Determine the Role of Nitrogen Ions in the Ionospheric Outflow: Tracking the Differential Behavior of N^+ and O^+ Ions from the Outflowing Ionosphere to the Inner Magnetosphere

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ABSTRACT

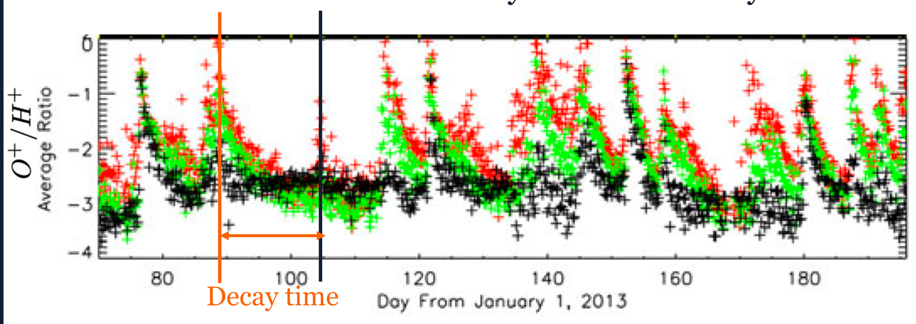
Knowledge of ion composition in the terrestrial ionosphere and magnetosphere is crucial to understand the plasma dynamics in the Earth's magnetosphere-ionosphere system. The discovery of O^+ and N^+ in the ionosphere and magnetosphere hinted to the connection between the ionospheric and magnetospheric plasma, suggesting that the ionosphere acts as a reservoir for the magnetospheric plasma. However, most instruments flying in space couldn't distinguish between O^+ and N^+ due to their close masses, and therefore the contribution of N^+ to the magnetosphere-ionosphere system has remained unknown. Idealized simulation results with the Hot Electron Ion Drift Integrator (HEIDI) point out the importance of N^+ in the ring current. The presence of N^+, even small amount of it, changes the magnetospheric dynamics and alters the ENA fluxes. In order to track the behavior and determine the role of N^+ in magnetosphere-ionosphere system, we properly include N^+ ions into the Polar Wind Outflow Model (PWOM). Preliminary simulation results indicate that the presence of N^+ in the ionospheric outflow can change ionospheric dynamics in the low altitudes where chemical reaction and collision are dominated. Our initial simulation results suggest that N^+ and O^+ are required to describe separately in the magnetosphere-ionosphere system, since they obey different chemical and physical reactions.

Key Points

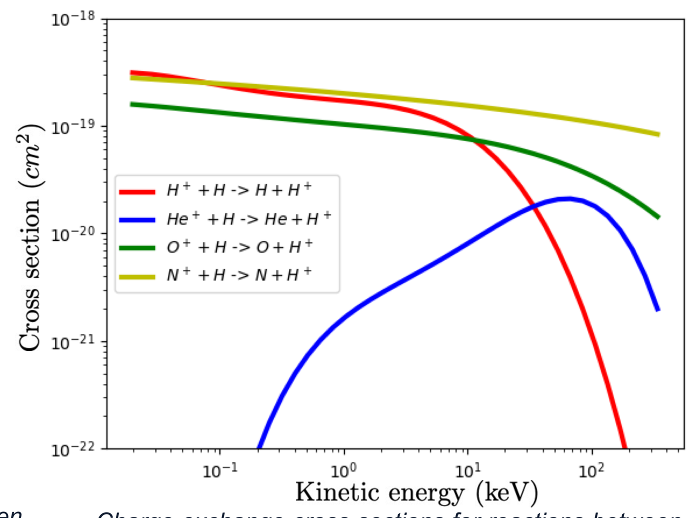
- Tracking the outflowing N^+ and O^+ ions using the Polar Wind Outflow Model (PWOM) shows that they behave differently along an open magnetic field line, in **production rate, chemical reaction rate and collision frequency**.
- Knowledge of the differential transport of N^+ and O^+ can advance our understanding of acceleration processes leading to the escape of heavy ionospheric ions, and their impact on magnetospheric dynamics. Furthermore, **inclusion of N^+ in global models may explain the fast decay of O^+ as observed by the Van Allen Probes.**

Motivation: Unexplained Fast Decay of O^+ in the Magnetosphere

- Van Allen Probes observe unexplained fast decay of O^+ at L=5-6.
- Van Allen Probes lack the possibility to separate N^+ from O^+ and assumes all heavy ions are O^+ only.



O^+/H^+ ratios across RBSPICE instrument energy range.(Black for L=3-4, Green for L=4-5 and Red for L=5-6) (Gerrard et al., 2014, JGR)



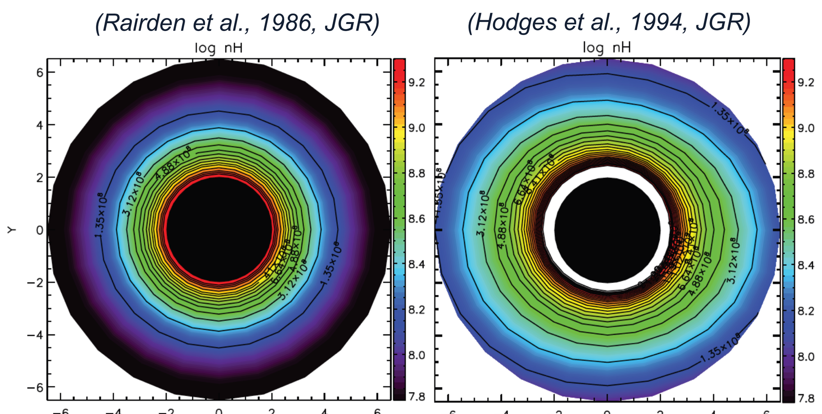
Charge exchange cross sections for reactions between ring current ions and geocorona neutral hydrogen.

Possible Explanation For Fast Decay of O^+ In the Magnetosphere

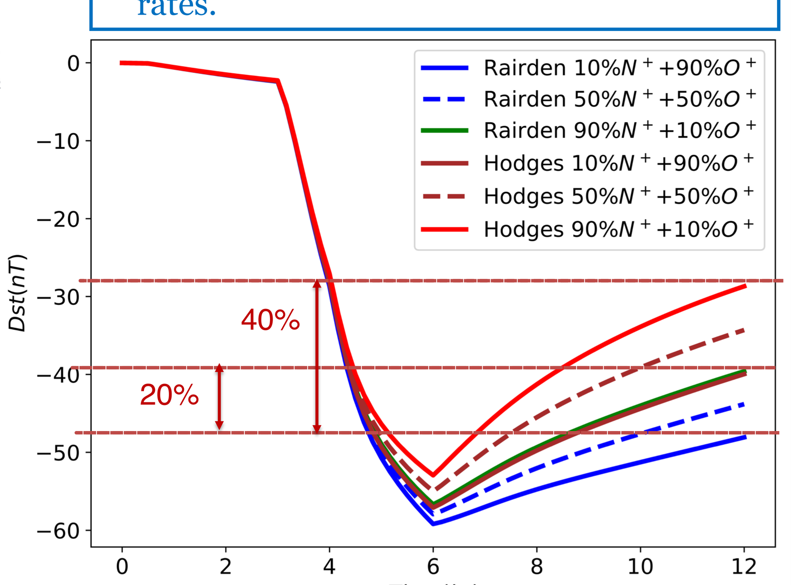
Magnetospheric Response for Different N^+/O^+ Ratio

- N^+/O^+ ratio and exospheric neutral hydrogen density are key for understanding the ring current dynamics.
- Neutral hydrogen models, Rairden and Hodges, can cause **~20%** difference in the estimation of the ring current decay.

- Different N+/O+ ratios and geocorona models → Different ring current recovery rates.



Equatorial profiles for the neutral hydrogen densities (Ilie et al., 2013, JASTP)



Dst vs. Time with idealized simulation of a 12 hr geomagnetic storm

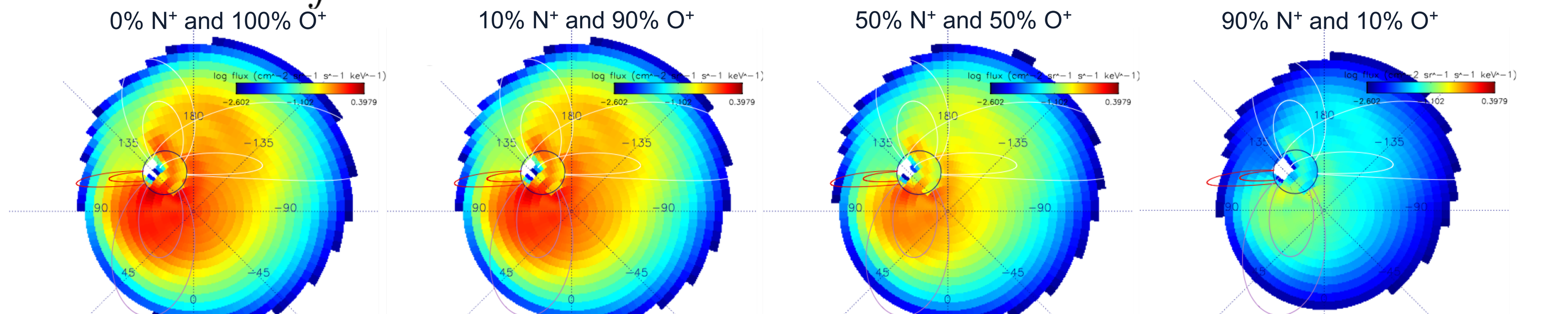
Energetic Neutral Atom (ENA) Image with Different N^+/O^+ Ratio

- TWINS-like oxygen ENA fluxes can be calculated from the HEIDI differential fluxes for different ion species. The plots below are extracted at the middle of recovery phase of a medium geomagnetic storm.
- When O^+ and N^+ densities are equal, the peak flux of O ENA is **half** of the O ENA flux when N^+ is absent.

$$\phi_{ENA} = \int \phi_{ion}(l)\sigma_{CE} n_H(l) dl$$

Composition	Oxygen ENA	Nitrogen ENA
0% N^+ + 100% O^+	1.64	0.0
10% N^+ + 90% O^+	1.47	0.28
50% N^+ + 50% O^+	0.82	1.39
90% N^+ + 10% O^+	0.16	2.50

Peak oxygen and nitrogen ENA fluxes for 4 different simulations for which the percentage of N+ varies from 0 to 90%.



Synthetic TWINS Oxygen ENA images for 4 different simulations

- Different N+/O+ → Different structure of ring current

Where Do the Nitrogen Ions Come From?

- The nitrogen ions come from **the Earth's polar ionosphere**.
- The ionospheric outflow is the supersonic flow of particles **along magnetic field lines at high latitudes.**

Polar Wind Outflow Model (PWOM)

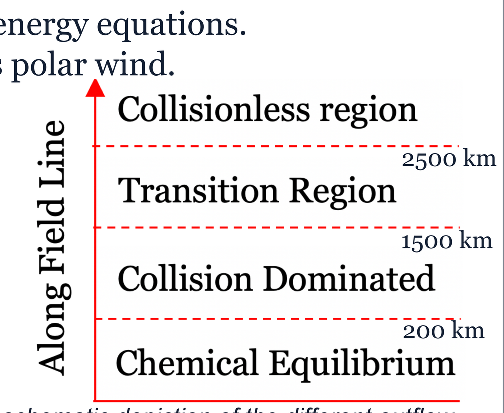
- From the ionosphere to the magnetosphere, the polar wind goes **from chemical to diffusion dominance, from collision dominated to collision less, and from heavy to light ion composition.** (Ganguli et al., 1996, RG)
- PWOM simulates the ionospheric outflow along high-latitude magnetic field lines **from 200 km to a few Earth radii** by solving the gyrotropic continuity, momentum, and energy equations.
- The modified PWOM can simulate O^+, H^+, He^+, $\mathbf{N^+}$, $\mathbf{N_2^+}$ and e^- in Earth's polar wind.

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

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

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

(Glocer et al., 2009, JGR)



A schematic depiction of the different outflow regions along field line (Glocer et al., 2018, JGR)

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ILLINOIS

New: Add Chemical Reactions

- The number of chemical reactions applied in the modified PWOM has more than **doubled** (see below).
- The inner boundary of PWOM is dominated by chemical equilibrium, for which production and losses are equal.

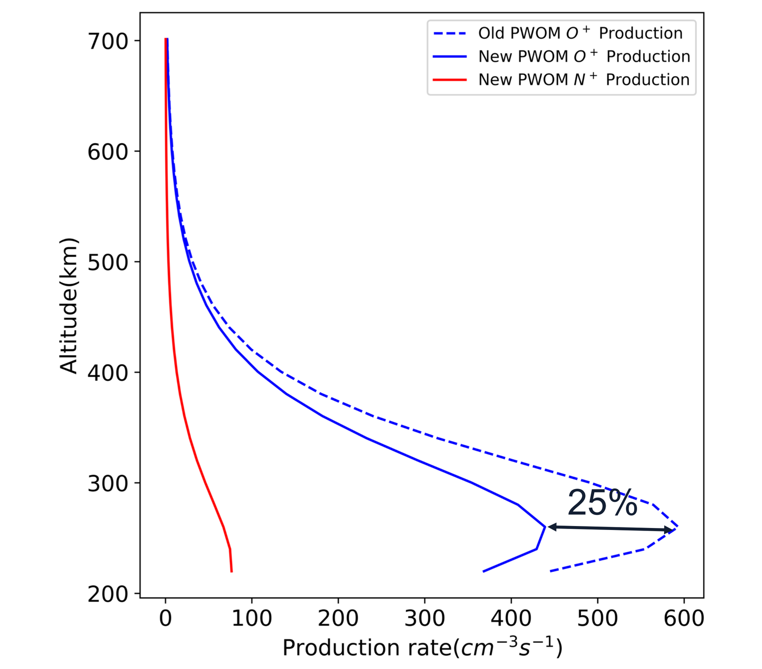
Type of Reaction	Chemical Reaction	Reaction Rate
Ion atom interchange	$N_2 + O^+ \longrightarrow NO^+ + N$	k_0=1.2 × 10^{-12}
Charge exchange	$O^+ + O_2 \longrightarrow {O_2}^+ + O$	k_1=2.1 × 10^{-11}
Dissociative charge transfer	$He^+ + O_2 \longrightarrow O^+ + O + He$	k_2=9.7 × 10^{-10}
Charge exchange	$He^+ + N_2 \longrightarrow {N_2}^+ + He$ $He^+ + N_2 \longrightarrow N^+ + N + He$	k_3=5.2 × 10^{-10} k_{15}=7.8 × 10^{-10}
Charge exchange	$H^+ + O \longrightarrow H + O^+$ $H + O^+ \longrightarrow H^+ + O$	k_{13}=2.2 × 10^{-11} × $T_e^{0.5}$ k_4=2.5 × 10^{-11} × $T_e^{0.5}$
Ion atom interchange	$N^+ + O_2 \longrightarrow NO^+ + O$ $N^+ + O_2 \longrightarrow {O_2}^+ + N$ $N^+ + O_2 \longrightarrow O^+ + NO$	k_5=3.07 × 10^{-10} k_{17}=2.32 × 10^{-10} k_{18}=4.6 × 10^{-11}
Charge exchange	$N^+ + NO \longrightarrow NO^+ + N$	k_6=2 × 10^{-11}
Charge exchange	$N^+ + O \longrightarrow N + O^+$	k_7=2.2 × 10^{-12}
Charge exchange	$N^+ + H \longrightarrow N + H^+$	k_8=3.6 × 10^{-12}
Charge exchange	${N_2}^+ + N \longrightarrow N^+ + N_2$	k_9=10^{-11}
Charge exchange	${N_2}^+ + NO \longrightarrow NO^+ + N_2$	k_{10}=4.1 × 10^{-10}
Ion atom interchange	${N_2}^+ + O \longrightarrow NO^+ + N$ ${N_2}^+ + O \longrightarrow O^+ + N_2$	k_{11}=1.3 × 10^{-10} k_{16}=1.0 × 10^{-11}
Charge exchange	${N_2}^+ + O_2 \longrightarrow {O_2}^+ + N_2$	k_{12}=5 × 10^{-11}
Charge Exchange	$O^+ + NO \longrightarrow NO^+ + O$	k_{14}=8.0 × 10^{-13}

Chemical reaction table for new PWOM. (Blue for the new reaction applied in the PWOM)
Ref: Shunk et al., 2009 & Anicich et al., 2003

New: Production Rate of N^+ and O^+

- The GLobal airglOW (GLOW) model provides photon and electron fluxes based on different photon and electron energy.
- The modified PWOM calculates production rate of N^+ and O^+ separately, based on photon and electron fluxes.

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

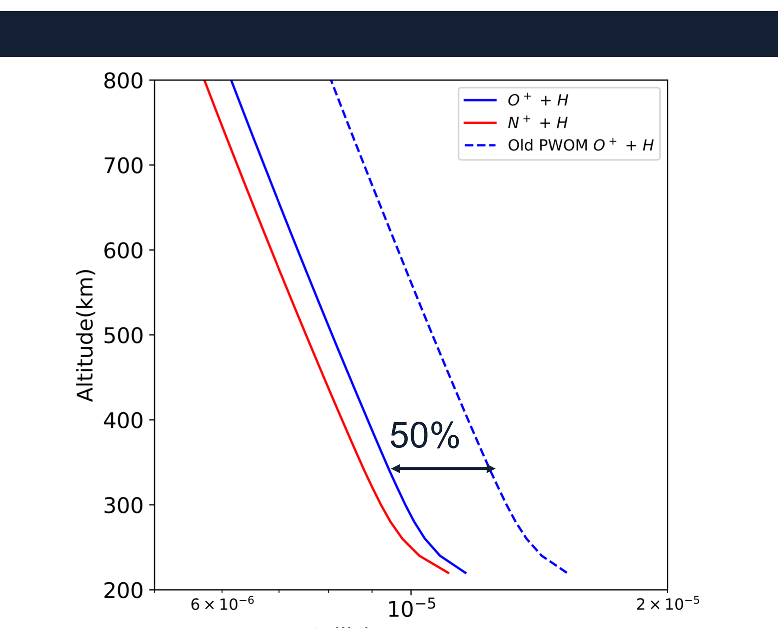


Total Production Rate vs. Altitude along an open magnetic field line (latitude=80°, longitude=20°) retrieved at 3rd hour simulation.

- The production rate of O^+ between the new PWOM and the old PWOM can have at most a **25%** difference.

New: Different Collision Mechanisms

- The modified PWOM includes collision parameters related to new ion species (O^+, H^+, He^+, $\mathbf{N^+}$, $\mathbf{N_2^+}$) and neutrals (O, H, O_2, N_2, He, **N, NO**).
- **N^+ and O^+ obey different collision mechanisms**. For example, N^+ and H obey a non-resonant neutral-ion collision, but O^+ and H obey a resonant neutral-ion collision (see plot of the right).
- When N^+ is present, the collision frequency between O^+ and H is **50% less** than the case when N^+ is absent.



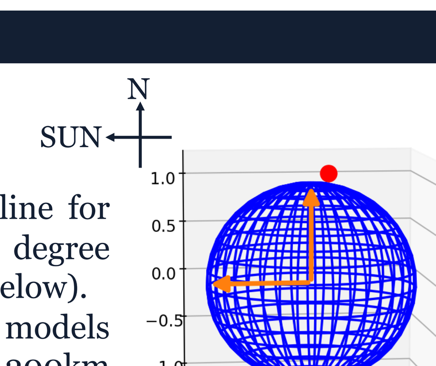
Collision frequency between N^+ and H & O^+ and H at 3rd hour of the simulation.

Challenge: NO Density

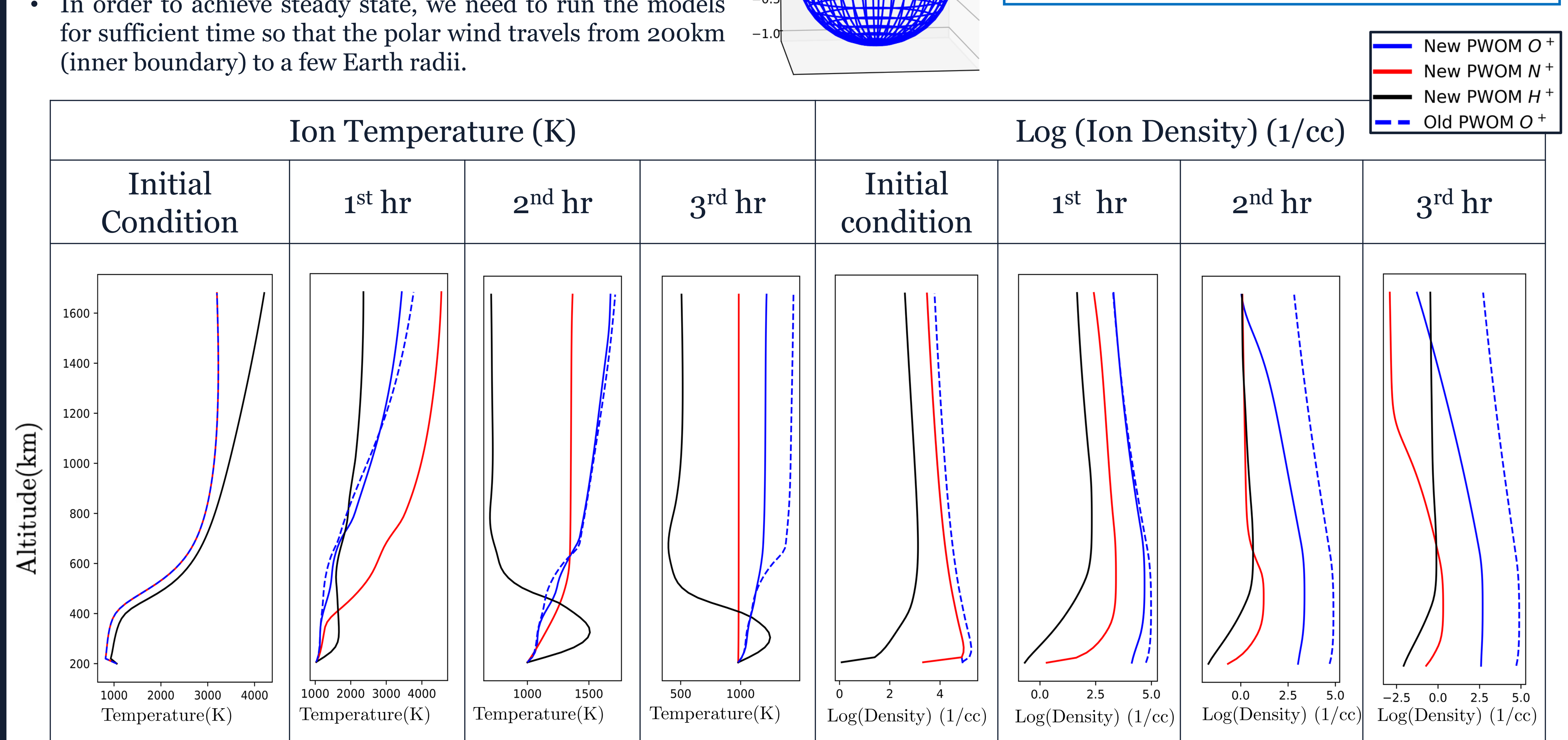
- The modified PWOM accounts for the behavior of O, H, O_2, N_2, He, N, NO.
- Most neutral densities, except NO, in PWOM comes from NRLMSISE-00 Model.
- **NO density is difficult to assess.**

Simulation: Obtain the Steady State

- The simulation starts with an open magnetic field line for which the latitude and longitude are 80 and 20 degree respectively, during **solar maximum** (see the plot below).
- In order to achieve steady state, we need to run the models for sufficient time so that the polar wind travels from 200km (inner boundary) to a few Earth radii.



- In the end of 3rd hr, the new PWOM predicts the temperature of O^+ less than 200K, as the old PWOM did.
- In the low altitude of open magnetic field line, the new PWOM predicts more N^+ than H^+.



Conclusions

- **To our knowledge, there is relatively little research on the contribution of N^+ to ionospheric outflow and its consequences for the magnetosphere dynamics.**
  - Simulations with the HEIDI model show that the presence of N^+ in the ring current can largely affect the **magnetospheric response**, the **structure of the ring current**, and thus, the **global magnetospheric dynamics**.
  - Since instruments onboard the Van Allen Probes lack the possibility to distinguish N^+ from O^+, it is possible that the fast decay of O^+ in the magnetosphere it is explained by the presence of N^+.
  - Tracking N^+ and O^+ using PWOM shows that in the ionospheric outflow, N^+ and O^+ behave differently along an open magnetic field line in **production rate, chemical reaction rate and collision frequency**.
  - Preliminary PWOM simulations show that the density and the temperature of N^+ can be used as potential tracers for the acceleration of heavy ions in the ionospheric.

Future Direction

- **Different solar wind conditions** will be applied to the new PWOM in order to investigate the impact of solar activity and seasonal variation on the behavior of N^+.
- The PWOM can assess the behavior of ionospheric outflow, which is a significant source of the Earth's inner magnetosphere plasma.
- The new PWOM provides the information on the escape of heavy ions from the ionosphere, and the coupling between PWOM and a global magnetospheric model such as the BATS-R-US model can provide insight into the differential transport of N^+ and O^+ through the magnetosphere-ionosphere system.