THE NEED FOR DETAILED IONIC COMPOSITION OF THE NEAR-EARTH PLASMA

An impressive body of work has been devoted to the escape of H\(^+\), He\(^+\) and O\(^+\) ions from Earth’s ionosphere, and their circulation and redistribution throughout the terrestrial magnetosphere (Schunk and Raitt, 1980; Schunk and Sojka, 1997; Winglee et al., 2002; Glo cer et al., 2009; Ilie et al., 2015; Ilie and Liemohn, 2016). However, the transport and energization of N\(^+\), in addition to that of O\(^+\), has not been considered by most studies, even though a number of direct and indirect measurements made to describe the ionic composition of the ionosphere-magnetosphere system, have established that N\(^+\) is a significant ion species in the ionosphere and its presence in the magnetosphere is significant. A wide range in the magnitude of the N\(^+\) to O\(^+\) density ratio has been reported, with significant variations not only with geomagnetic activity but also with solar cycle, season, time of day, latitude, etc (Mall et al., 2002; Christon et al., 2002). These variations suggest that N\(^+\) and O\(^+\), while relatively close in mass, they obey different chemical and energization processes, and possibly follow different paths of energization.

In addition, observations from the ISIS 2 spacecraft (Hoffman et al., 1974) indicated that not only N\(^+\), but also molecular ions were observed in the Earth’s magnetosphere and ionosphere. Measurements from the Arase satellite (Miyoshi et al., 2018) showed the existence of molecular ions in the Earth’s ring current region, even under moderate geomagnetic storm conditions. The Low-Energy Particle experiments-Ion mass analyzer (LEPi) instrument (Asamura et al., 2018) on board the Arase satellite clearly identified the energies of the molecular ions above \(\sim 12\) keV during most magnetic storms, and the average energy density ratio of the molecular ions to O\(^+\) is \(\sim 3\%\) (Seki et al., 2019). Furthermore, recent observations based on the CASSIOPE Enhanced Polar Outflow Probe (e-POP) mission data report on the presence of cold atomic N\(^+\), and molecular N\(_2^+\) and NO\(^+\) densities in both ion up-flows and down-flows. Interestingly enough, the densities of N\(^+\) can contribute up to 10-50\% of the plasma density, at all times, independent of geomagnetic activity (Yau et al., 2019).

Although limited, observations of outflowing nitrogen ions have been reported by early missions, spanning a wide range of altitudes, from \(\sim 200\) km for the Sputnik III spacecraft, to millions of km for the WIND spacecraft (see Figure 1 for their solar cycle coverage). However, most space missions lacked the possibility to reliably separate the N\(^+\) from O\(^+\) owning to their very close masses, and relatively few currently active ion spectrometers in space are capable of separating N\(^+\) from O\(^+\), therefore the observational record of its existence and significance has been overlooked. Although these observations show the importance of heavy ions in the high-altitude ionosphere and magnetosphere, the mechanisms responsible for accelerating the ionospheric heavy ions from eV to keV energies are still largely unknown. Their transport and acceleration in the ionospheric

Figure 1. Sunspot number from 1958 to 2020 (black lines) indicative of solar cycles 19 through 24 (numbers in grey). Overplotted are the “nitrogen measuring” missions and their corresponding operating altitude (perigee to apogee) vs. time.
outflow, as well as the relative abundance of the molecular ions in the low-altitude ionosphere, is still unknown.

Recently, numerical simulations using the 7iPWOM Lin et al. (2020), which solves for the transport of H\(^+\), He\(^+\), O\(^+\), N\(^+\), and e\(^-\), and includes three static minor ion species, NO\(^+\), N\(_2\)\(^+\) and O\(_2\)\(^+\), showed that N\(^+\) ions play a key role in the ionospheric outflow for all conditions. Accounting for the presence of N\(^+\) ions in the lower ionosphere and their transport outwards drastically improved the polar wind solution. Furthermore, as it leads to an improved solution for He\(^+\) ions and captures their seasonal variations. Figure 2, from Lin et al. (2020) shows the simulation results from eight different sets of numerical experiments. The upward transport of these ions in the Earth’s polar ionosphere is solved for using both the 7iPWOM (solid line) and the 3iPWOM (dashed line) which only considers H\(^+\), He\(^+\), O\(^+\), and e\(^-\), and comparison with the appropriate data (dotted line) from OGO-6 and AE-C for various solar flux and seasonal conditions is presented.

Understanding plasma composition requires to ultimately include a variety of ions that are currently known, although neglected, to be present in the low altitude ionosphere. Spatial and temporal variations in the heavy ion composition can provide unique insights into the dynamics of the terrestrial magnetosphere, as heavy ions alter the plasma mass density, the Alfvén velocity, they modulate wave-particle interactions and alter the development and decay of the ring current and radiation belt (e.g. Bashir and Ilie, 2018).

Appropriate knowledge of the ionic composition will guide the development of instrumentation and space missions, capable of distinguishing between O\(^+\) and N\(^+\) ions, since the differences between O\(^+\) and N\(^+\) transport and energization are not quantified, nor understood, at this time. Furthermore, understanding the differential transport of nitrogen and oxygen ions, together with molecular ions, throughout the ionosphere-magnetosphere region can also provide knowledge of: i. **Exospheric morphology**, which at this time is unknown. Several models to predict the exosphere density have been developed throughout the years; however, aside form their lack of temporal variation, there is strong disagreement between all models. ii. **Ionospheric physics**, since ionosphere-exosphere-magnetosphere coupling is controlled by the ionization at the topside ionosphere, which is strongly dependent on external driving. iv. **Planetary atmospheric evolution**, by providing hints about variation in the nitrogen budget with solar activity over geological scales time periods.

- The atmospheric escape via the polar wind is highly affected by the ionospheric composition, as the escape of the nitrogen ions three gigayears ago increases by \( \sim 3 \)
orders of magnitude compared to its present value (Kislyakova et al., 2020).

References


