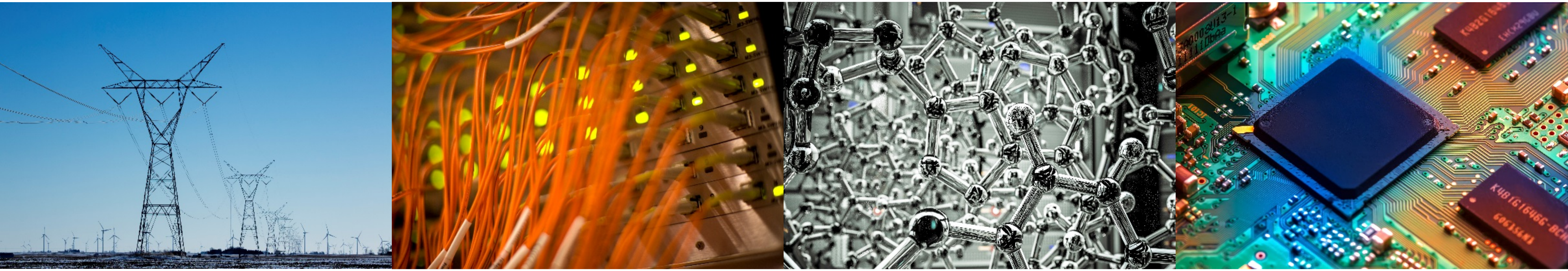
The Contribution of N^+ Ions to Earth's Polar Wind

[1]Mei-Yun Lin, [1]Raluca Ilie and [2]Alex Glocer

[1]Department of Electrical and Computer Engineering, University of Illinois at Urbana-Champaign

[2]NASA Goddard Space Flight Center, Greenbelt, Maryland



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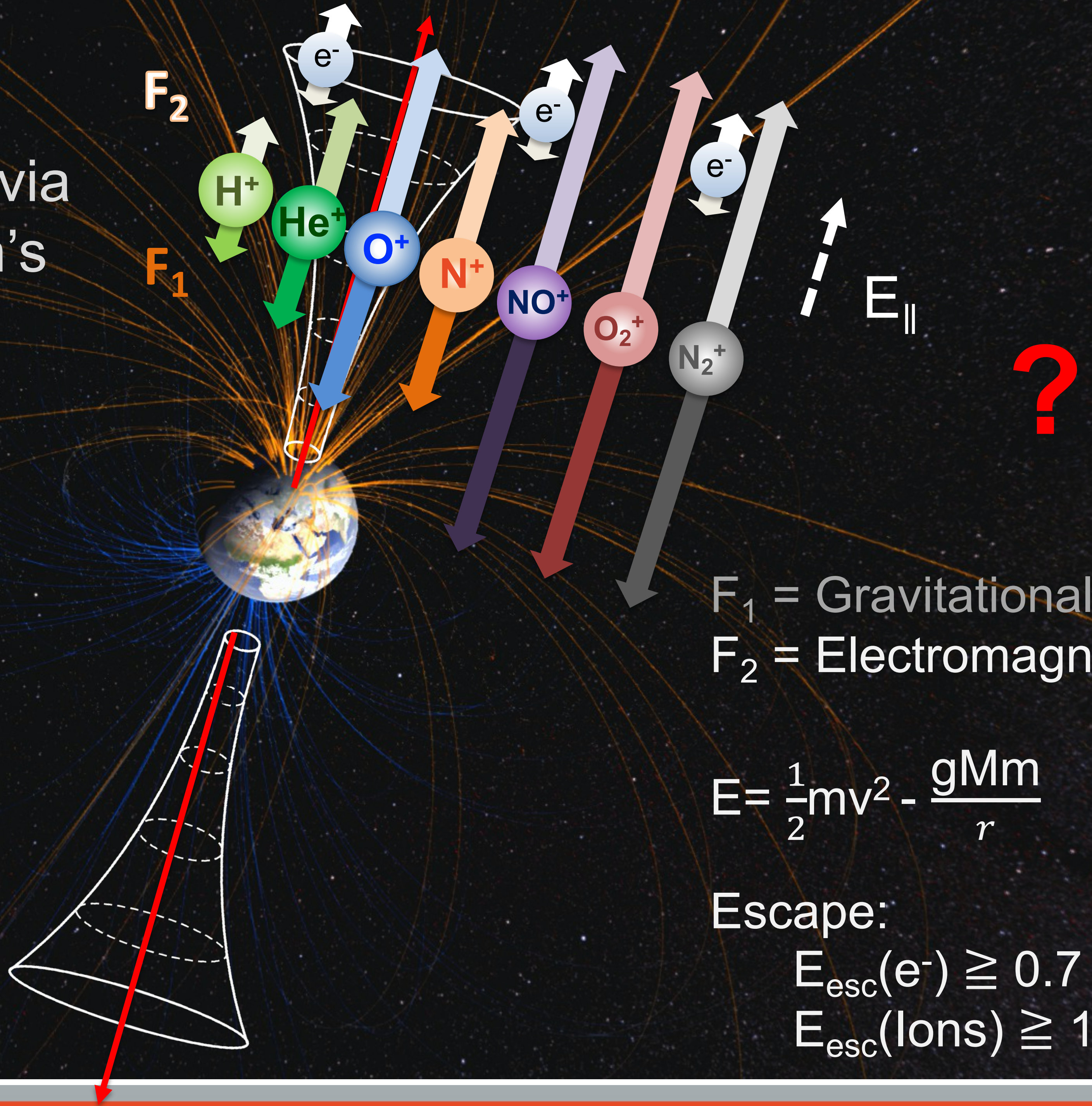
Ions and electrons escape via open field lines to the Earth's magnetosphere

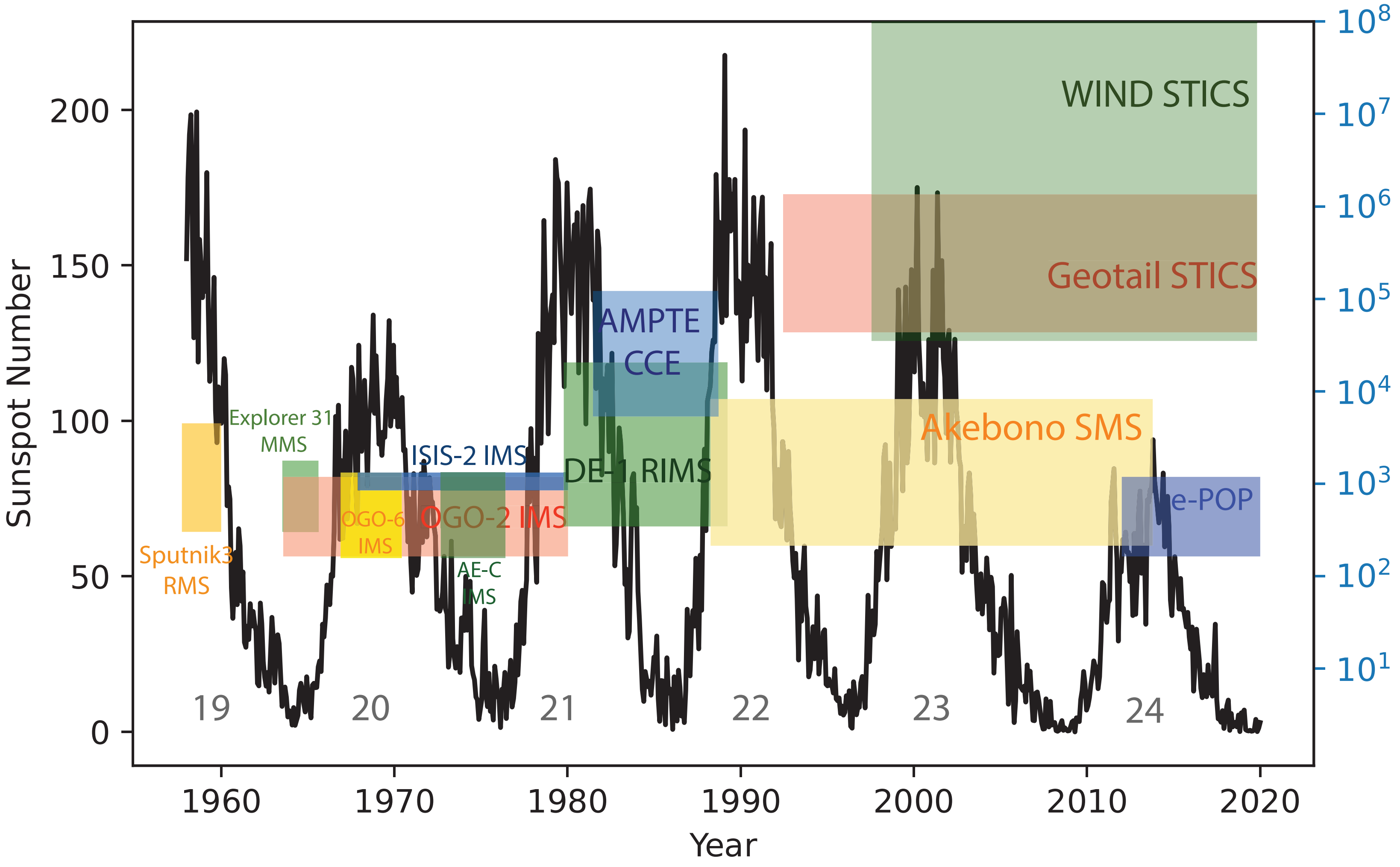


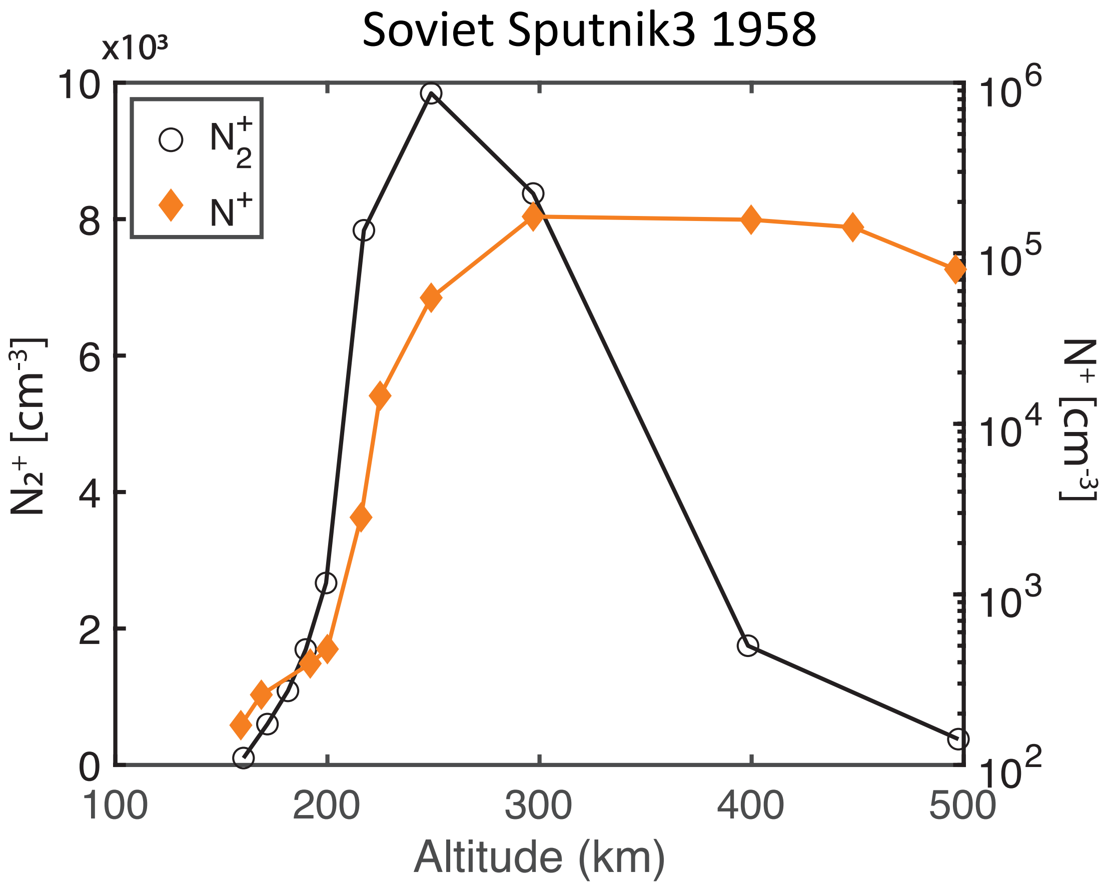
F_1 = Gravitational
F_2 = Electromagnetic

$$E = \frac{1}{2}mv^2 - \frac{gMm}{r}$$

Escape:
$E_{esc}(e^-) \geqq 0.7$ eV
$E_{esc}(\text{Ions}) \geqq 10$ eV

Observation of N⁺ ions





First observation of N⁺ ions in the upper atmosphere

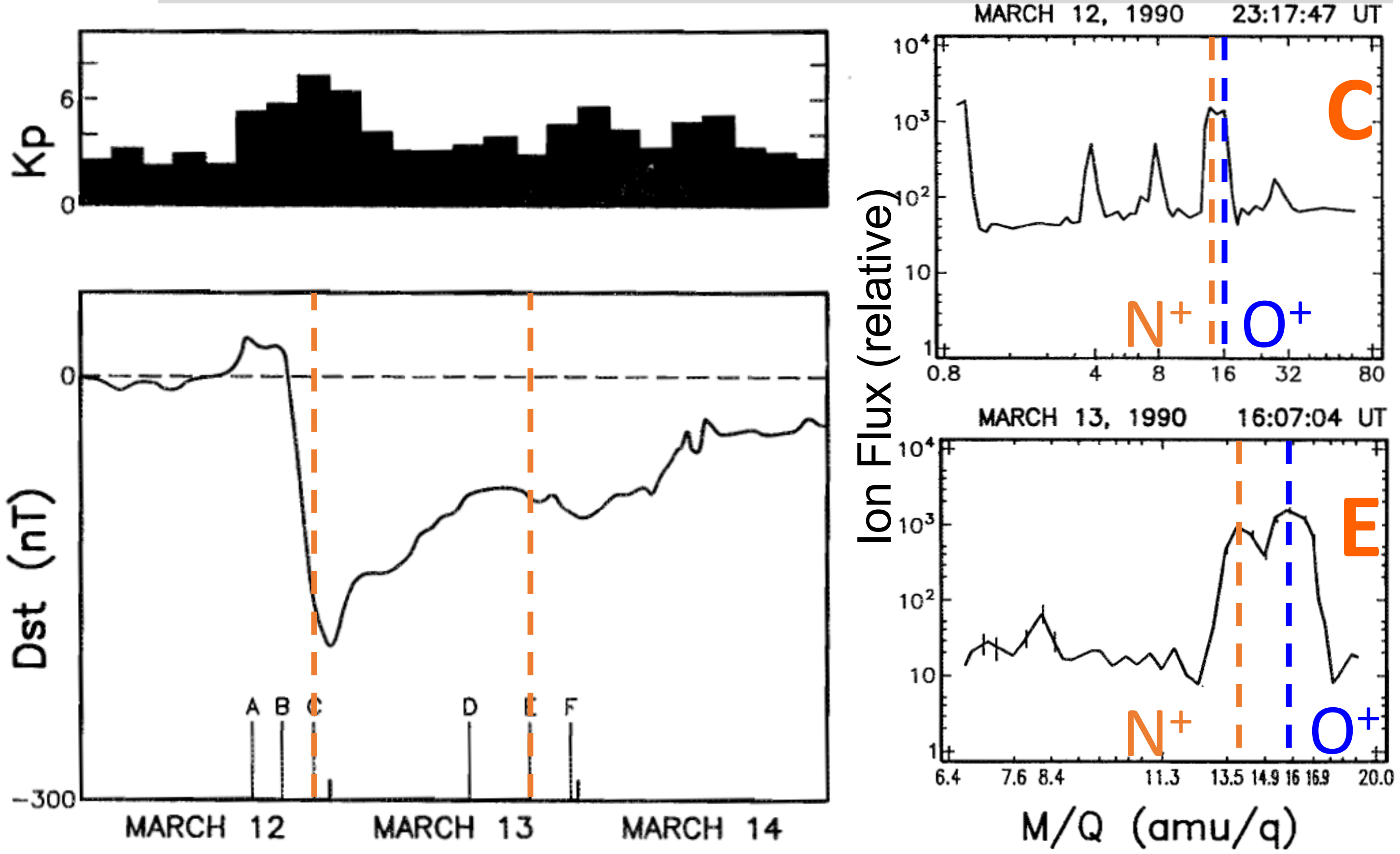
(Credit: Ilie et al., 2020, submitted to JASTP)

Difficulty to distinguish N^+ from O^+ ions

THE PROBLEM:

Most instruments flying in space cannot distinguish them apart, due to instrument poor mass resolution.

- Albeit limited, the existing



  - ➢ different pathways of energization

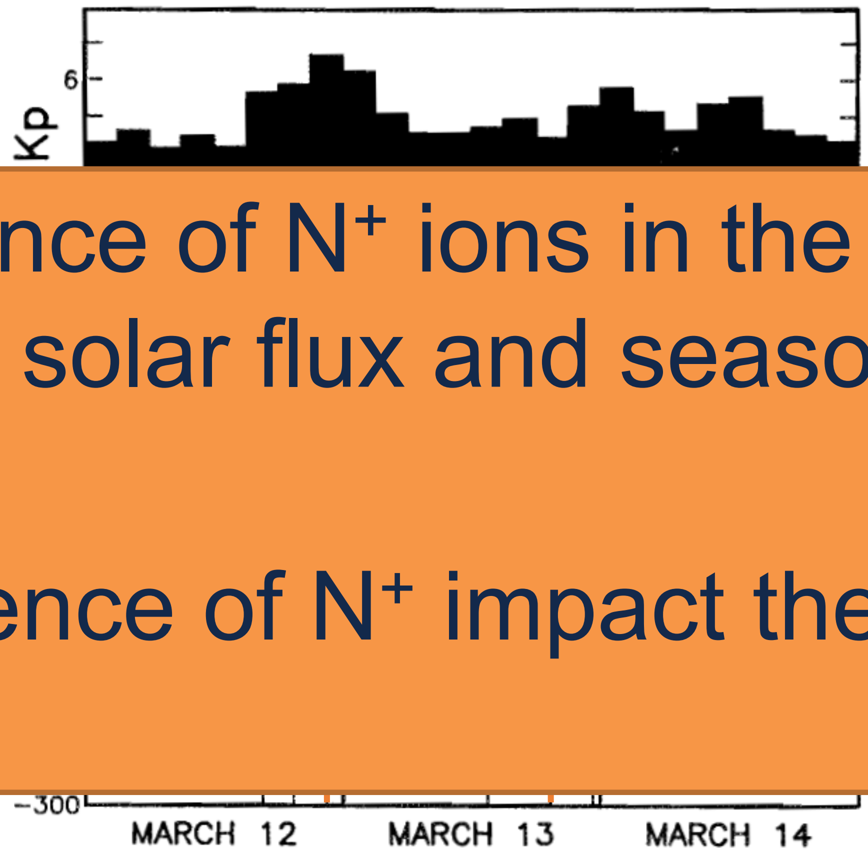
Difficulty to distinguish N^+ from O^+ ions

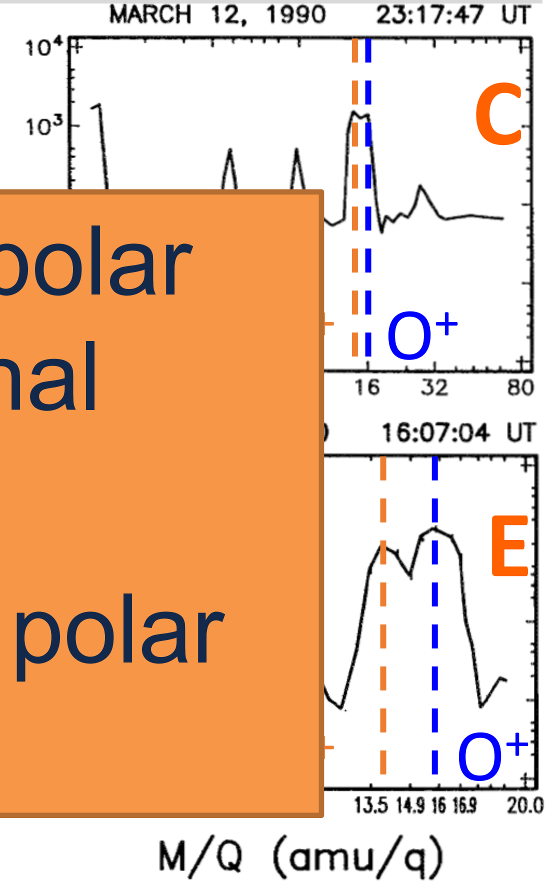
THE PROBLEM:
Most instruments flying in space cannot distinguish them apart, due to instrument poor mass resolution.

- Albeit limited, the existing observations indicate that **O^+ and N^+ exhibit a different behavior as affected by solar radiation, solar wind, and geomagnetic activities**
- **No studies considered the outflow of N^+**, in addition to that of O^+ from first principles, in spite of:
  - different ionization potential,
  - different chemistry
  - different scale heights
  - different pathways of energization

Difficulty to distinguish N^+ from O^+ ions

- Albeit limited, the existing





- What is the abundance of N^+ ions in the polar wind in response to solar flux and seasonal variations?
- How does the presence of N^+ impact the polar wind solution?

THE PRO

Most instruments flying in space cannot distinguish them apart, due to instrument poor mass resolution.

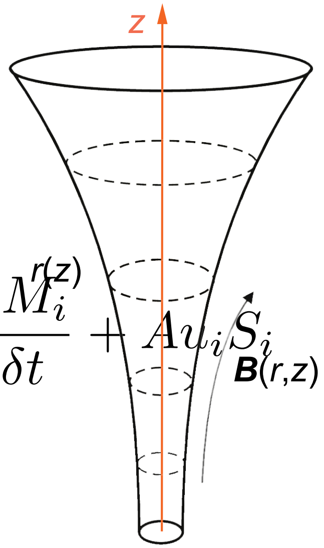
- ➢ different pathways of energization

Polar Wind Outflow Model (referred to as 3iPWOM)

- Chemical & Collisional Scheme
- Suprathermal Electron: GLOW
- Neutral Density: NRLMSISE-90

For each time step, solve n, T, v, and $E_{\|}$

Solves Transport Equations and $E_{\|}$ equation for H^+, He^+, O^+



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

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

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

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

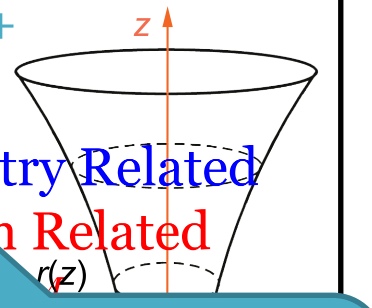
(Credit: Glocer et al., 2009)

Seven Ion Polar Wind Outflow Model (7iPWOM)

- New **Chemical** & **Collisional** Scheme
- **Suprathermal Electron: GLOW**
- Neutral Density: NRLMSISE-00

For each time step, solve n, T, v, and $E_\parallel$

Solves Transport Equations and $E_\parallel$ equation for H^+, He^+, N^+, O^+, $N_2{}^+$, NO^+, $O_2{}^+$



Blue: C…mistry Related

Red: Co…n Related

Static molecular ions (zero v and constant T)

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

Source term

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

$$\frac{\partial}{\partial t}(\frac{1}{2}A\rho_i u_i^2 + \frac{1}{\gamma_i - 1}Ap_i) + \frac{\partial}{\partial r}(\frac{1}{2}A\rho_i u_i^3 + \frac{\gamma_i}{\gamma_i -$$

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

Energy Change

[3]

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

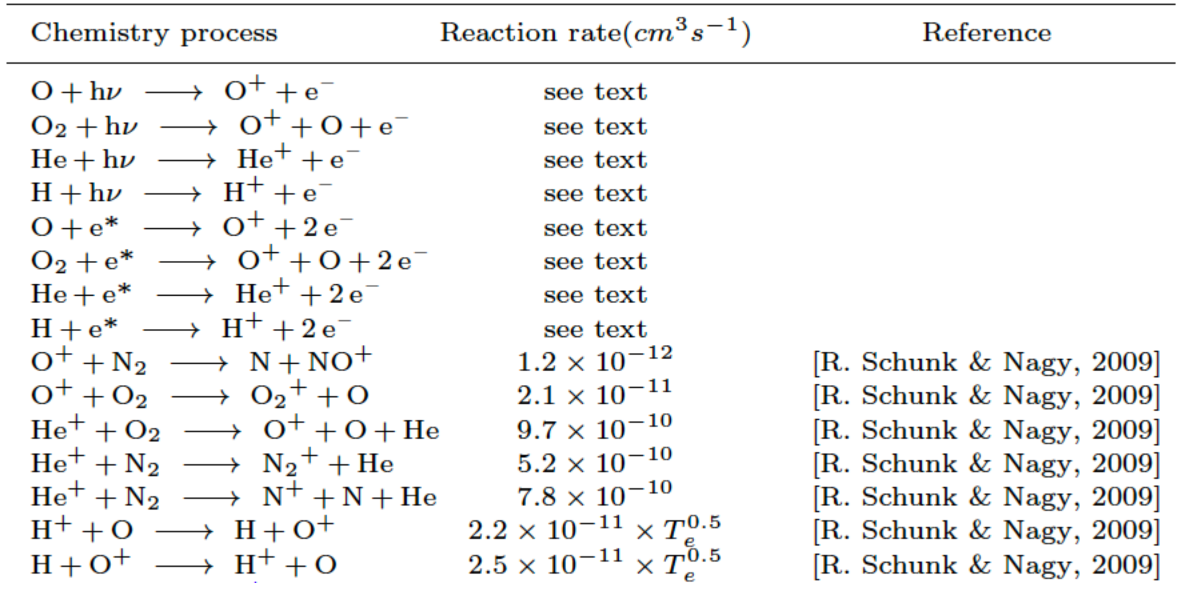
Correct Equation

(Credit: Glocer et al., 2009)

Chemistry and Collisions

3iPWOM

H^+, He^+, O^+

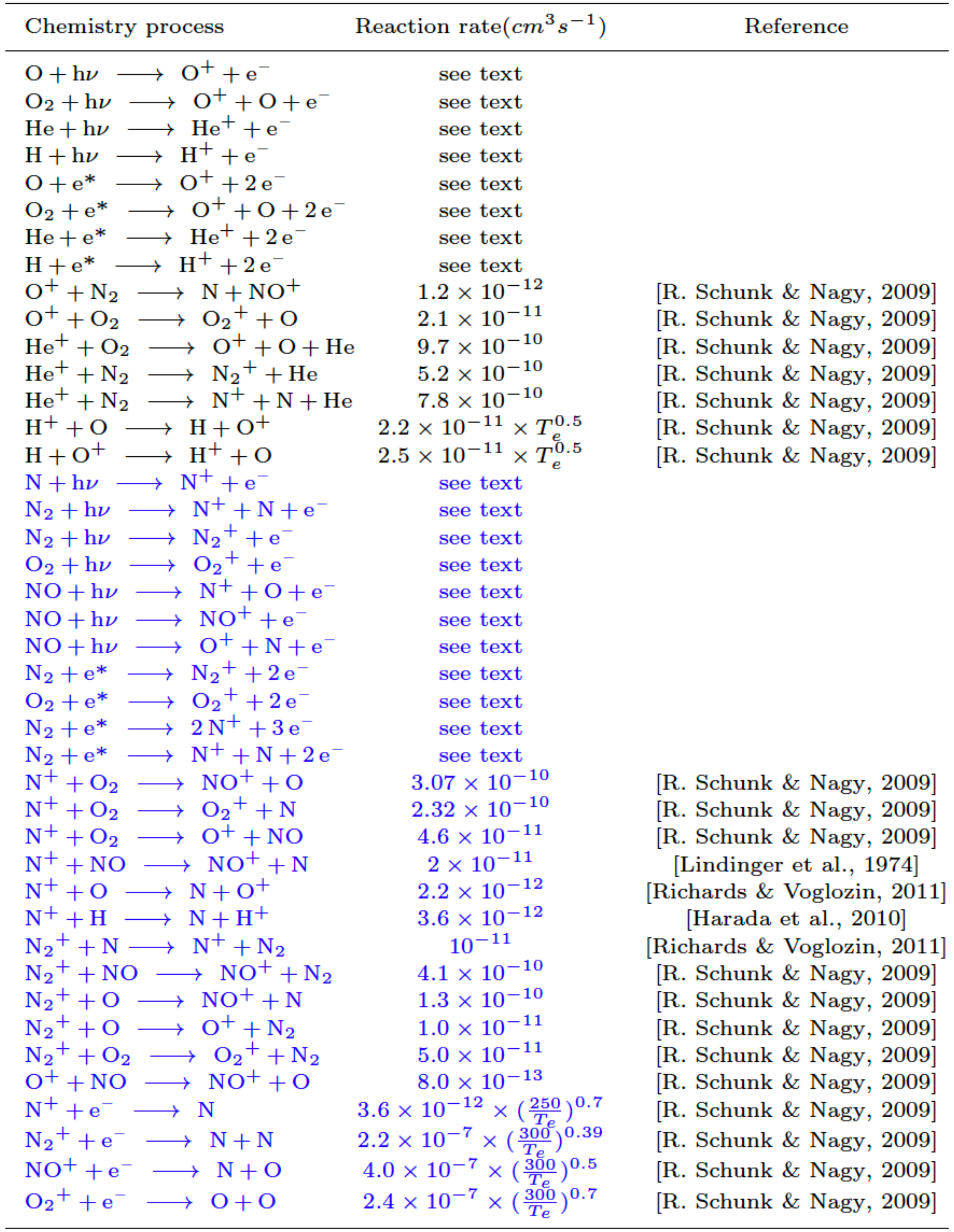


Chemistry process	Reaction rate$(cm^3 s^{-1})$	Reference
$O + h\nu \longrightarrow O^+ + e^-$	see text	
$O_2 + h\nu \longrightarrow O^+ + O + e^-$	see text	
$He + h\nu \longrightarrow He^+ + e^-$	see text	
$H + h\nu \longrightarrow H^+ + e^-$	see text	
$O + e^* \longrightarrow O^+ + 2\,e^-$	see text	
$O_2 + e^* \longrightarrow O^+ + O + 2\,e^-$	see text	
$He + e^* \longrightarrow He^+ + 2\,e^-$	see text	
$H + e^* \longrightarrow H^+ + 2\,e^-$	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]

Chemistry and Collisions

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

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



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$O + e^* \longrightarrow O^+ + 2\,e^-$	see text	
$O_2 + e^* \longrightarrow O^+ + O + 2\,e^-$	see text	
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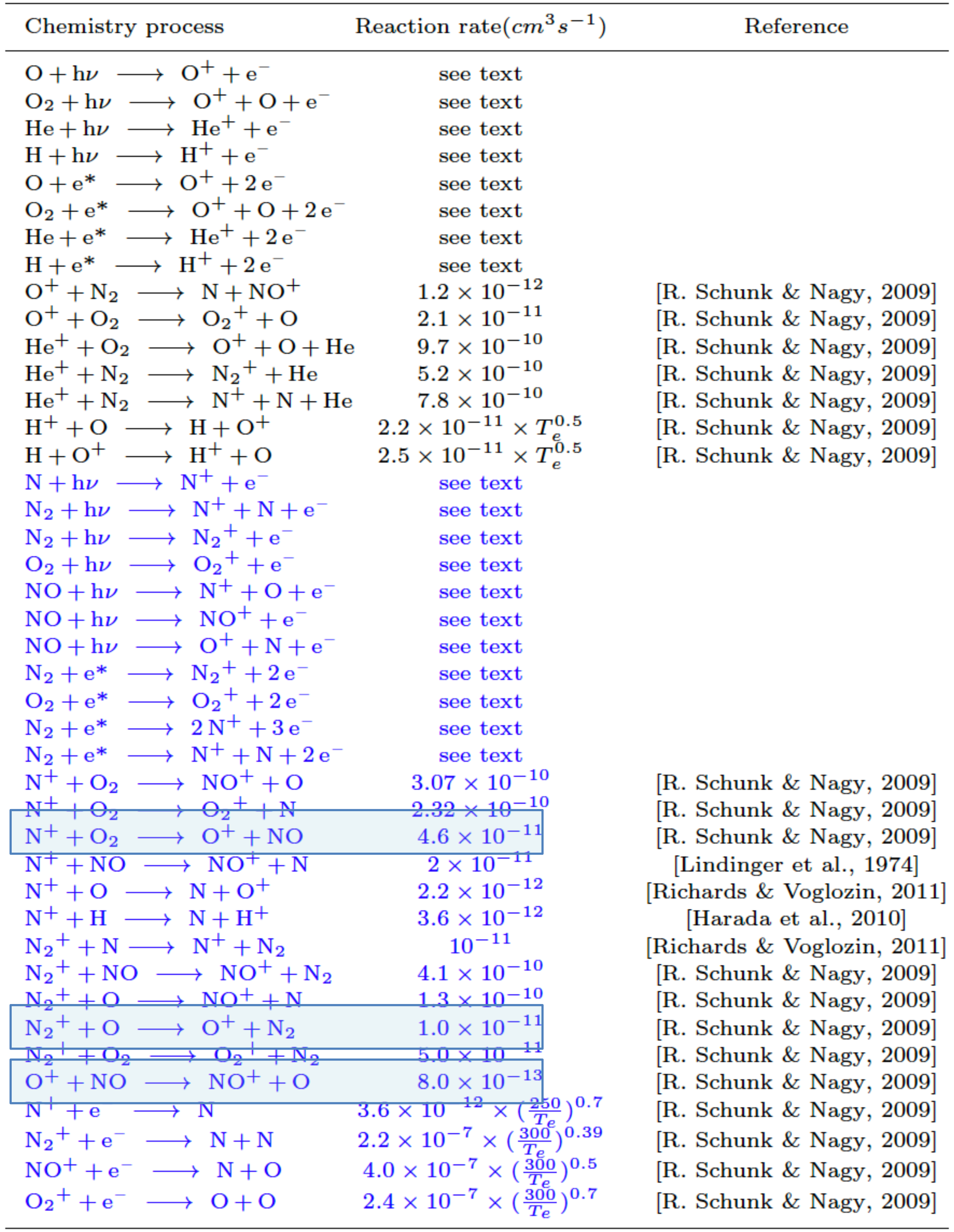
$H + O^+ \longrightarrow H^+ + O$	$2.5 \times 10^{-11} \times T_e^{0.5}$	[R. Schunk & Nagy, 2009]
$N + h\nu \longrightarrow N^+ + e^-$	see text	
$N_2 + h\nu \longrightarrow N^+ + N + e^-$	see text	
$N_2 + h\nu \longrightarrow {N_2}^+ + e^-$	see text	
$O_2 + h\nu \longrightarrow {O_2}^+ + e^-$	see text	
$NO + h\nu \longrightarrow N^+ + O + e^-$	see text	
$NO + h\nu \longrightarrow NO^+ + e^-$	see text	
$NO + h\nu \longrightarrow O^+ + N + e^-$	see text	
$N_2 + e^* \longrightarrow {N_2}^+ + 2\,e^-$	see text	
$O_2 + e^* \longrightarrow {O_2}^+ + 2\,e^-$	see text	
$N_2 + e^* \longrightarrow 2\,N^+ + 3\,e^-$	see text	
$N_2 + e^* \longrightarrow N^+ + N + 2\,e^-$	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]

Chemistry and Collisions

New sources/losses for O^+

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

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



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$O_2 + h\nu \longrightarrow O^+ + O + e^-$	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	
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$N + h\nu \longrightarrow N^+ + e^-$	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	
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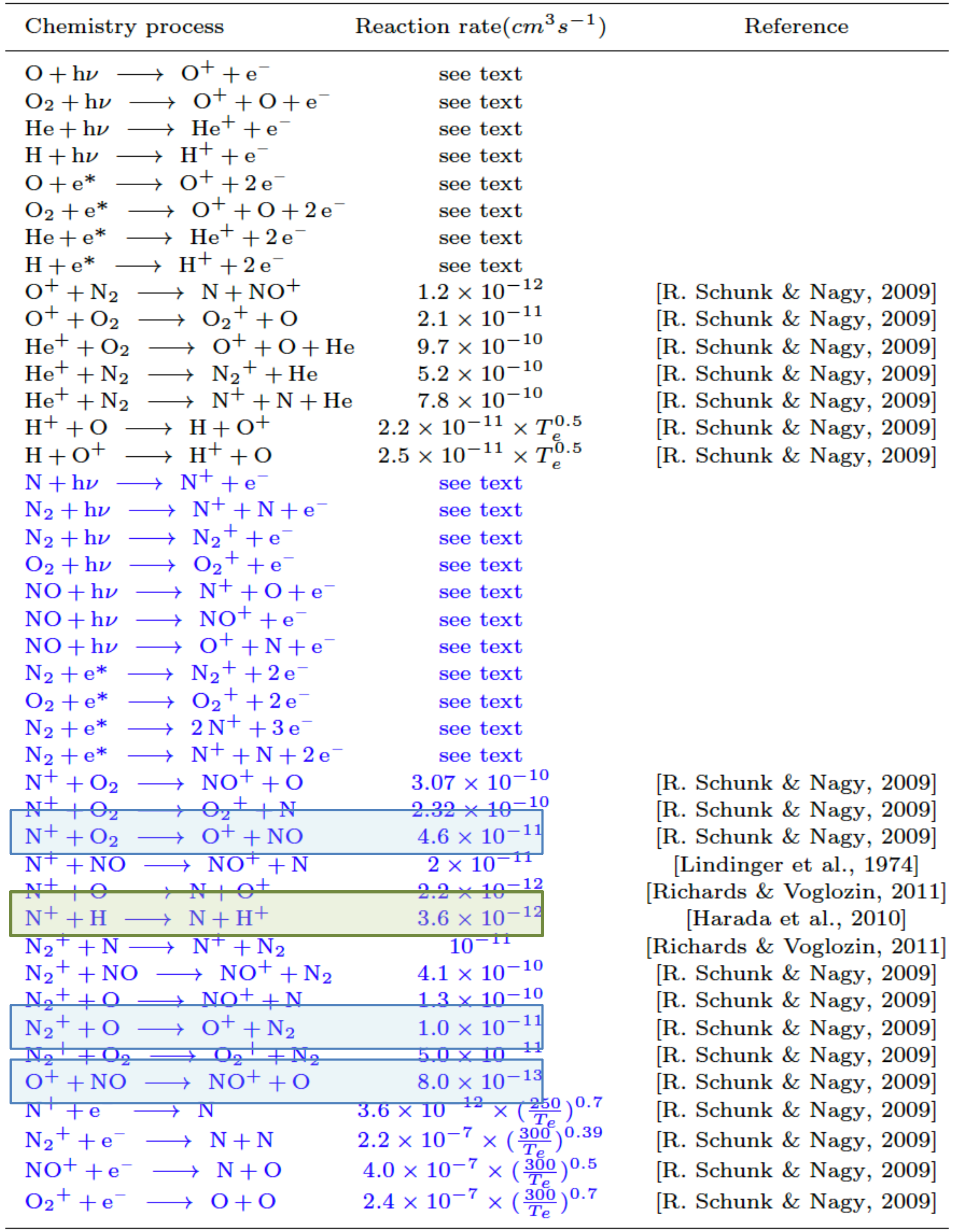
Chemistry and Collisions

New sources/losses for O^+

New sources for H^+

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

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



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Chemistry and Collisions

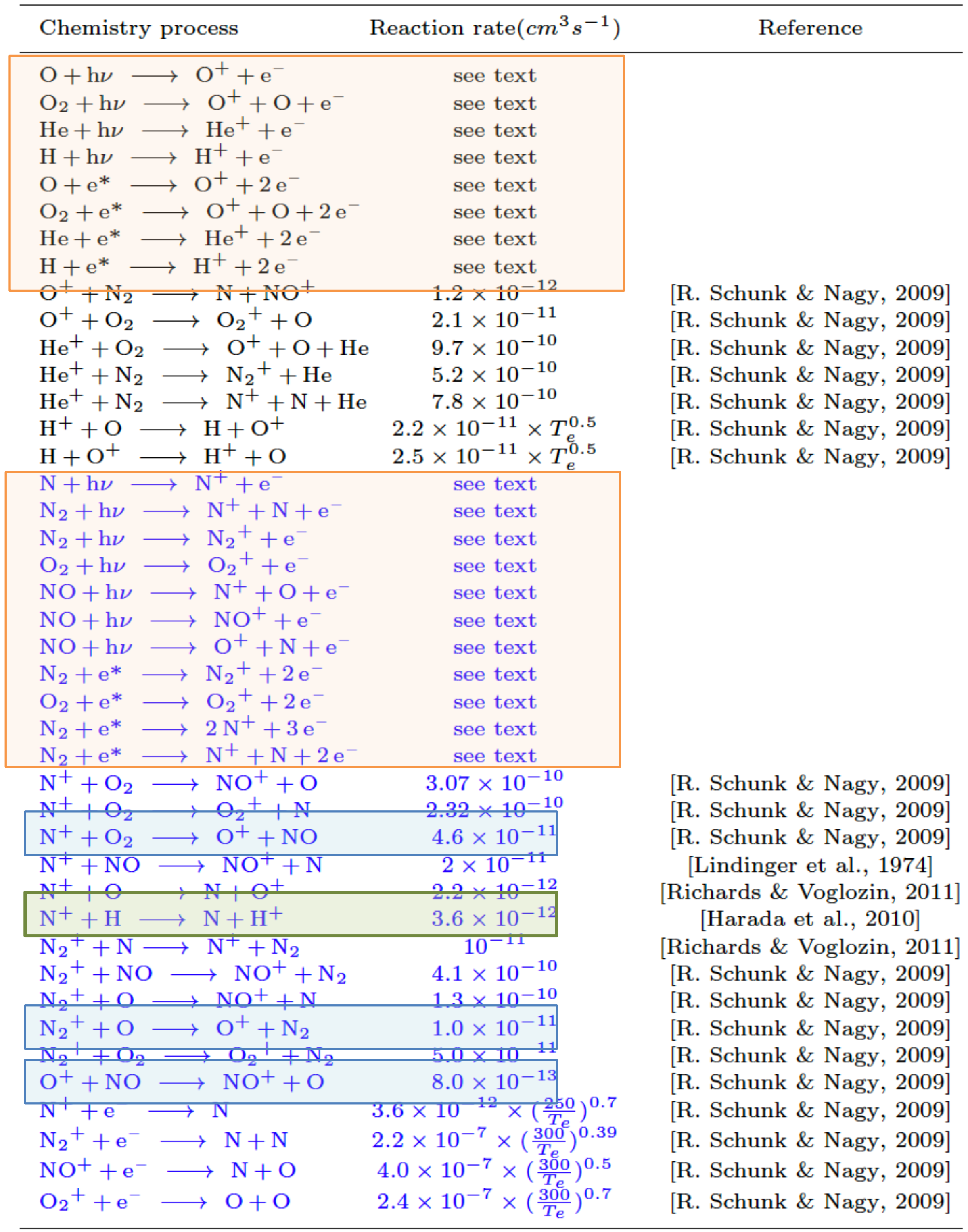
New sources/losses for O^+

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

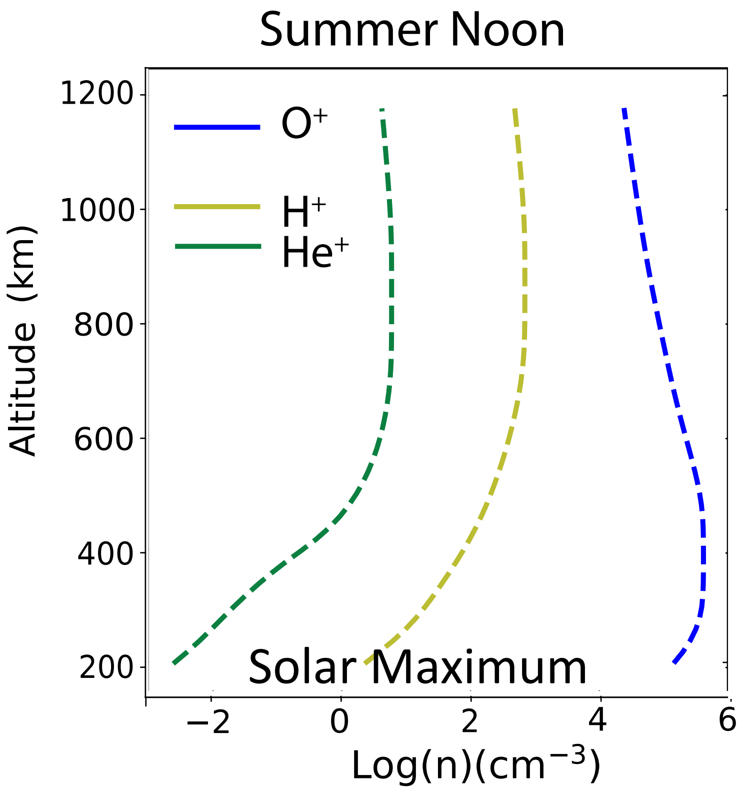
Suprathermal Electron (SE) Production

New sources for H^+

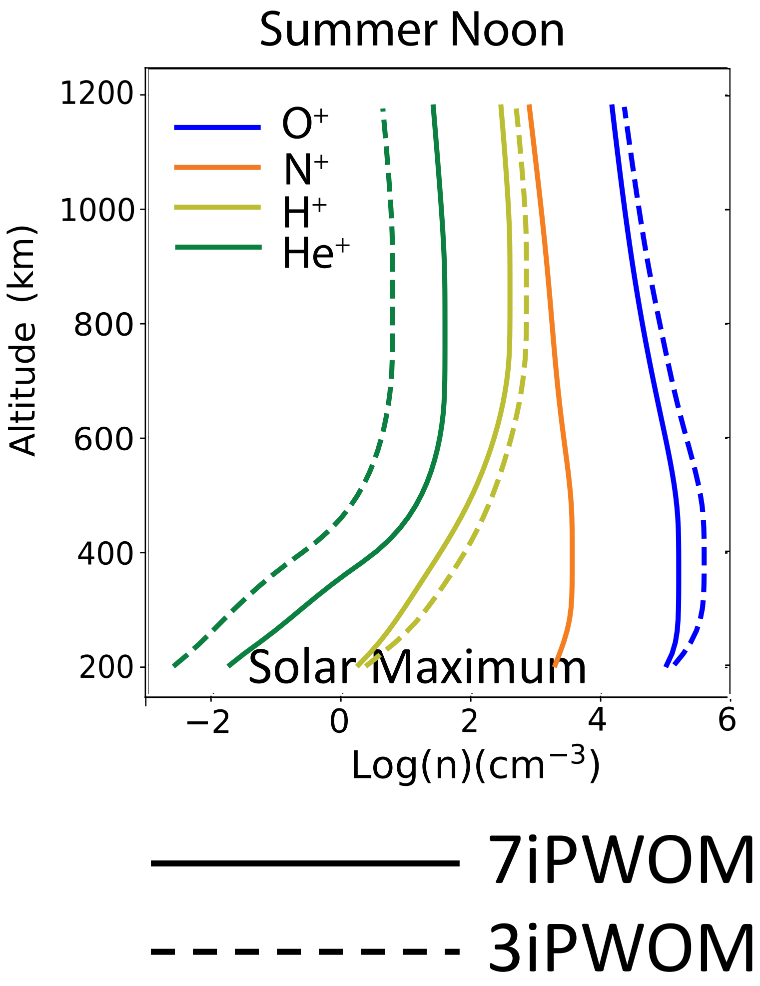
7iPWOM
H^+, He^+, N^+, O^+, N_2^+, NO^+, O_2^+

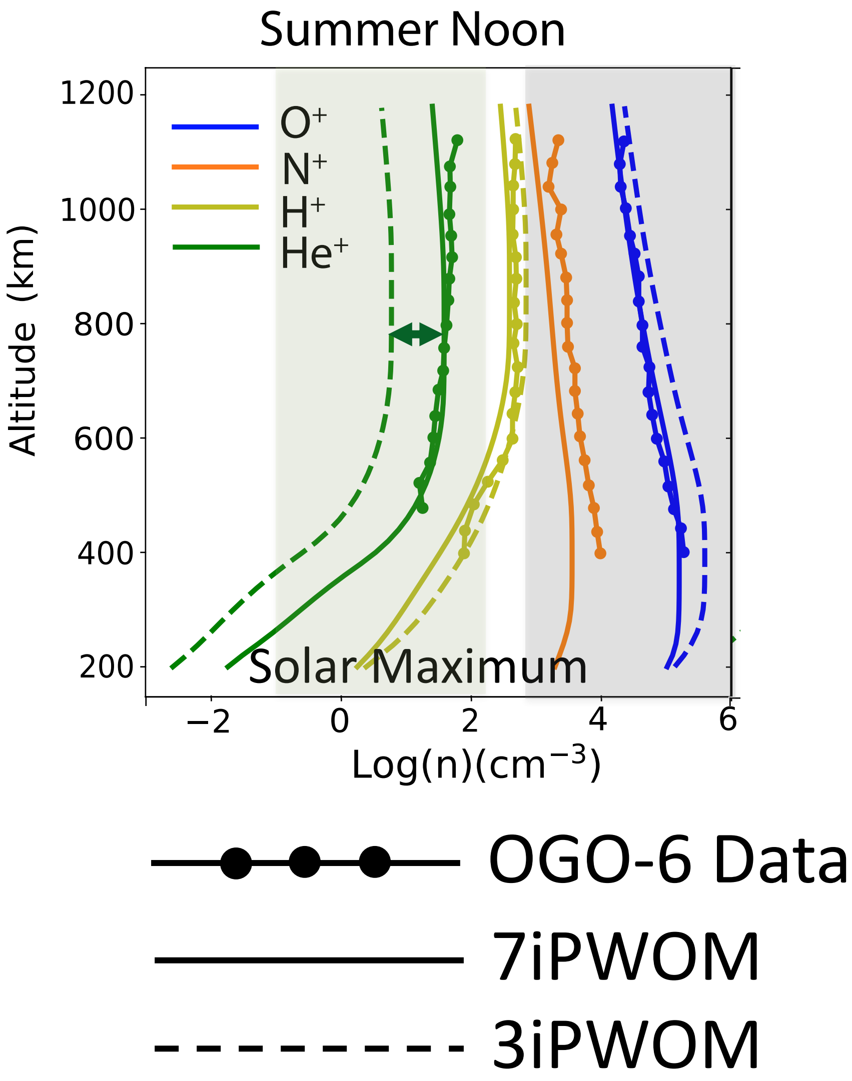


Chemistry process	Reaction rate($cm^3 s^{-1}$)	Reference
$O + h\nu \longrightarrow O^+ + e^-$	see text	
$O_2 + h\nu \longrightarrow O^+ + O + e^-$	see text	
$He + h\nu \longrightarrow He^+ + e^-$	see text	
$H + h\nu \longrightarrow H^+ + e^-$	see text	
$O + e^* \longrightarrow O^+ + 2\,e^-$	see text	
$O_2 + e^* \longrightarrow O^+ + O + 2\,e^-$	see text	
$He + e^* \longrightarrow He^+ + 2\,e^-$	see text	
$H + e^* \longrightarrow H^+ + 2\,e^-$	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	
$N_2 + e^* \longrightarrow N_2^+ + 2\,e^-$	see text	
$O_2 + e^* \longrightarrow O_2^+ + 2\,e^-$	see text	
$N_2 + e^* \longrightarrow 2\,N^+ + 3\,e^-$	see text	
$N_2 + e^* \longrightarrow N^+ + N + 2\,e^-$	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]


Summer Noon
1200
1000
800
600
400
200
Altitude (km)
O+
H+
He+
Solar Maximum
−2
0
2
4
6
Log(n)(cm−3)

-------- 3iPWOM

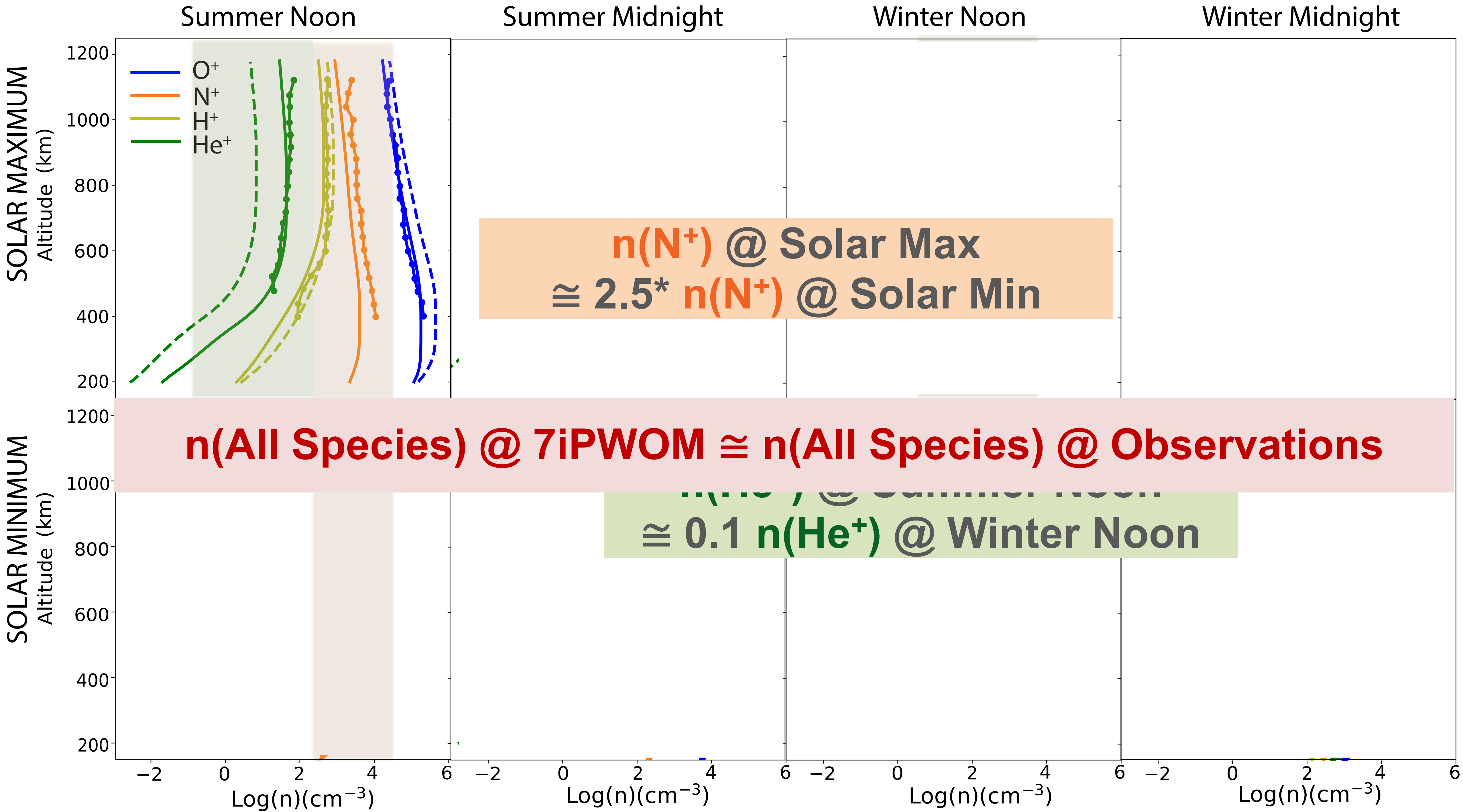

Summer Noon
Altitude (km)
1200
1000
800
600
400
200
−2
0
2
4
6
Log(n)(cm^{-3})
O$^+$
N$^+$
H$^+$
He$^+$
Solar Maximum
7iPWOM
3iPWOM



- Comparison with observations shows that the presence of **N^+** improves the outflow solution for *all species.*

- **He^+** solution shows the biggest improvement, as 7iPWOM predicts a density **one order of magnitude higher than 3iPWOM,** aligned with observations.

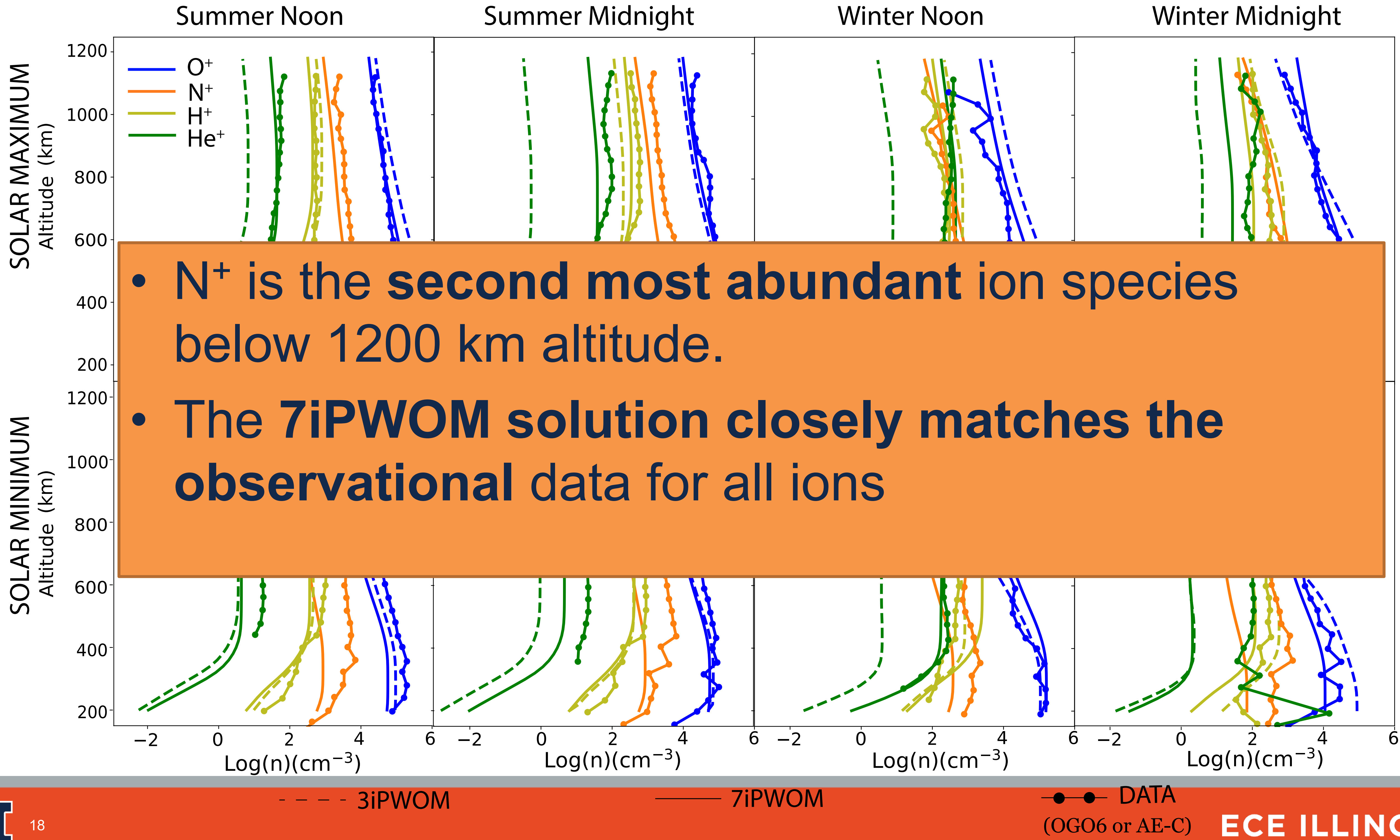
$n(N^+) \cong 10\%$ of $n(O^+)$



$n(N^+)$ @ Solar Max
≅ 2.5* $n(N^+)$ @ Solar Min

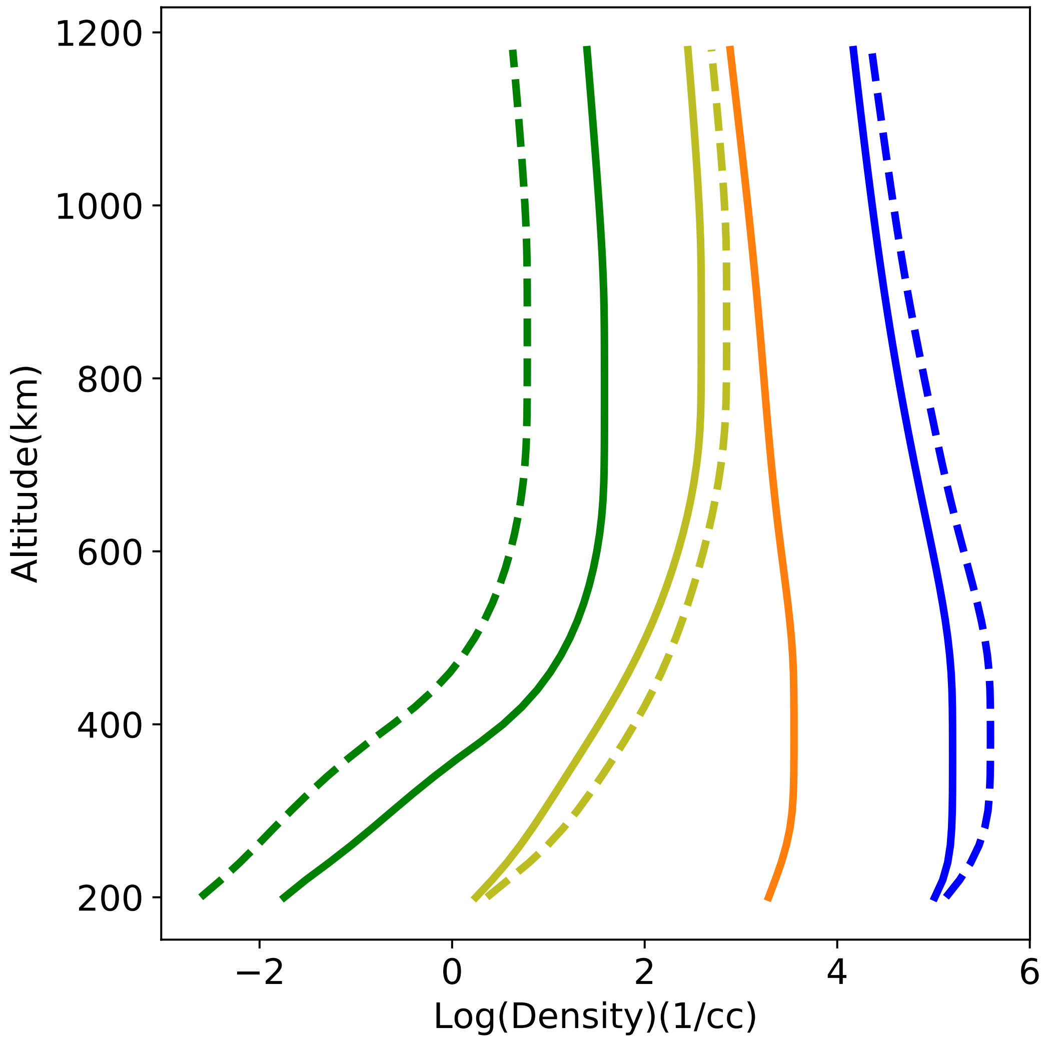
n(All Species) @ 7iPWOM ≅ n(All Species) @ Observations

≅ 0.1 $n(He^+)$ @ Winter Noon



- N^+ is the **second most abundant** ion species below 1200 km altitude.
- The **7iPWOM solution closely matches the observational** data for all ions

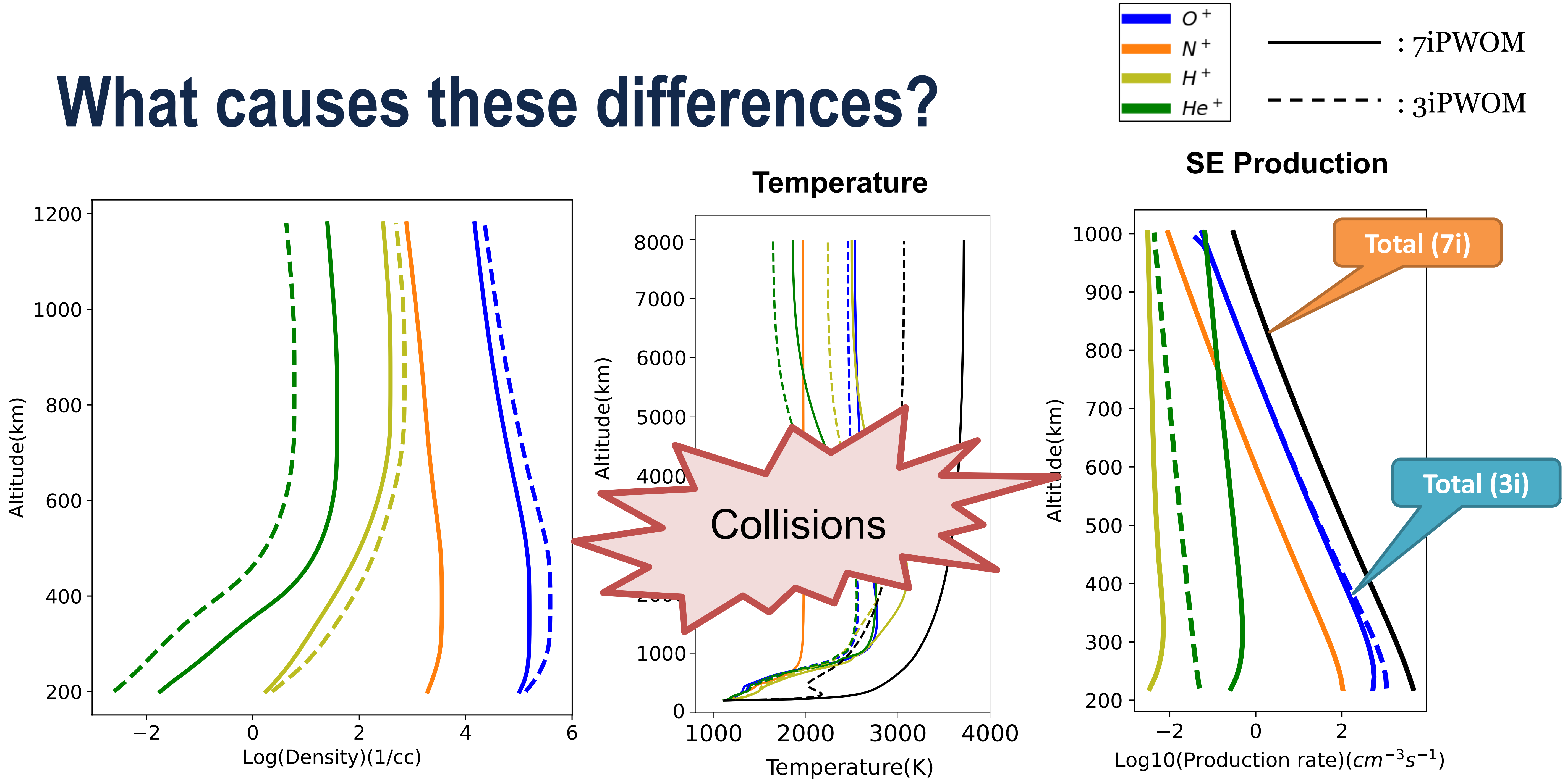
What causes these differences?



Presence of **N^+** and molecular species leads to :

- A significant increase (~1 an order of magnitude) in **He^+** density.
- **H^+** solution improves as compared with measurements
- **O^+** density profile better matches the data, and the density is a factor 2 larger.
- **N^+** profile matches observations
- ***All species show an increase in temperature/energy.***

What causes these differences?



Temperature

SE Production

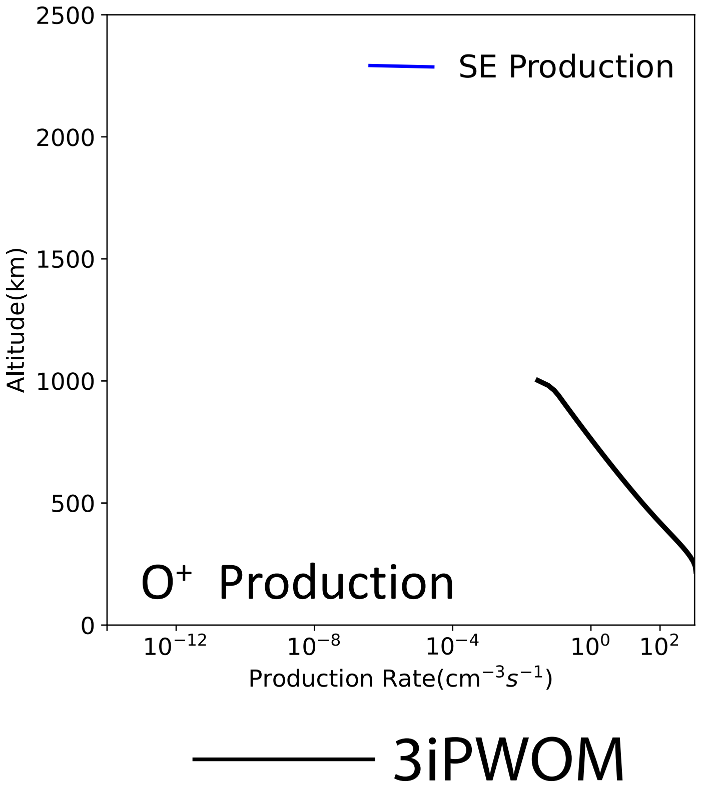
Total (7i)

Total (3i)

Collisions

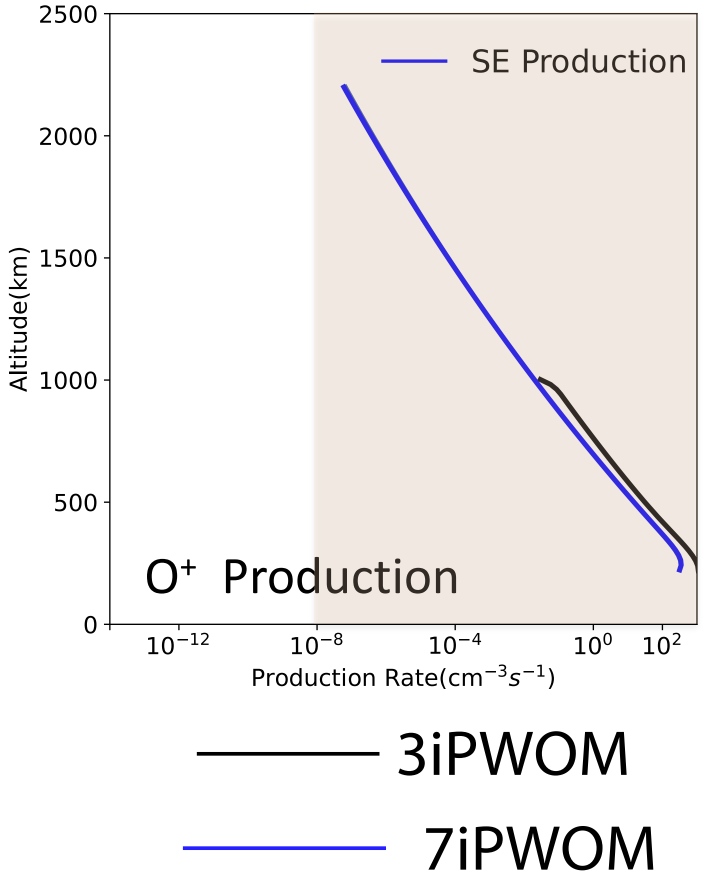
Chemistry?

SE production



Chemistry?

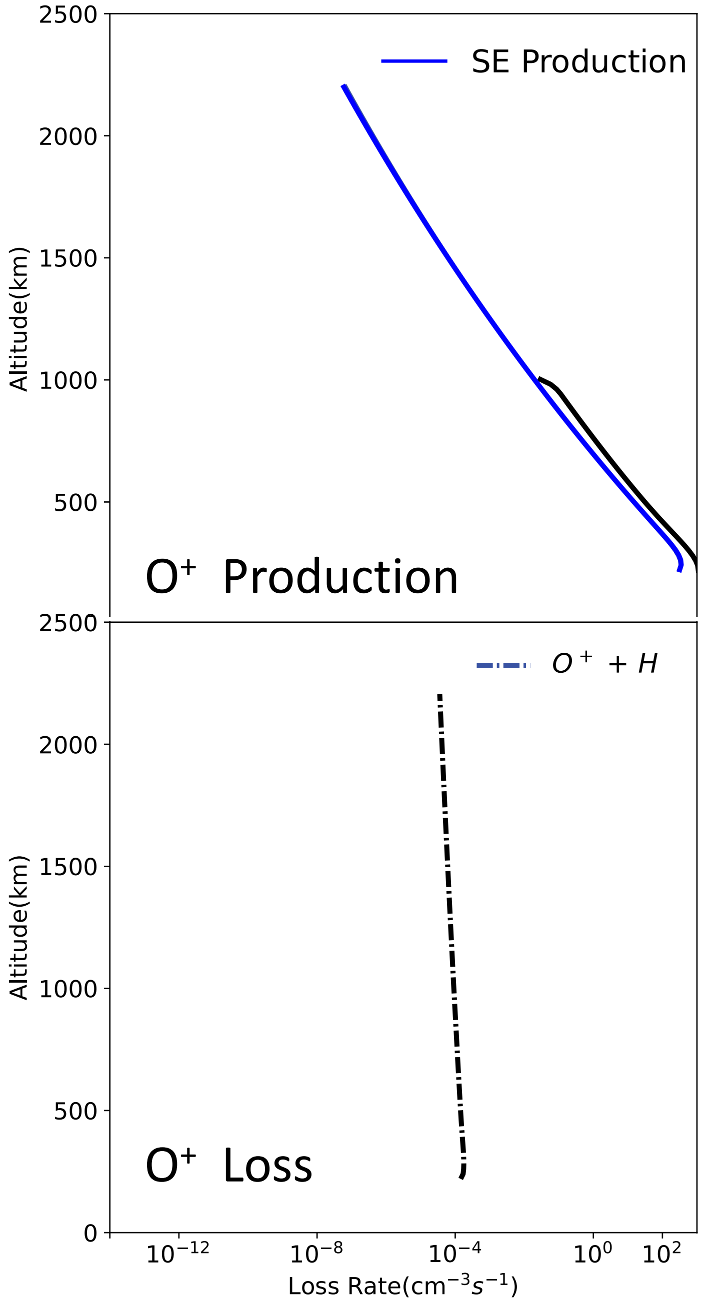
SE production



Chemistry?

SE production

Charge exchange with H^+



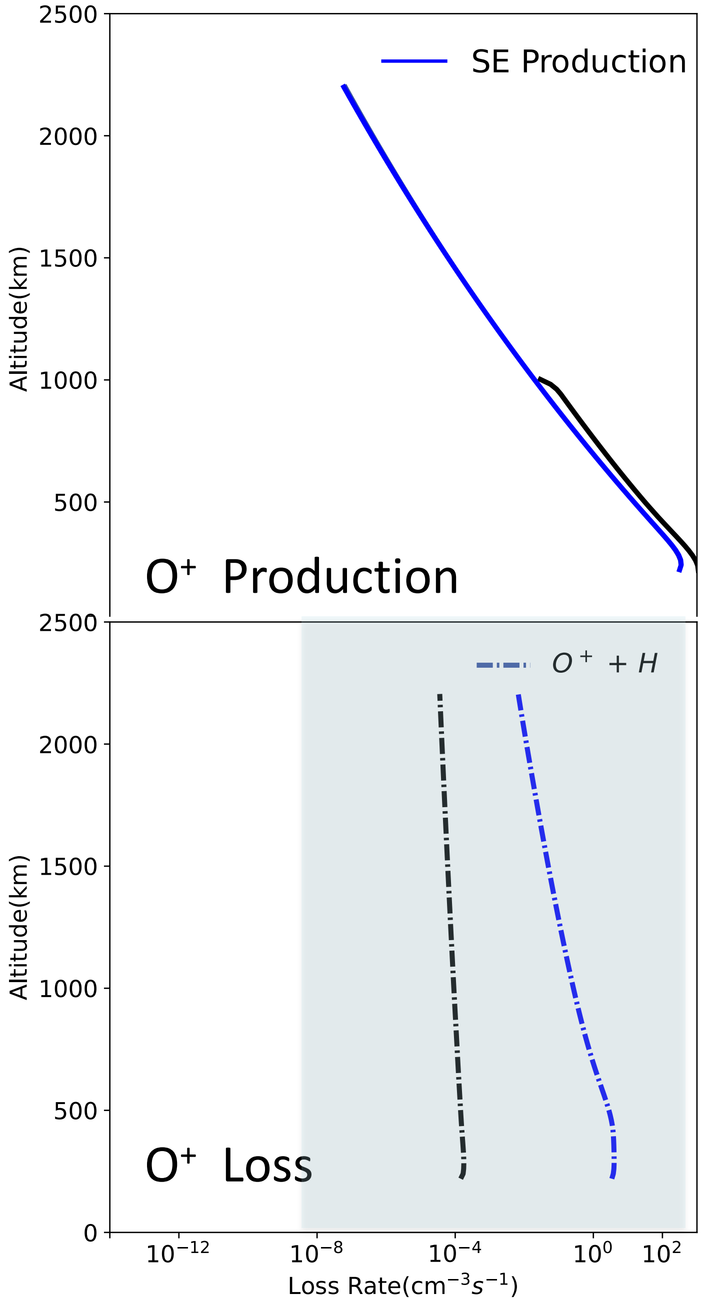
7iPWOM

3iPWOM

Chemistry?

SE production

Charge exchange with H^+



7iPWOM

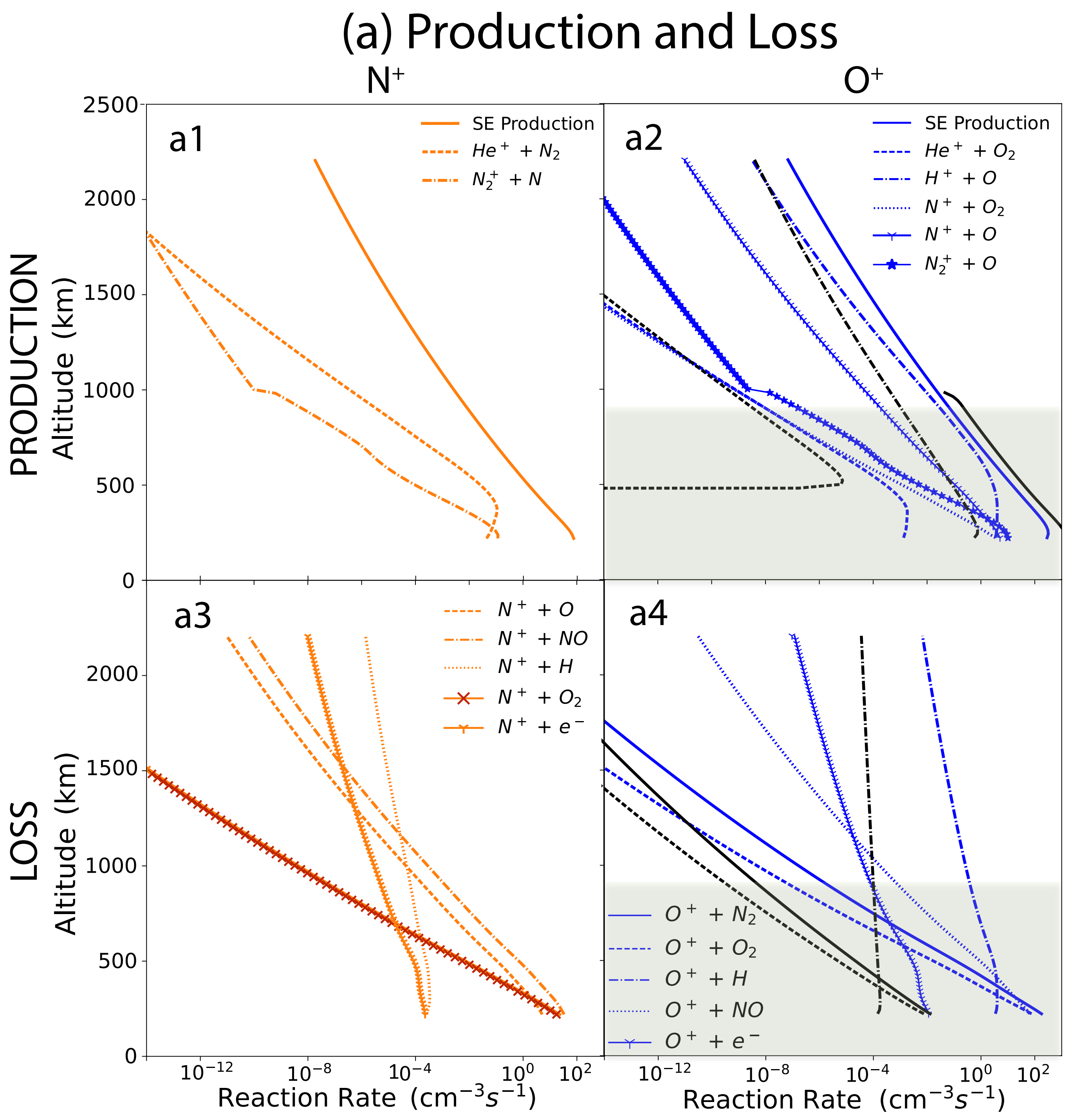
3iPWOM

Chemistry?

Different Chemistry at low altitude

SE production

Charge exchange with H^+



7iPWOM

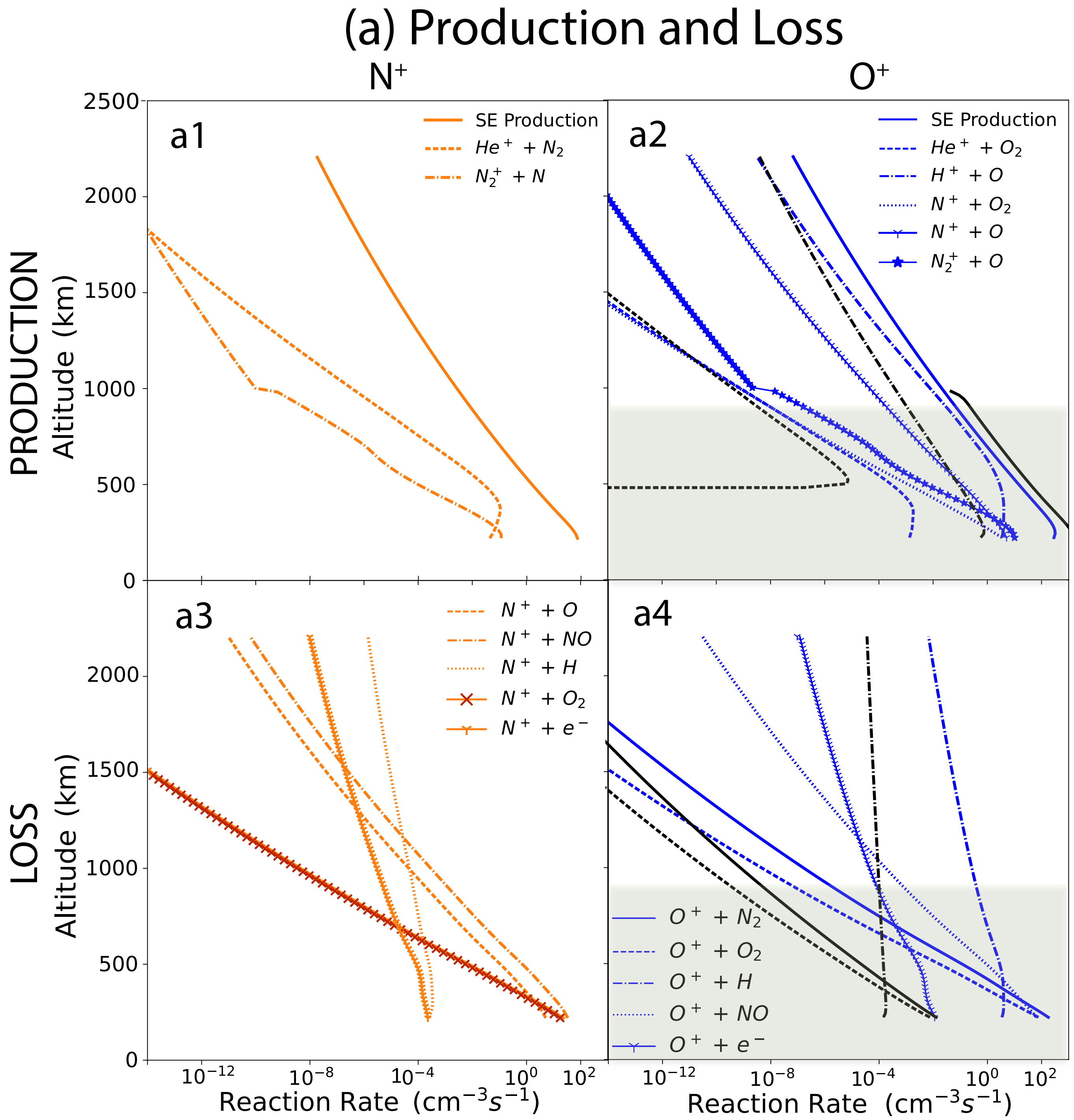
3iPWOM

Chemistry?

Different Chemistry at low altitude

SE production

Charge exchange with H^+



7iPWOM

3iPWOM

Conclusion

- N^+ ions are the second most abundant ion species in the ionospheric outflow, for all conditions.
- Data-model comparison shows that the presence on N^+ improves the polar wind solution significantly.
  - 7iPWOM predicts the seasonal variation with He^+ due to expanded scheme of SE production.
  - Expanded chemical scheme leads to a redistribution of the ion density in the topside ionosphere.
- Extra energy source, such as through wave particle interactions, could have a profound influence on the upward transport of the N^+.
  - N^+ ions are likely to couple with cold neutral species than the O^+ ions.