How are the N⁺ ions affecting the transport and acceleration of ionospheric outflowing ions?

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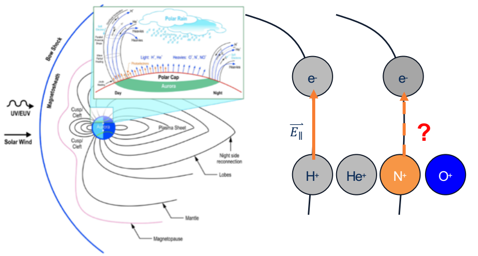
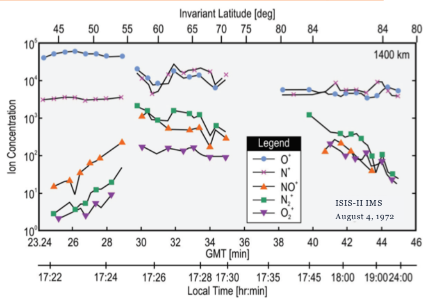
ABSTRACT Changes in the heavy ion composition in the terrestrial ionosphere and magnetosphere can have significant impact on particle dynamics in the Earth's magnetosphere-ionosphere system. Most instruments flying in space, such as MMS and Van Allen Probes, lack the possibility to distinguish N^+ from O^+ due to their close masses. However, observations of N^+ both in the ionosphere and magnetosphere indicate that N^+ is a constant companion of O^+, especially during the storm time. Because N^+ originates from the Earth's ionosphere, we further develop the Polar Wind Outflow Model (PWOM) to investigate the behavior and acceleration mechanisms of heavy ions in Earth's ionosphere. PWOM solves the particle dynamics of O^+, H^+ and He^+ in the ionospheric outflow, and the modified PWOM can further simulate the behavior of N^+ and N_2^+ in Earth's polar wind. The escape of heavy ions from the Earth atmosphere is consequences of energization and transport mechanisms, including photoionization, electron precipitation, ion-electron-neutral chemistry and collisions. The modified PWOM is coupled with a two-stream model of superthermal electrons (GLobal airglow, or GLOW) to deal with attenuated radiation, electron beam energy dissipation, and secondary electron impact. In this study, we show that during various solar conditions, the ion-electron-neutral densities in the ionospheric outflow show significant difference when we consider N^+ ions in the polar wind. Furthermore, we will compare the simulation results of the modified PWOM with observation data for validation.

Challenge: Unknown Transport Mechanisms of Polar Wind Heavy Ions

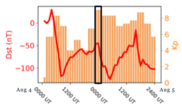


- While the transport of O^+ in the polar wind can be explained by both classical and non-classical polar wind theory, the acceleration mechanisms for N^+ ions are largely unknown.

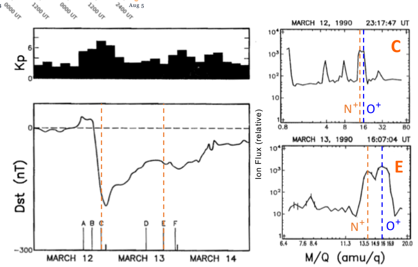
Observations of N⁺ in the Earth's Ionosphere



ISIS 2 measurements of ion composition during August 1972 storm (kp=9) showing increased N⁺, O⁺ and molecular ions species abundances at 1400 km.



- During active times, O^+ and N^+ have comparable ion concentrations in the polar ionosphere (Hoffman et al., 1974).



Selected SMS mass spectra in storm time during 12-13 March 1990 storm shows the ion abundance of O⁺ and N⁺.

- During the main phase of a large storm, the ratio of N^+/O^+ can be around unity in the dayside at the high-altitude (>1000 km) polar ionosphere (Yau et al., 1992).

Seven Ion Polar Wind Outflow Model (7iPWOM)

Blue: Chemistry Related Red: Collision Related

$$\frac{\partial}{\partial t}(A\rho_i) + \frac{\partial}{\partial r}(A\rho_i u_i) = AS_i \quad [1]$$

(Source term)

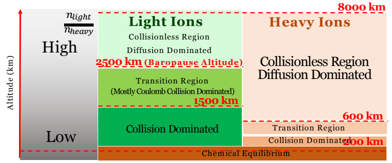
$$\frac{\partial}{\partial t}(A\rho_i u_i) + \frac{\partial}{\partial r}(A\rho_i u_i^2) + A\frac{\partial p_i}{\partial r} = A\rho_i\left(\frac{e}{m_i}E_\parallel - g\right) + A\frac{\delta M_i}{\delta t} + Au_iS_i \quad [2]$$

(Momentum Change)

$$\frac{\partial}{\partial t}\left(\frac{1}{2}A\rho_i u_i^2 + \frac{1}{\gamma_i - 1}Ap_i\right) + \frac{\partial}{\partial r}\left(\frac{1}{2}A\rho_i u_i^3 + \frac{\gamma_i}{\gamma_i - 1}Au_ip_i\right) = A\rho_i u_i\left(\frac{e}{m_i}E_\parallel - g\right) + \frac{\partial}{\partial r}\left(A\kappa_i\frac{\partial T_i}{\partial r}\right) + A\frac{\delta E_i}{\delta t} + Au_i\frac{\delta M_i}{\delta t} + \frac{1}{2}Au_i^2S_i \quad [3]$$

(Energy Change)

(Glocer et al., 2009, JGR)



3iPWOM
H^+, He^+, O^+

↓

7iPWOM
H^+, He^+, N^+, O^+, N_2^+, NO^+, O_2^+

Chemistry reaction	Chemistry process	Reaction rate
Ion atom interchange	$N_2 + O^+ \longrightarrow NO^+ + N$	1.2×10^{-12}
Charge exchange	$O^+ + O_2 \longrightarrow O_2{}^+ + O$	2.1×10^{-11}
Dissociative charge transfer	$He^+ + O_2 \longrightarrow O^+ + O + He$	9.7×10^{-10}
Charge exchange	$He^+ + N_2 \longrightarrow N_2{}^+ + He$ $He^+ + N_2 \longrightarrow N^+ + N + He$	5.2×10^{-10} 7.8×10^{-10}
Charge exchange	$H^+ + O \longrightarrow H + O^+$ $H + O^+ \longrightarrow H^+ + O$	$2.2\times10^{-11}\times T_e^{0.5}$ $2.5\times10^{-11}\times T_e^{0.5}$
Recombination	$O^+ + e^- \longrightarrow O$	$3.7\times10^{-12}\times(\frac{250}{T_e})^{0.7}$
Recombination	$H^+ + e^- \longrightarrow H$	$4.8\times10^{-12}\times(\frac{250}{T_e})^{0.7}$
Recombination	$He^+ + e^- \longrightarrow He$	$4.8\times10^{-12}\times(\frac{250}{T_e})^{0.7}$
Ion atom interchange	$N^+ + O_2 \longrightarrow NO^+ + O$ $N^+ + O_2 \longrightarrow O_2{}^+ + N$ $N^+ + O_2 \longrightarrow O^+ + NO$	3.07×10^{-10} 2.32×10^{-10} 4.6×10^{-11}
Charge exchange	$N^+ + NO \longrightarrow NO^+ + N$	2×10^{-11}
Charge exchange	$N^+ + O \longrightarrow N + O^+$	2.2×10^{-12}
Charge exchange	$N^+ + H \longrightarrow N + H^+$	3.6×10^{-12}
Charge exchange	$N_2{}^+ + N \longrightarrow N^+ + N_2$	10^{-11}
Charge exchange	$N_2{}^+ + NO \longrightarrow NO^+ + N_2$	4.1×10^{-10}
Ion atom interchange	$N_2{}^+ + O \longrightarrow NO^+ + N$ $N_2{}^+ + O \longrightarrow O^+ + N_2$	1.3×10^{-10} 1.0×10^{-11}
Charge exchange	$N_2{}^+ + O_2 \longrightarrow O_2{}^+ + N_2$	5×10^{-11}
Charge Exchange	$O^+ + NO \longrightarrow NO^+ + O$	8.0×10^{-13}
Recombination	$N^+ + e^- \longrightarrow N$	$3.6\times10^{-12}\times(\frac{250}{T_e})^{0.7}$
Dissociation	$N_2{}^+ + e^- \longrightarrow N + N$	$2.2\times10^{-7}\times(\frac{300}{T_e})^{0.39}$
Dissociation	$NO^+ + e^- \longrightarrow N + O$	$4.0\times10^{-7}\times(\frac{300}{T_e})^{0.5}$
Dissociation	$O_2{}^+ + e^- \longrightarrow O + O$	$2.4\times10^{-7}\times(\frac{300}{T_e})^{0.7}$

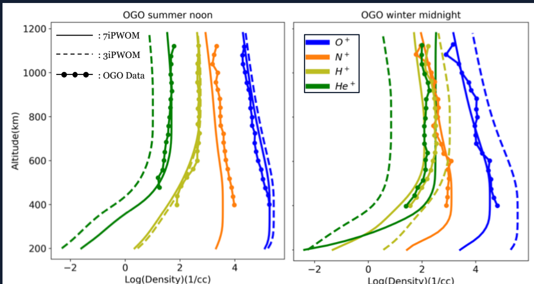
Chemical reaction table for 7iPWOM. Blue color indicates the new reaction applied in the PWOM. Ref: Shunk et al., 2009 & Anicich et al., 2003.

NEW: Chemistry, Collision, Photoionization

- Chemistry: Changes in the transport equations source terms are due to chemistry.
- Collision: 7iPWOM includes collision parameters related to both additional ion (O^+, H^+, He^+, $\mathbf{N^+}$, $\mathbf{N_2^+}$, $\mathbf{NO^+}$, $\mathbf{O_2^+}$) and neutral (O, H, O_2, N_2, He, **N**, **NO**) species.
- Photoionization: GLobal airglOW (GLOW) model provides photon and electron fluxes based on different photon and electron energy.
  - 7iPWOM calculates production rate of N^+ and O^+ separately, based on photon and electron fluxes.

$$\text{Production} = \int Flux(E)\sigma(E, neutral, ion)n(neutral)\, dE$$

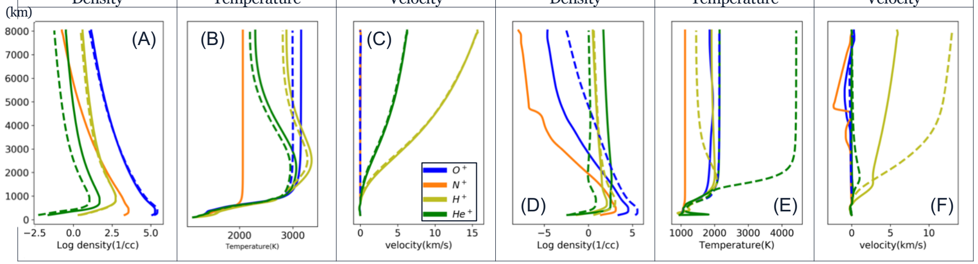
Data - Model Comparison



- The simulated ion number densities using the 7iPWOM are closed to the averaged OGO data (Craven Paul, 1995) in the Earth's polar ionosphere (200 - 1200 km).
- Heavy ions abundances dramatically vary with season.

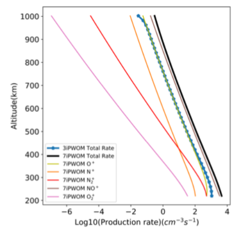
Steady State: n, T, v

- Consequences of N^+ presence in the ionospheric outflow solution:
  → The N^+ ion is the second most abundant ion species in the polar wind.
  → The presence of N^+ alters both the number densities and the temperatures of O^+, H^+ and He^+.



Which Mechanism Causes the Differences?

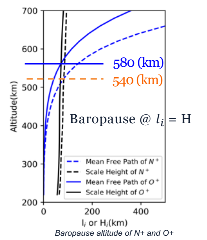
Photoionization Rate



Photoionization rate between 3iPWOM and 7iPWOM

- Same O^+ ionization rate in 3iPWOM and 7iPWOM → Photoionization rate is unlikely to be the reason.

Collision: Baropause Altitude



Baropause altitude of N+ and O+

- The baropause altitude can explain the temperature profiles of N^+ (see Panel A and E).

(Lemaire et al., 1972)

Chemical Reaction

Ions (1/cc)	Chemical Equilibrium Number Density	
	3iPWOM	7iPWOM
O^+	**1.17E05**	**4.86E04**
H^+	3.60E-02	7.54E-01
He^+	1.14E-01	4.42E-02
N^+		**5.73E03**
N_2^+		2.73E02
NO^+		6.2E04
O_2^+		9.7E03
Total number density	**1.17E05**	**1.21E05**

O^+ decreases one order magnitude

Total number density doesn't change

The number density of chemical equilibrium solution between 3iPWOM and 7iPWOM.

Conclusion

- Although limited, existing observations highlight the importance of N^+ in the Earth's ionosphere, and show that N^+ is a constant companion of O^+ during the storm time.
- **We developed the 7iPWOM model to include the behavior of H^+, He^+, N^+, O^+, N_2^+, NO^+, O_2^+ in ionospheric outflow, using advanced schemes for photoionization calculation, chemical reactions, and ion-neutral-electron collisions.**
- The data-model comparison shows that **including N^+ in the polar wind improves the outflow solution when compared with observations.**
- The 7iPWOM model suggests that heavy ions undergo large seasonal variations, and hints to the importance of N^+ in the polar ionosphere from 200 – 1200 km.
- The presence of N^+ in the polar wind influences the transport and acceleration of other species, by altering their overall abundance temperature.

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