dynamics of the magnetosphere should be investigated by the Arase (ERG) satellite or future missions, and the effect of N_2^+ ion outflow on the atmospheric escape is an important task for the long-term evolution of planetary atmosphere.