

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

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This is the author manuscript accepted for publication and has undergone full peer review but has not been through the copyediting, typesetting, pagination and proofreading process, which may lead to differences between this version and the Version of Record. Please cite this article as doi:10.1029/2015JA022362

Received 10 September 2015, 1:19pm

D R A F T

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 vs. light ionospheric species can provide the connection between the macro-scale dynamics and micro-scale 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.

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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 prevalence 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 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 Raith*, 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; *Fu et al.*, 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 very 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 an 100 eV O^+ and N^+ with neutral H can be as high as a factor of 4 and increases with decreasing energy [Stebbing *et al.*, 1960]. Furthermore, the peak production rates for those two ionospheric heavy ions usually happen 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 remains 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; Verner *et al.*, 1996; Verner and Yakovlev, 1995],



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



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



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



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



Consequently, 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*],



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



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 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 disparate differential transport of N^+ and O^+ ions. The neutral atmosphere also changes with geomagnetic activity [Hedin, 1987; Hedin, 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.

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 the ones of He^+ and sometimes even H^+ [Brinton *et al.*, 1968]. Data from the magnetic mass spectrometer of the Explorer 31 mission shows 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 August 4, 1972 ($K_p=9$), shows that the N^+ ions become the dominant species from 55° latitude towards 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 ($\sim 10^3$ 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 shows 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] onboard 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 December 30, 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 $\sim 10\%$ 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; Christon *et al.*, 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 remains largely unknown at this time. Knowledge of their separate behavior could provide insight into the differential transport of heavy vs. 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 macro-scale dynamics and micro-scale 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 not quantified nor understood at this time and it could play a crucial role in the interpretations and analysis of data from many magnetospheric current missions. For instance, Van Allen Probes data is 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 1500km.

This commentary attempts to bring attention to a long ignored problem. 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 “non-classical” 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 $\sim eV$ particle energy range; (2) the equatorial nightside magnetosphere, where these outflowing ions join the plasma sheet and become accelerated up to $\sim keV$ 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.

Acknowledgments. Work at University of Michigan was performed with financial support from the NASA under grants NNX11A060G, and NNX14AC02G and NSF through grants AGS-1102863 and AGS-1414517. All data for this paper is properly cited and referred to in the reference list.

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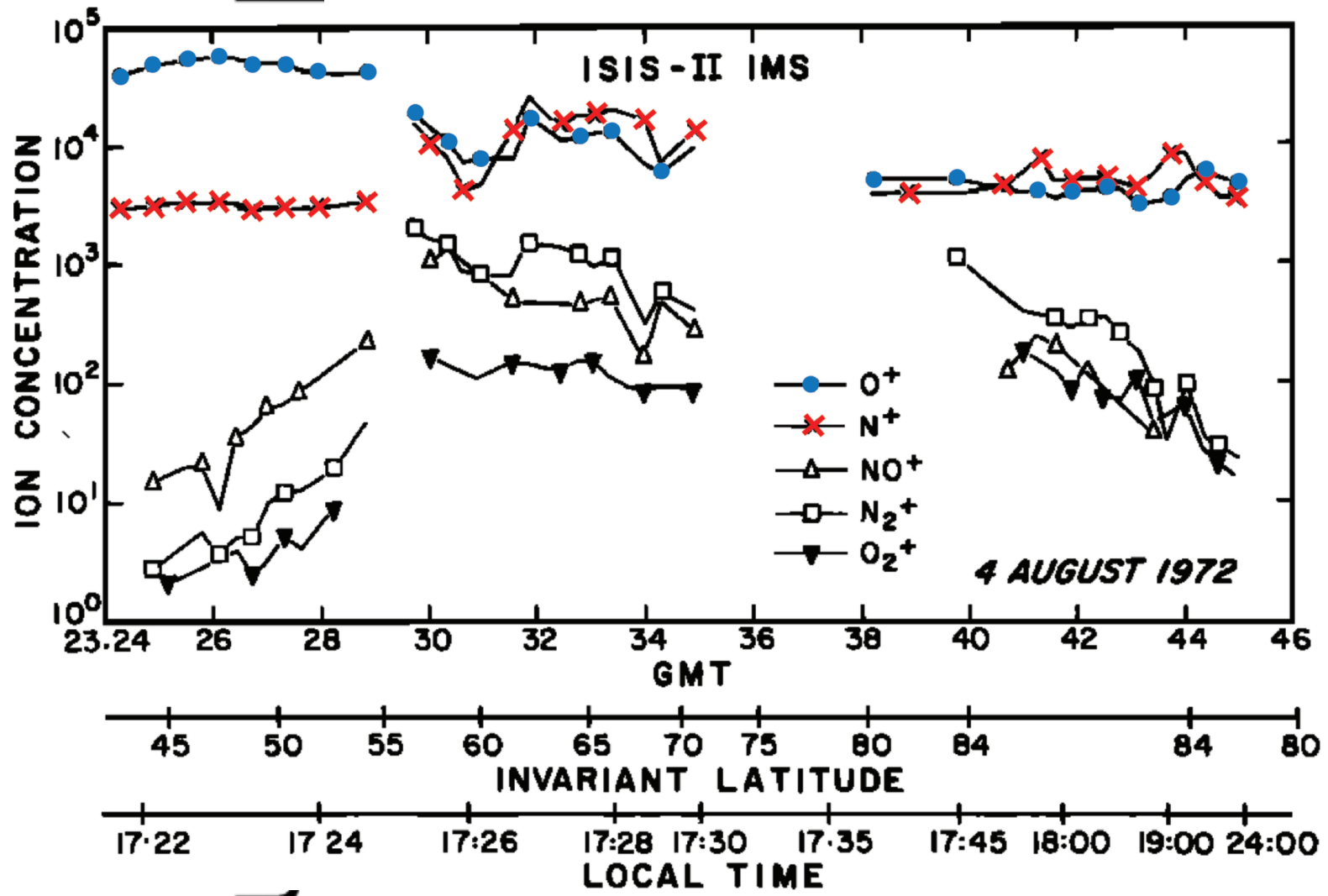
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Figure 1. ISIS 2 measurements of ion composition during August 1972 storm which shows that during this time the N^+ ion (and molecular ions species) dominate the ionosphere at 1400 km. For easy reference, O^+ and N^+ ions traces are highlighted with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

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