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- Though limited, the existing observational data indicate N^+ as a signification in the ionosphere
- Differential transport of heavy versus light ionospheric species
- N^+ ion could dominate the ionospheric outflow during disturbed conditions

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The outflow of ionospheric nitrogen ions: A possible tracer for the altitude-dependent transport and energization processes of ionospheric plasma

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Abstract Though limited, the existing observational data set indicates that N^+ is a significant ion in the ionosphere, and its concentration varies with season, time of day, solar cycle, latitude, and geomagnetic conditions. Knowledge of the differential transport of heavy versus light ionospheric species can provide the connection between the macroscale dynamics and microscale processes that govern the near-Earth space. The mass distribution of accelerated ionospheric ions reflects the source region of the low-altitude ion composition, and the minor ion component can serve as a tracer of ionospheric processes since they can have a significant influence on the local plasma dynamics.

1. The Neglected Component of Ionospheric Outflow: Nitrogen Ions

The polar wind consists of outflowing plasma from the high-latitude ionosphere into the low pressure magnetosphere, along open magnetic field lines. By the time it reaches the magnetosphere, this plasma undergoes transitions from chemical to diffusion dominance, from collision dominated to collision less, and from subsonic to supersonic flow. While the provenance of H^+ in the magnetosphere is usually ambiguous because it is the major component of both the solar wind and topside ionosphere, the presence of heavy, single charged ions is predominantly linked with outflowing of ions of ionospheric origin.

Since first suggested by *Shelley et al.* [1972], the dynamics leading to the ionospheric outflow of O^+ ions and the impact on the evolution of the magnetosphere-ionosphere system have been the subject of numerous studies [e.g., *Schunk and Raitt*, 1980; *Mukai et al.*, 1994; *Schunk and Sojka*, 1997; *Seki et al.*, 1998; *Daglis et al.*, 1999; *Winglee et al.*, 2002; *Nosé et al.*, 2005; *Barakat and Schunk*, 2006; *Glocer et al.*, 2009; *Garcia et al.*, 2010; *Glocer et al.*, 2012; *Ilie et al.*, 2013, 2015]. For instance, several studies [e.g., *Young et al.*, 1982; *Hamilton et al.*, 1988; *Daglis et al.*, 1999; *Fu et al.*, 2001, 2002; *Winglee et al.*, 2002; *Kozyra et al.*, 2002; *Nosé et al.*, 2005] find that O^+ can dominate not only the mass density but even the number density in the magnetosphere, therefore controlling the large-scale processes of mass and energy flow through geospace. However, the transport and energization of N^+, in addition to that of O^+, have not been considered by most studies, simply because the observational record of its existence and significance has been overlooked. Most past missions lacked the possibility to reliably separate the N^+ from O^+ owing to their close masses, and therefore, we lack statistical knowledge of the relative contribution N^+ to the outflow of the heavy ionospheric ions. But in spite of only 12% mass difference, nitrogen and oxygen have different ionization energies (15.581 eV and 12.069 eV, respectively) as well as different scale heights. In addition, the cross section for charge transfer between atomic hydrogen and nitrogen ions ($N^+ + H \rightarrow N + H^+$) is significantly different than the cross section for charge transfer between atomic hydrogen and oxygen ions ($O^+ + H \rightarrow O + H^+$). That is, the difference between the charge exchange cross sections of a 100 eV O^+ and N^+ with neutral H can be as high as a factor of 4 and increases with decreasing energy [*Stebbings et al.*, 1960]. Furthermore, the peak production rates for those two ionospheric heavy ions is usually at different altitudes. Therefore, based on these differences, tracking the behavior of oxygen and nitrogen ions could serve as a tracer for the altitude-dependent transport and energization processes of ionospheric plasma. Limited studies based on theoretical models of the ionospheric outflow [*Schunk and Raitt*, 1980; *Sojka et al.*, 1982] predict significant densities of N^+, showing a strong dependence on diurnal, seasonal, and geomagnetic activity as well as Universal Time. Nevertheless, the overall outflow of N^+ ions and its consequences for the magnetosphere remain an unaddressed question.

2. Production and Loss of the N^+ Ion

There are several mechanisms for the production of N^+: photoionization [*Verner et al.*, 1993, 1996; *Verner and Yakovlev*, 1995],

$$N + h\nu \rightarrow N^+ + e^- \tag{1}$$

dissociative ionization of N_2 by sunlight [*Kronebusch and Berkowitz*, 1976],

$$N_2 + h\nu \rightarrow N^+ + N + e^- \tag{2}$$

dissociative ionization of N_2 by photoelectrons [*Kronebusch and Berkowitz*, 1976],

$$N_2 + e^- \rightarrow N^+ + N + 2e^- \tag{3}$$

charge transfer between N_2^+ and N [*Stebbings et al.*, 1960],

$$N_2^+ + N \rightarrow N^+ + N_2 \tag{4}$$

and dissociative charge transfer between He^+ and N_2 [*Lindinger et al.*, 1974; *Huntress and Anicich*, 1976].

$$He^+ + N_2 \rightarrow N^+ + N + He \tag{5}$$

Conversely, the N^+ ions are lost through reactions with O_2, H, NO, and O, such as ion atom interchange [*Lindinger et al.*, 1974; *Huntress and Anicich*, 1976],

$$N^+ + O_2 \rightarrow NO^+ + O \tag{6}$$

and charge exchange reactions [*Stebbings et al.*, 1960; *McElroy*, 1967; *Lindinger et al.*, 1974; *Kosmider and Hasted*, 1975; *Huntress and Anicich*, 1976].

$$N^+ + O_2 \rightarrow O_2^+ + N \tag{7}$$

$$N^+ + NO \rightarrow NO^+ + N \tag{8}$$

$$N^+ + O \rightarrow N + O^+ \tag{9}$$

$$N^+ + H \rightarrow N + H^+ \tag{10}$$

When N_2 is photoionized, the results could be either N_2^+ or N^+ and the production of N^+ from the photoionization of N_2 was suggested to occur with an efficiency factor of 0.21 [*McElroy*, 1967]. Since N^+ is produced by reactions involving N, N_2, and He^+ and lost in reactions involving O_2, H, and NO, it is apparent that the number density of N^+ increases with increasing solar activity, at least under conditions of photochemical equilibrium. However, the loss rate due to increased O_2 could act to further alter the production of N^+. Similarly, the O^+ ion is produced in reactions with O and He and lost through its interaction with N_2, O_2, and O. Therefore, any change in the neutral densities and temperatures will change the production rate for both O^+ and N^+. The incoming solar flux has a strong influence on the ionization rates and collision distributions. Determining the seasonal effect on the source region of the low altitude ion composition and the minor ion component of the accelerated plasma will help trace the ionospheric processes that lead to a significant influence on the local plasma dynamics.

The change in convection as well as precipitation during quiet and disturbed times might lead to horizontal and vertical differential transport of N^+ and O^+ ions. The neutral atmosphere also changes with geomagnetic activity [*Hedin*, 1987, 1992] which will affect all chemical production and loss rates. Therefore, it is important to note that an appropriate description of ionospheric outflow requires separating the N^+ and O^+ ions as they obey different chemical and physical reactions and dynamical forces.

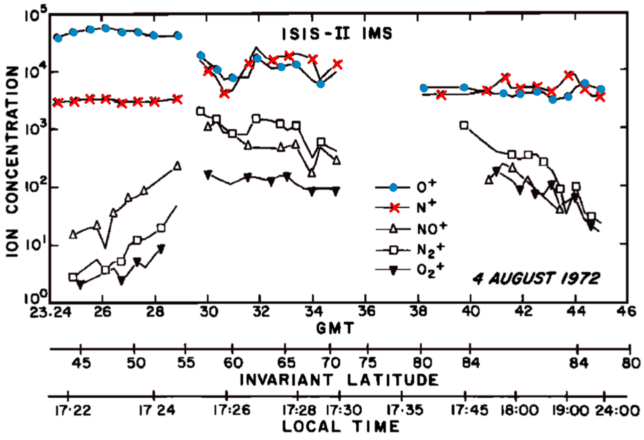

Figure 1. ISIS 2 measurements of ion composition during August 1972 storm which shows that during this time the N^+ ion (and molecular ions species) dominate the ionosphere at 1400 km. For easy reference, O^+ and N^+ ions traces are highlighted with blue and red symbols, respectively. Figure adapted from *Hoffman et al.* [1974].

3. Observational Evidence

Observations of outflowing nitrogen ions from the terrestrial ionosphere have been reported by early NASA missions, spanning a wide range of altitudes, from 276 km on the short lived Explorer 32 to 23,289 km on Dynamics Explorer 1 (DE-1). The first detailed experimental study of observational evidence which showed latitudinal variation in the exospheric ion composition, based on measurements from the ion spectrometer on board of Polar Orbiting Geophysical Observatory (OGO 2), revealed that not only does N^+ becomes significantly important at high latitudes but also in the polar and auroral regions it reaches concentration levels exceeding that of He^+ and sometimes even H^+ [*Brinton et al.*, 1968]. Data from the magnetic mass spectrometer of the Explorer 31 mission show that the ionosphere above 1000 km usually consists of hydrogen ions as the predominant species. However, between this altitude and perigee (500 km), the dominant ion species shifts to atomic oxygen, with a significant amount of atomic nitrogen ions also present [*Hoffman*, 1967]. The N^+ concentration varies from 5 to 30% of the total O^+ concentration and H^+ is generally only 5% of the O^+ concentration at these altitudes. These measurements also reflect that even during solar minimum, the nitrogen ions are the second most abundant ion population in the Earth's upper ionosphere [*Hoffman*, 1970]. Observations from the Bennett radio frequency ion spectrometer on Explorer 32 reveal that during disturbed times the concentrations of oxygen and nitrogen ions between 500 and 1500 km were found to be a factor of up to 2.5 higher than during quiet times [*Brinton et al.*, 1971].

Initial results from the Ion Mass Spectrometer (IMS) instrument on International Satellite for Ionospheric Studies-2 (ISIS-2) [*Hoffman et al.*, 1974] show a wide variation in ion composition even during undisturbed conditions, with the N^+ ion density consistently tracking the behavior of oxygen ions. However, during active times, the picture changes dramatically. Figure 1, with IMS observations during the geomagnetic storm of 4 August 1972 ($Kp = 9$), shows that the N^+ ions become the dominant species from 55° latitude toward the pole [*Hoffman et al.*, 1974] at ~1400 km. Furthermore, molecular ions species that under quiet time go undetected, such as N_2^+, NO^+, and O_2^+, are observed in large concentrations (~10^3 cm^{-3}). Their presence at the top of the ionosphere and beyond is indicative of significant electrodynamic processes which are necessary in order to accelerate these heavy ions to energies beyond tens of eV [see *Wilson and Craven*, 1998, and reference therein]. Measurements from a neutral mass spectrometer during a similar event show significant enhancement of N_2 at high altitudes, which could be the source of N^+ and N_2^+ and therefore leading to the enhancement in their concentrations.

The Retarding Ion Mass Spectrometer (RIMS) [*Chappell et al.*, 1981] on board the DE-1 satellite was also able to resolve masses near the O^+ peak in the mass spectrum and showed that N^+ is a constant companion of O^+ as an outflowing ion [*Craven et al.*, 1995]. Data during almost a complete orbit on 30 December 1981 reveals outflowing, cold (<30 eV) N^+ ions from the polar ionosphere up to 3 R_E altitude in the polar cap [*Chappell et al.*, 1982], with density profiles comparable with the ones of O^+. Observations based on Akebono SMS measurements [*Whalen et al.*, 1990] also confirmed the presence of N^+ above the ionosphere with an O^+/N^+ density ratio of ~2. In addition, Akebono SMS measurements have demonstrated that the thermal ion population in the high altitude polar ionosphere is dominated not by H^+ as it was previously believed but by N^+, He^+, O^+, and O^{2+} for energies below 30 keV [*Yau et al.*, 1991]. Even though the data set was insufficient for statistical value, these limited measurements also confirm previous findings that the N^+ fluxes make up ~10% of those of O^+ even during undisturbed conditions.

In addition, energetic nitrogen ions of above 10 keV have also been detected to higher altitudes in the magnetosphere by the AMPTE CHEM instrument [*Hamilton et al.*, 1988], the WIND/STICS instrument [*Mall et al.*, 2002], the Geotail/STICS instrument [*Christon et al.*, 2000, 2002], and the CRRES/MICS instrument [*Liu et al.*, 2005]. Recently, mass composition measurements from the Enhanced Polar Outflow Probe show enhanced densities of N^+, O^{++}, and molecular ions in localized regions of the quiet time topside high-latitude ionosphere [*Yau and Howarth*, 2016]. This attests to the outflow of ionospheric N^+ ion and its presence in the magnetosphere; therefore, its contribution to the total ionospheric outflow cannot be overlooked.

4. Summary

The relative contributions of oxygen and nitrogen ions to ionospheric outflow remain largely unknown at this time. Knowledge of their separate behavior could provide insight into the differential transport of heavy versus light ionospheric species can be used as a tracer for the altitude-dependent transport and energization processes of ionospheric plasma since the mass distribution of accelerated ionospheric ions reflects the source region of the low altitude ion composition and the minor ion component of the accelerated plasma. Furthermore, knowledge of the differential transport of N^+ and O^+ ions will provide insight into the connection between the macroscale dynamics and microscale processes that govern this region.

The presence of these heavy ions in the near-Earth environment has a profound implications on the global magnetosphere-ionosphere dynamics, especially during times of increased geomagnetic activity. The outflow of N^+ from the ionosphere, in addition to O^+, could affect the global structure and properties of the current sheet, the mass loading of the magnetosphere and lead to changes in the local properties of the plasma. The reconnection process is strongly influenced by heavy ions; therefore, a detailed composition of the local plasma (i.e., distinguishing between O^+ and N^+ ions) is required in order to thoroughly understand the leading causes of magnetic reconnection. The presence of N^+ in the thermal plasma can influence the waves properties since their propagation and frequency are dependent on the mass composition.

Furthermore, the differences between O^+ and N^+ transport and energization are neither quantified nor understood at this time and it could play a crucial role in the interpretation and analysis of data from many magnetospheric current missions. For instance, Van Allen Probes data are being analyzed assuming that all “heavy ions” are O^+, which could be wrong. N^+ has a different charge exchange cross section than O^+, which leads to different lifetimes of these ions in the magnetosphere, altering the plasma composition. Storm time ring current measurements of ions composition [*Hamilton et al.*, 1988] reveal that the enhancement of N^+ is the second strongest, after O^+.

Albeit limited, the existing observations indicate that O^+ and N^+ exhibit a different behavior as affected by solar radiation, solar wind, and geomagnetic activities. The overall dependence of those two ions on solar UV is not understood. Furthermore, the role of the exospheric neutrals and how they couple with the ionospheric heavy ions is unknown above 1500 km.

Appropriate instrumentation, capable of distinguishing between O^+ and N^+ ions, together with a strong numerical modeling efforts are needed in order to appropriately address the “nonclassical” polar wind problem. These data and model capabilities need to be applied across geospace, most notably in four locations: (1) the high-latitude region above 1000 km where ionospheric upflow becomes outflow, with mass resolution in the ~eV particle energy range; (2) the equatorial nightside magnetosphere, where these outflowing ions join the plasma sheet and become accelerated up to ~keV energies; (3) near magnetic reconnection sites where the distinct mass of N^+ could modify the ion diffusion region; and (4) in the inner magnetosphere, particularly during storms, when N^+ could significantly contribute to the mass density and plasma wave environment. Furthermore, treating the magnetosphere-ionosphere-thermosphere as a unified whole is required in order to account for the effects of solar input, chemistry, convection, and neutral dynamics on the differential transport of O^+ and N^+ throughout system. Reaching a solid understanding of this issue requires a community wide effort.

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