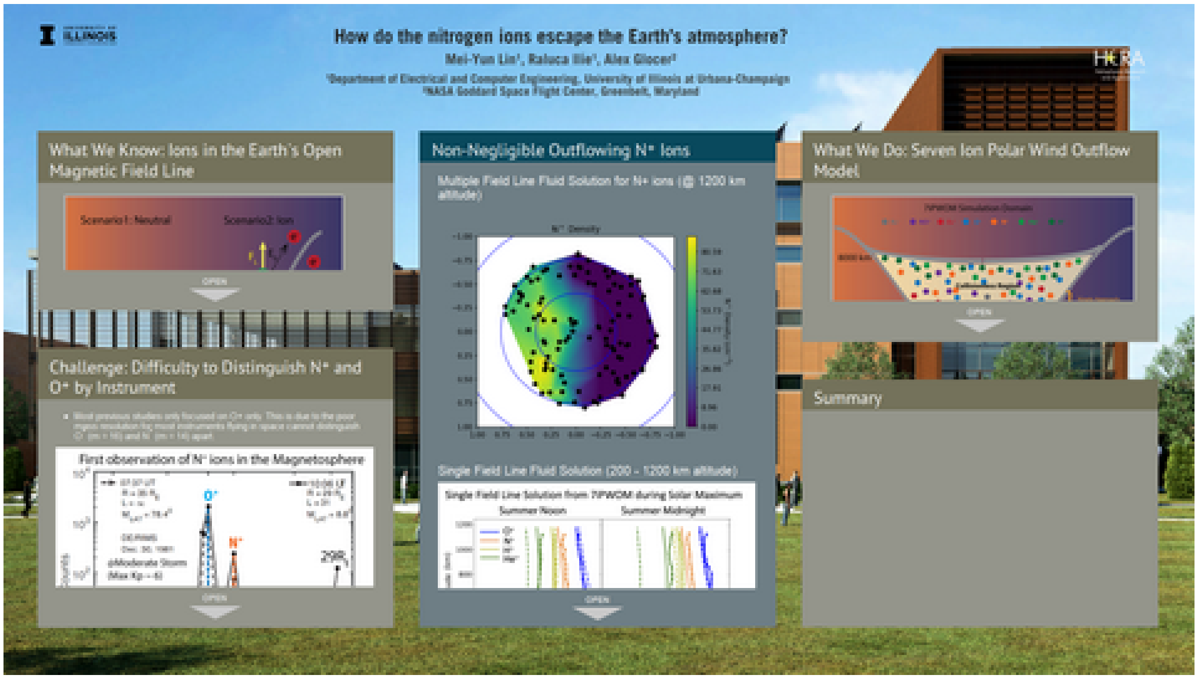
How do the nitrogen ions escape the Earth's atmosphere?



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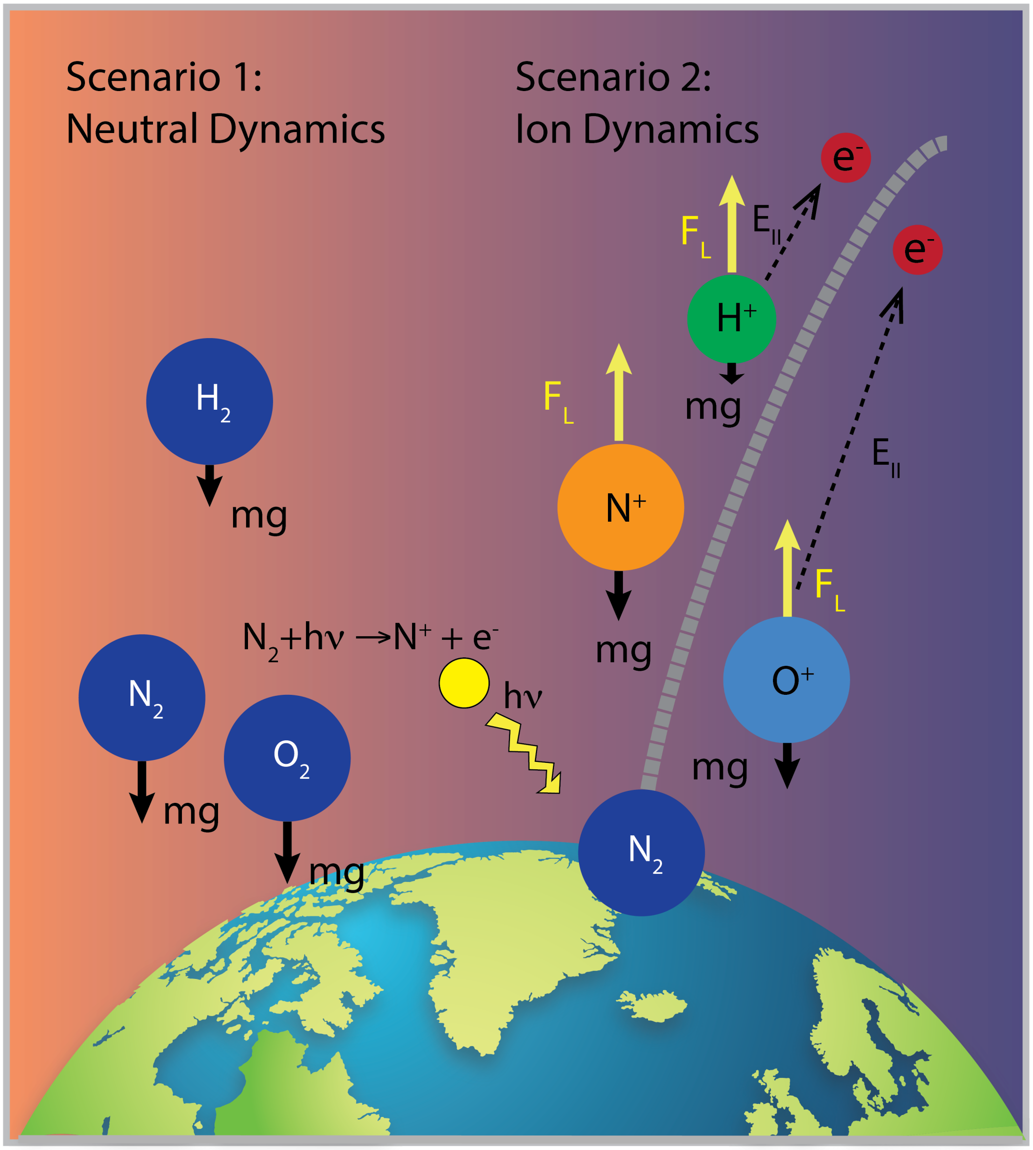
What We Don't Know: ATMOSPHERIC ESCAPE



- The dynamics of outflowing ionospheric charged particles, different from neutrals, are controlled by gravity (m**g**) and Lorentz force (**F$_L$**). Typically, charged particles with energies over 10eV have ability to escape from the Earth's atmosphere.
- Ambipolar electric field ($E_{\parallel}$), arising from the charge separation of particles of opposite polarity but different masses, is sufficient to explain the escape of H^+ ions from the atmosphere. However, additional sources of energization are needed to explain the escape of heavier ions, such as O^+ and N^+.

What We Know: N^+ IONS EVERYWHERE

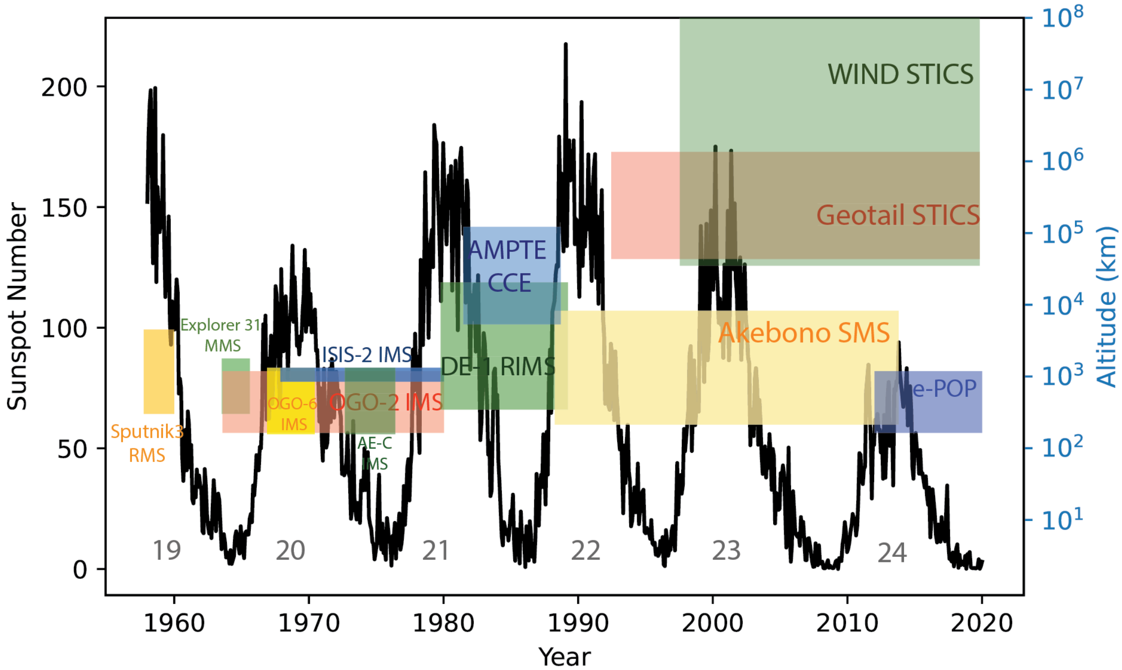


Fig 1: 60 Years of N+ Measurement (Ilie et al., 2020, *submitted to JATSP*)

- The first observation of outflowing N^+ ions in the ionosphere dates back to Soviet Sputnik III satellite, which showed the existence of N^+ ions at 500 km altitude.

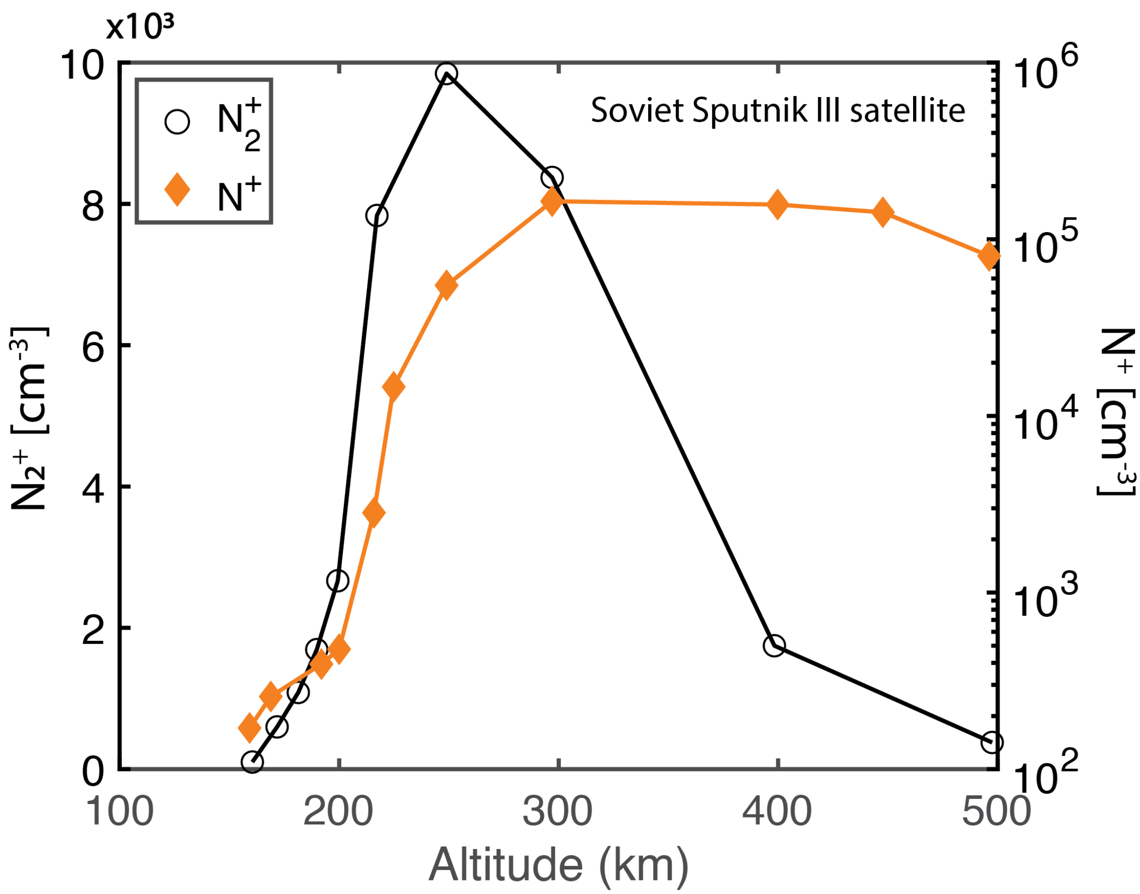


Fig 2: First observation of N^+ ions in the upper atmosphere (Nauk et al., 1961, *SSSR*)

- Most previous studies only focused on the outflow of O^+., mainly due to the poor mass resolution for most instruments flying in space, which cannot distinguish O^+ (m = 16) from N^+ (m = 14).

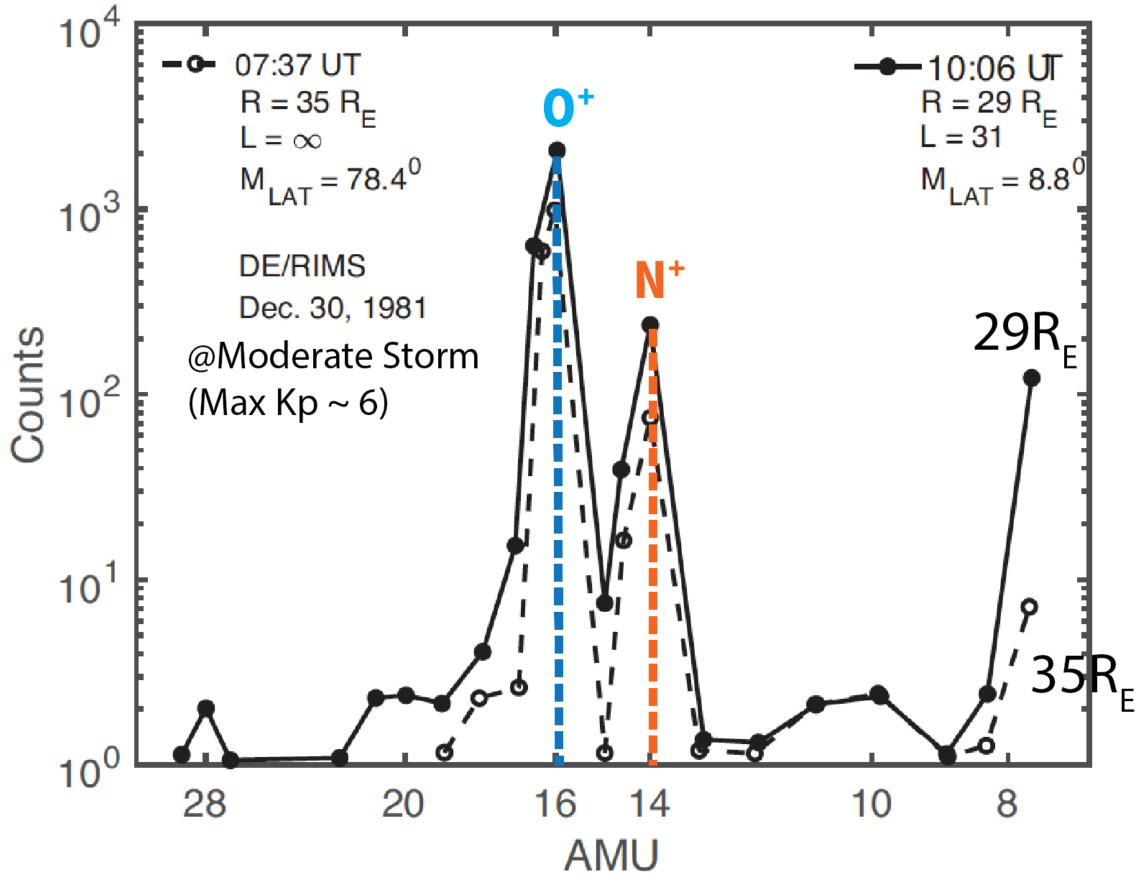
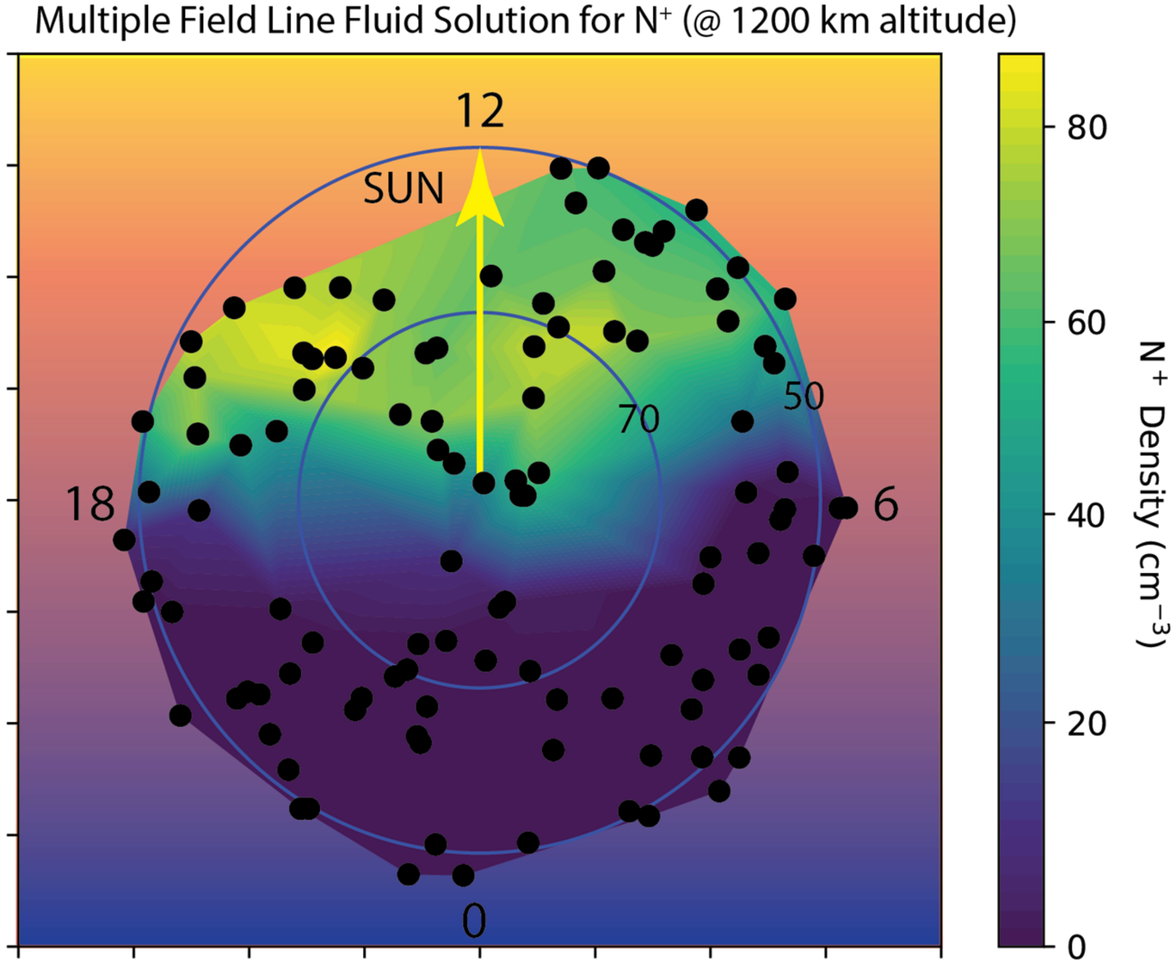


Fig 3: First observation of N^+ ions in the Magnetosphere, showing the difficulty to separate N^+ and O^+ ions (Chappell et al., 1982, *GRL*)

- Albeit limited, the existing observations indicate that O^+ and N^+ exhibit a different behavior as affected by solar radiation, solar wind, and geomagnetic activities.

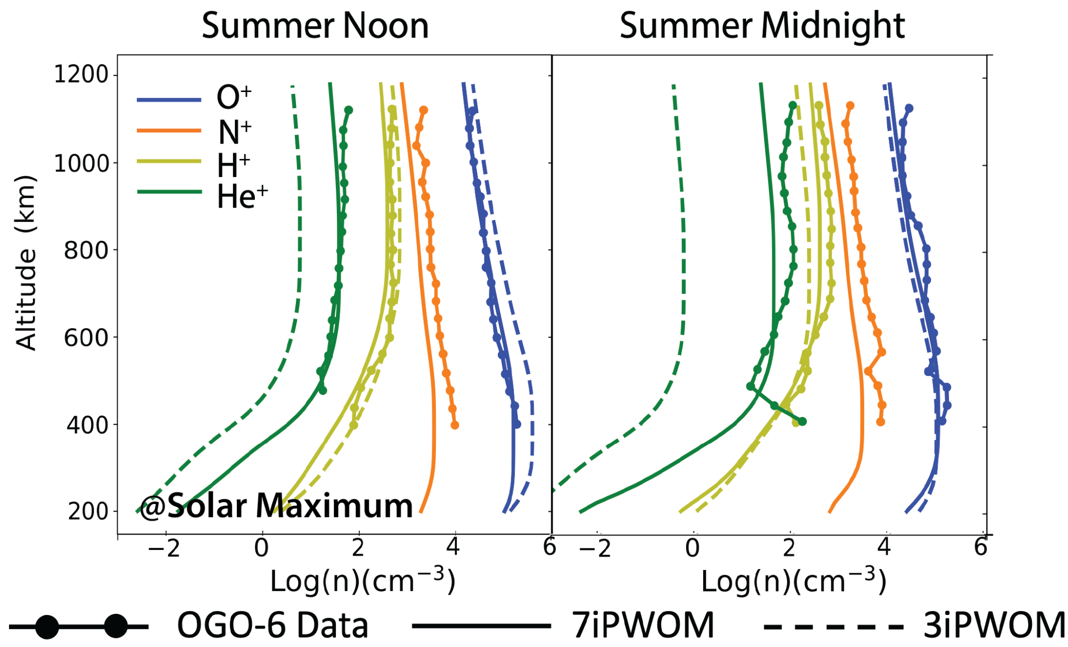
What We Learn: NON-NEGLIGIBLE N^+ IONS

~2,500 lbs of N^+ lost per day



- Multi field line simulations reveal that the loss rates for H^+, O^+ and N^+ are about 1.85×10^{25}, 2.85×10^{25}, and 6.47×10^{23} (1/s) respectively.

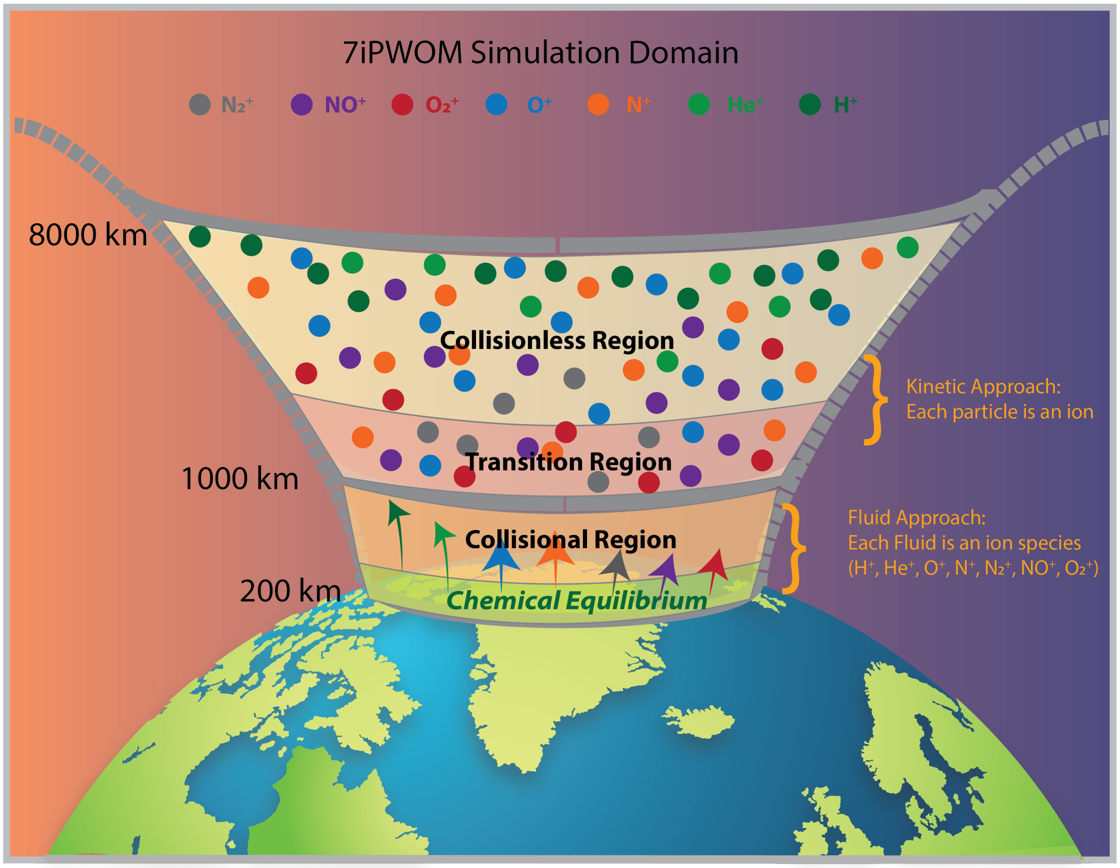
Model-Data Validation



- Comparison of 7iPWOM solution with observations from AE and OGO spacecraft show that the presence of N^+ improves the outflow solution for all species and all conditions.

- He^+ solution shows the most improvement, as 7iPWOM predicts He^+ density one order of magnitude higher than that predicted by the 3iPWOM, aligned with observations.

What We Do: 7IPWOM



- The Seven Ion Polar Wind Outflow Model (7iPWOM), developed from the Glocer et al. 2020 model (referred as 3iPWOM), solves for the polar wind solution for 7 ions (O^+, H^+, He^+, O^+, $\mathbf{N^+}$, $\mathbf{NO^+}$, $\mathbf{O_2^+}$, $\mathbf{N_2^+}$), as compared to 3 ion (O^+, H^+, He^+) solution provided by the 3iPWOM.
- The inner boundary is set at 200 km altitude, where the atmosphere is assumed to be in chemical equilibrium, while the outer boundary is at few Earth radii.
- To account for the possible energization mechanisms to increase or decrease the kinetic energy of ions, the 7iPWOM adopts two different approaches: fluid treatment below 1000 km and kinetic approach above 1000 km.

Equation solved in the 7iPWOM

- The 7iPWOM solves for the gyrostropic transport equations below 1000km: (Gombosi et al., [1989], *JGR;* Glocer et al., [2009], *JGR*)

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

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

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

$$E_\parallel = -\frac{1}{en_e}[\frac{\partial}{\partial r}(p_e + \rho_e u_e^2) + \frac{A'}{A}\rho_e u_e^2] + \frac{1}{en_e}(\sum_i \frac{m_e}{m_i}[(u_e - u_i)S_i - \frac{\delta M_i}{\delta t}] + \frac{\delta M_e}{\delta t})$$

- And for the equation of motion for all particles above 1000 km: (Glocer et al., [2009], *JGR*)

$$m\frac{\partial v_\parallel}{\partial t} - qE_\parallel + \frac{GmM_{planet}}{r^2} + \mu\frac{\partial B}{\partial s} = 0$$

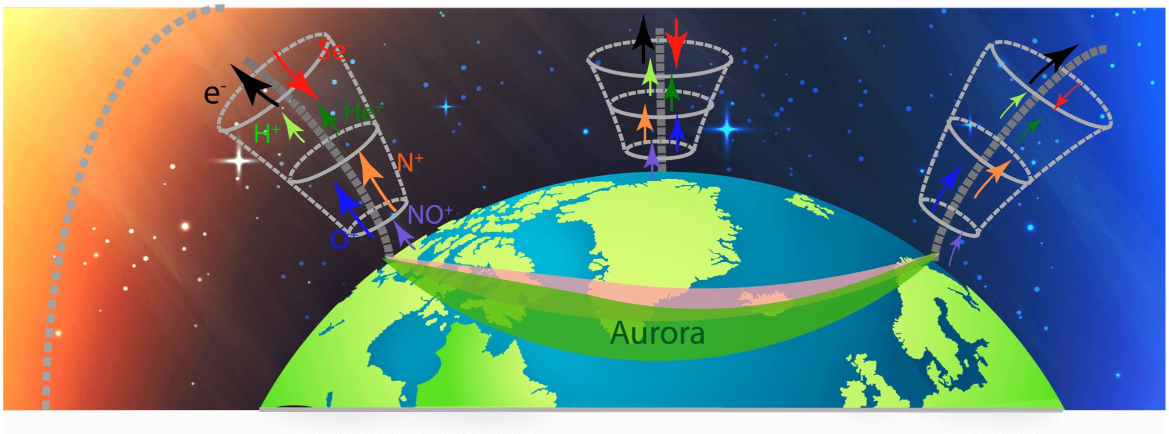
Chemical Table in the 7iPWOM

- Compared with the 3iPWOM, the number of chemical reactions applied in the 7iPWOM has more than doubled. (Lin et al., 2020, *GRL*)

Chemistry process	Reaction rate($cm^3 s^{-1}$)	Reference
$O + h\nu \longrightarrow O^+ + e^-$	see text	
$O_2 + h\nu \longrightarrow O^+ + O + e^-$	see text	
$He + h\nu \longrightarrow He^+ + e^-$	see text	
$H + h\nu \longrightarrow H^+ + e^-$	see text	
$O + e^* \longrightarrow O^+ + 2e^-$	see text	
$O_2 + e^* \longrightarrow O^+ + O + 2e^-$	see text	
$He + e^* \longrightarrow He^+ + 2e^-$	see text	
$H + e^* \longrightarrow H^+ + 2e^-$	see text	
$O^+ + N_2 \longrightarrow N + NO^+$	1.2×10^{-12}	[R. Schunk & Nagy, 2009]
$O^+ + O_2 \longrightarrow O_2{}^+ + O$	2.1×10^{-11}	[R. Schunk & Nagy, 2009]
$He^+ + O_2 \longrightarrow O^+ + O + He$	9.7×10^{-10}	[R. Schunk & Nagy, 2009]
$He^+ + N_2 \longrightarrow N_2{}^+ + He$	5.2×10^{-10}	[R. Schunk & Nagy, 2009]
$He^+ + N_2 \longrightarrow N^+ + N + He$	7.8×10^{-10}	[R. Schunk & Nagy, 2009]
$H^+ + O \longrightarrow H + O^+$	$2.2 \times 10^{-11} \times T_e^{0.5}$	[R. Schunk & Nagy, 2009]
$H + O^+ \longrightarrow H^+ + O$	$2.5 \times 10^{-11} \times T_e^{0.5}$	[R. Schunk & Nagy, 2009]
$N + h\nu \longrightarrow N^+ + e^-$	see text	
$N_2 + h\nu \longrightarrow N^+ + N + e^-$	see text	
$N_2 + h\nu \longrightarrow N_2{}^+ + e^-$	see text	
$O_2 + h\nu \longrightarrow O_2{}^+ + e^-$	see text	
$NO + h\nu \longrightarrow N^+ + O + e^-$	see text	
$NO + h\nu \longrightarrow NO^+ + e^-$	see text	
$NO + h\nu \longrightarrow O^+ + N + e^-$	see text	
$N_2 + e^* \longrightarrow N_2{}^+ + 2e^-$	see text	
$O_2 + e^* \longrightarrow O_2{}^+ + 2e^-$	see text	
$N_2 + e^* \longrightarrow 2N^+ + 3e^-$	see text	
$N_2 + e^* \longrightarrow N^+ + N + 2e^-$	see text	
$N^+ + O_2 \longrightarrow NO^+ + O$	3.07×10^{-10}	[R. Schunk & Nagy, 2009]
$N^+ + O_2 \longrightarrow O_2{}^+ + N$	2.32×10^{-10}	[R. Schunk & Nagy, 2009]
$N^+ + O_2 \longrightarrow O^+ + NO$	4.6×10^{-11}	[R. Schunk & Nagy, 2009]
$N^+ + NO \longrightarrow NO^+ + N$	2×10^{-11}	[Lindinger et al., 1974]
$N^+ + O \longrightarrow N + O^+$	2.2×10^{-12}	[Richards & Voglozin, 2011]
$N^+ + H \longrightarrow N + H^+$	3.6×10^{-12}	[Harada et al., 2010]
$N_2{}^+ + N \longrightarrow N^+ + N_2$	10^{-11}	[Richards & Voglozin, 2011]
$N_2{}^+ + NO \longrightarrow NO^+ + N_2$	4.1×10^{-10}	[R. Schunk & Nagy, 2009]
$N_2{}^+ + O \longrightarrow NO^+ + N$	1.3×10^{-10}	[R. Schunk & Nagy, 2009]
$N_2{}^+ + O \longrightarrow O^+ + N_2$	1.0×10^{-11}	[R. Schunk & Nagy, 2009]
$N_2{}^+ + O_2 \longrightarrow O_2{}^+ + N_2$	5.0×10^{-11}	[R. Schunk & Nagy, 2009]
$O^+ + NO \longrightarrow NO^+ + O$	8.0×10^{-13}	[R. Schunk & Nagy, 2009]
$N^+ + e^- \longrightarrow N$	$3.6 \times 10^{-12} \times (\frac{250}{T_e})^{0.7}$	[R. Schunk & Nagy, 2009]
$N_2{}^+ + e^- \longrightarrow N + N$	$2.2 \times 10^{-7} \times (\frac{300}{T_e})^{0.39}$	[R. Schunk & Nagy, 2009]
$NO^+ + e^- \longrightarrow N + O$	$4.0 \times 10^{-7} \times (\frac{300}{T_e})^{0.5}$	[R. Schunk & Nagy, 2009]
$O_2{}^+ + e^- \longrightarrow O + O$	$2.4 \times 10^{-7} \times (\frac{300}{T_e})^{0.7}$	[R. Schunk & Nagy, 2009]

[a]The complete chemical scheme adopted in the 7iPWOM (blue and black) vs. in 3iPWOM (black only). Note that e^* represents the suprathermal electrons.

What's Next: IMPLICATIONS FOR HABITABILITY



The 7iPWOM numerical simulations show that:

- N^+ ions are a key species in the Earth's ionosphere and their presence alter the outflow for all conditions.
- Comparison with available data below 1200km, 7iPWOM shows tremendous improvement of the outflow solution when N^+ is included.
- Understanding the outflow of ionospheric heavy ions provides a reference to understand atmospheric escape on geological times.

DISCLOSURES

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AUTHOR INFORMATION

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Mei-Yun is a Ph.D. candidate in HeRA group within the Department of Electrical and Computer Engineering in University of Illinois at Urbana-Champaign, advised by Prof. Raluca Ilie. Her primary research focus is understanding the acceleration mechanisms responsible for ionospheric outflow, and its impacts on the magnetospheric dynamics.

Mei-Yun joined the group with an Electrical Engineering background and almost zero knowledge about the Space Science. However, through her rigorous training at UIUC she quickly developed the skills to become an expert in modeling the ionospheric outflow. Mei-Yun's woks has been recognized by the American Geophysical Union, where she was awarded the Outstanding Student Presentation Award in 2019. In 2020, Mei-Yun has been elected as the Student Representative of the NSF Geospace Environment Modeling Program, where she will serve for the next two years.

Her long term goal is to become a successful computational scientist, who will implement engineering skills to augment the accuracy and efficiency of space weather modeling.

ABSTRACT

Nitrogen is the most abundant element in the Earth's atmosphere. Around 78% N_2 and 21% O_2 form the air we breathe and expand into high-altitude atmosphere, the thermosphere, and eventually the ionosphere. The neutral molecules in the ionosphere are ionized by solar radiation, and some of them break up into atoms, and others become charged particles. The ionospheric ions with sufficient energy can flow out into space, and the abundances of these outflowing ionospheric ions highly impact the near-Earth plasma properties. Studies focused on outflowing O^+ ions have been conducted for many years. However, the contribution of N^+ to the outflow solution is still largely unknown due to the instrumental limitations. We developed a first-principled physics model to understand how N^+ and molecular ions, including NO^+, N_2^+ and O_2^+, acquire the sufficient energy to escape Earth's atmosphere. This study reveals the importance of N^+ ions in the high-altitude polar ionosphere, from few hundred kilometers to thousands of kilometers in the space, and examines the possible mechanisms to accelerate and removed them from Earth's atmosphere.