Tracking the Differential Transport and Acceleration of Nitrogen and Oxygen Ions from the Terrestrial Ionosphere to the Inner Magnetosphere

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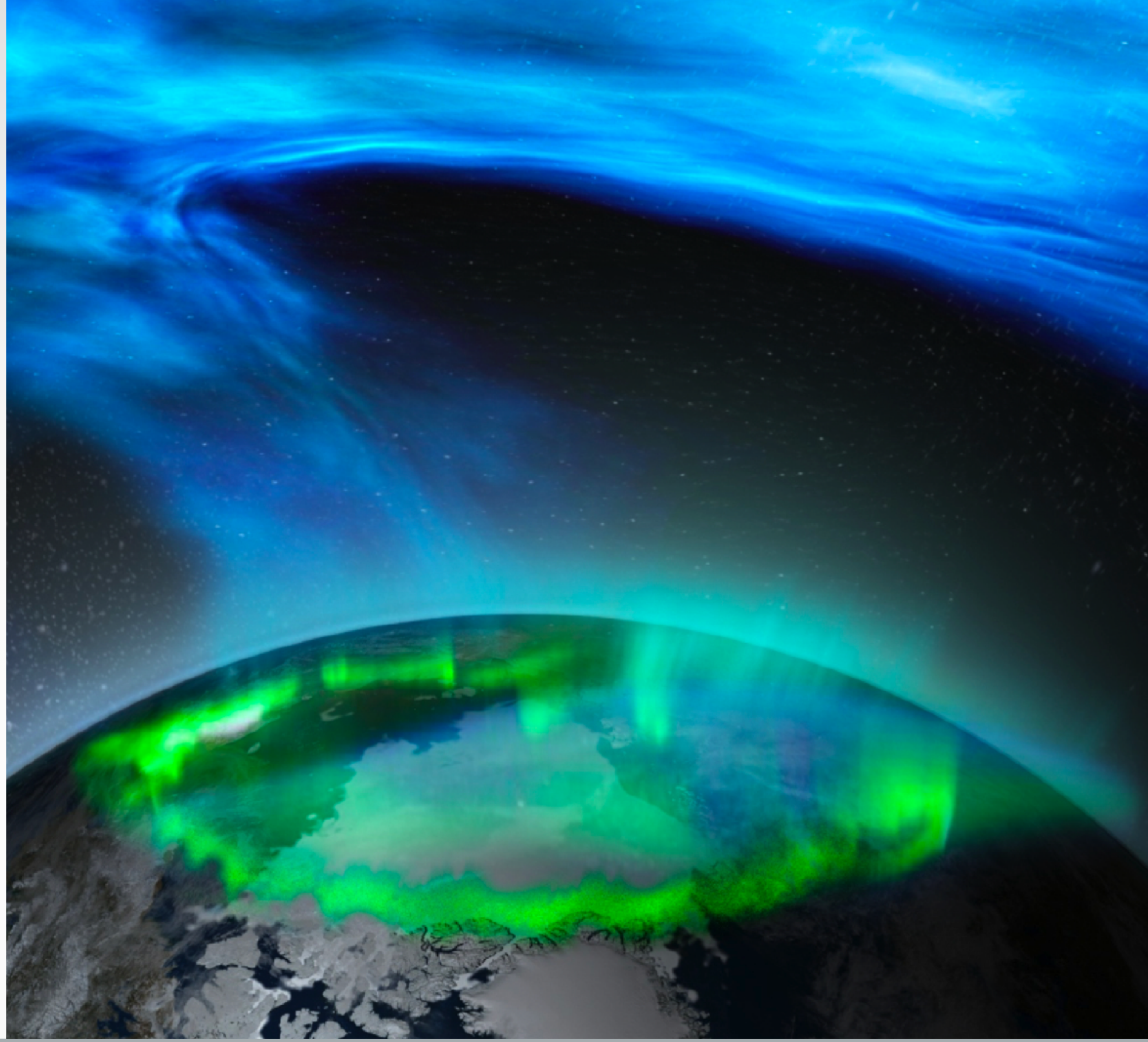

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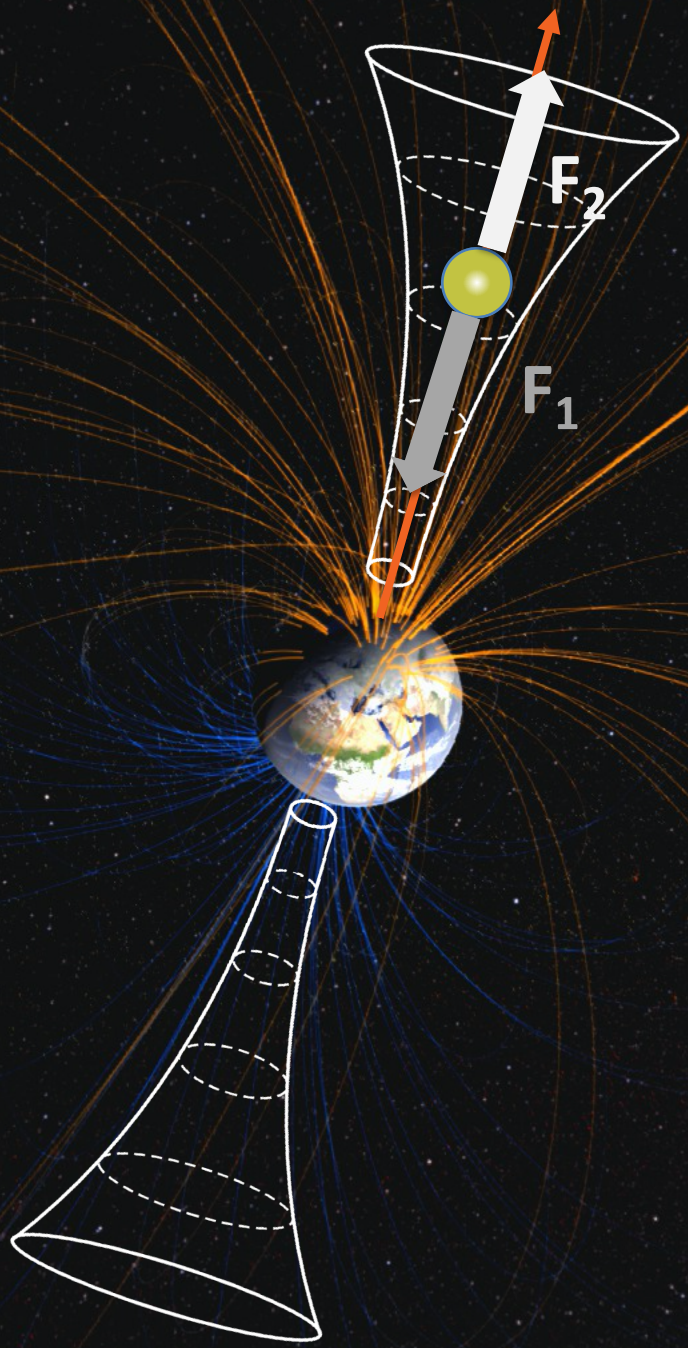
Charged particles escape via open field lines to outer space or the Earth magnetosphere



F_1 = Gravitational

F_2 = Electromagnetic

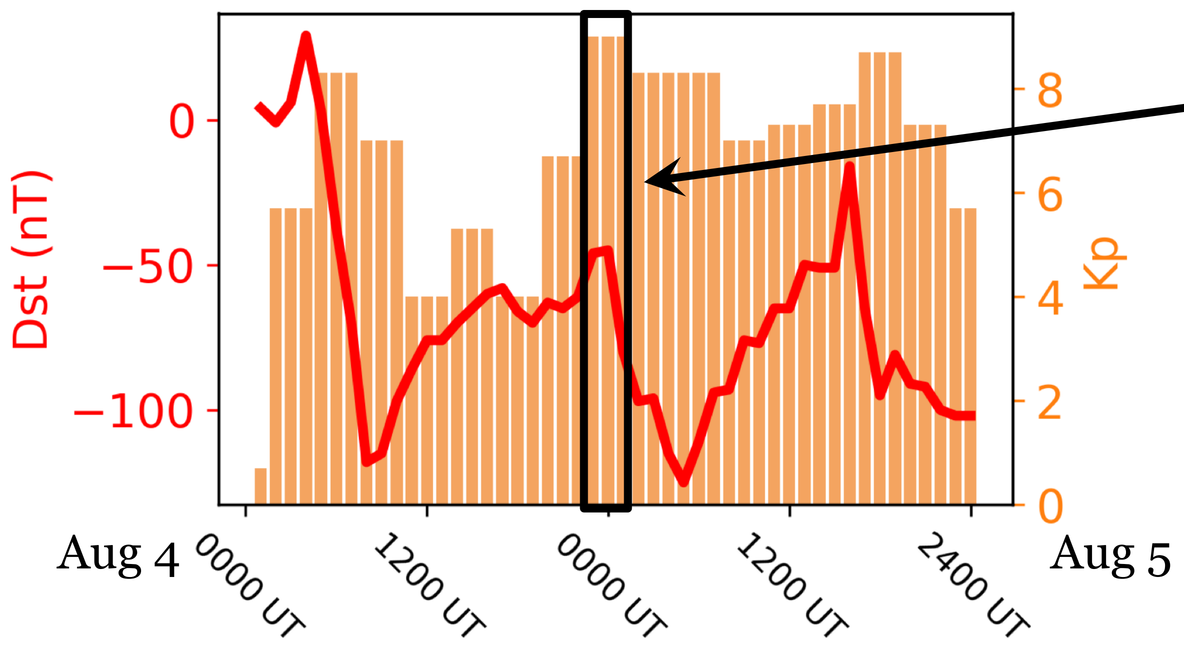
$$E = \frac{1}{2}mv^2 - \frac{gMm}{r}$$

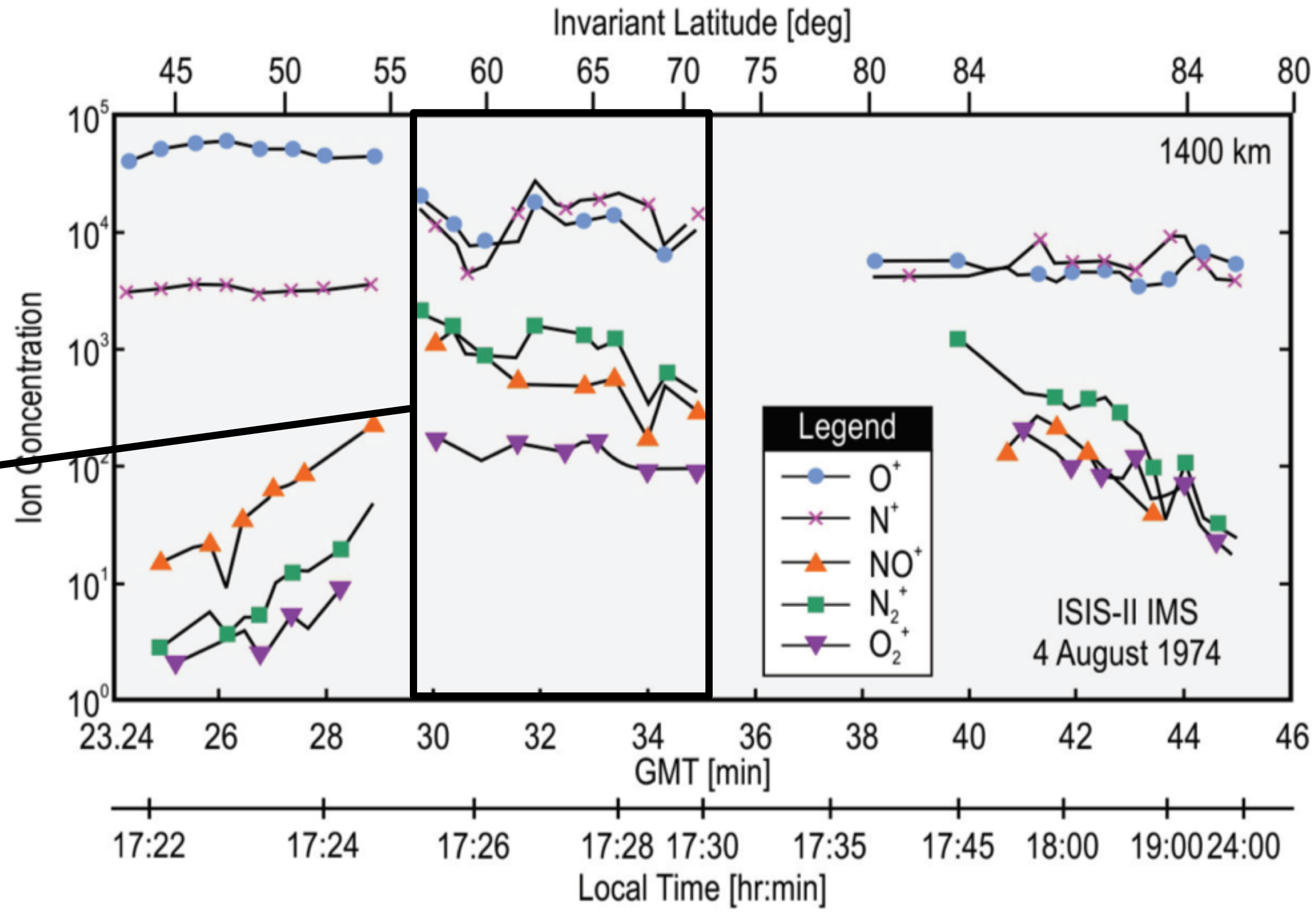
$E_{esc}(H^+) \sim 10eV$

$E_{esc}(e^-) = 0.7eV$

Observations of N^+ in the Earth's Ionosphere

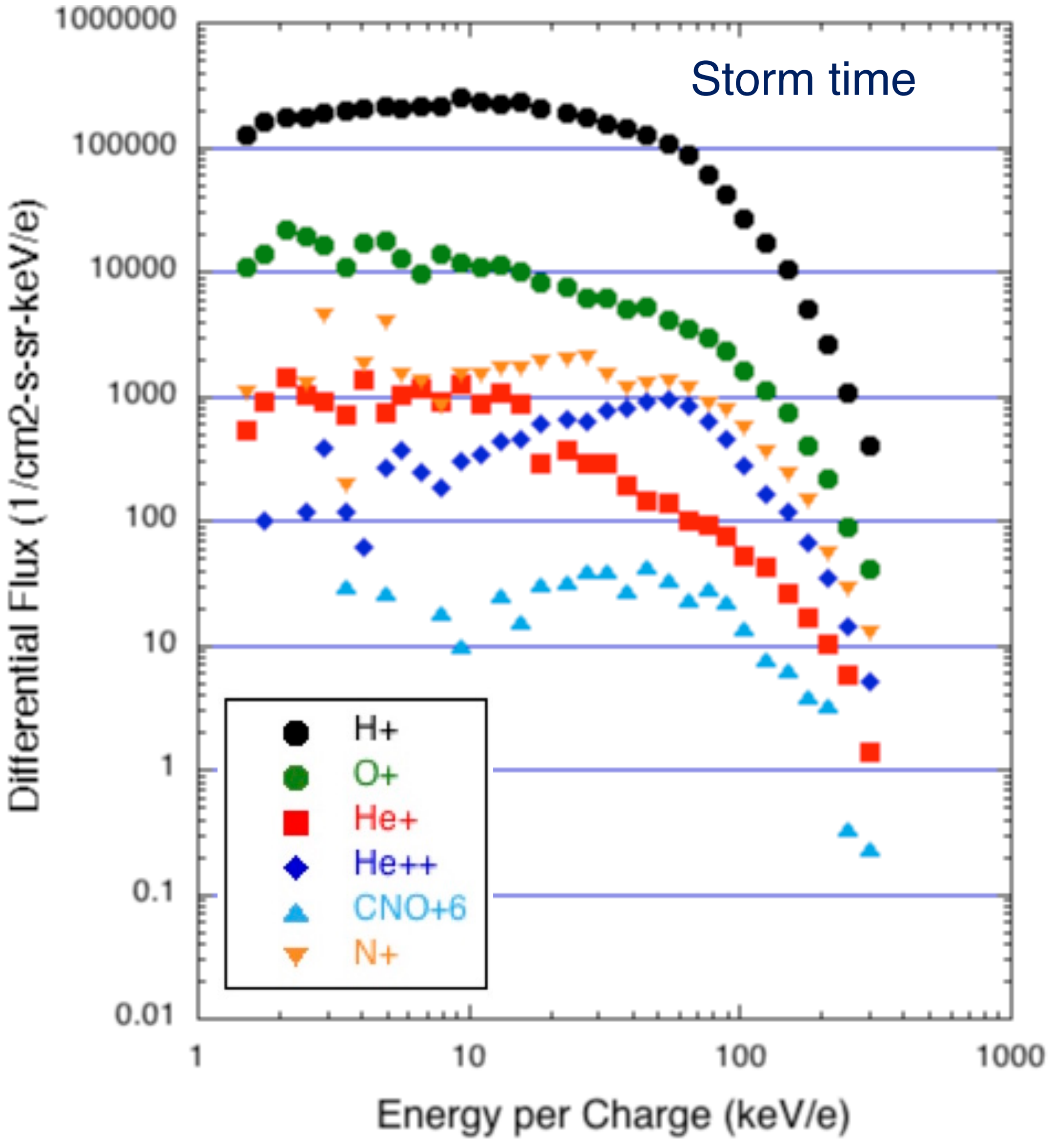
- ISIS 2 measurements of ion composition during August 1972 storm (Kp=9).
- During active times, O^+ and N^+ have comparable ion concentrations in the polar ionosphere.



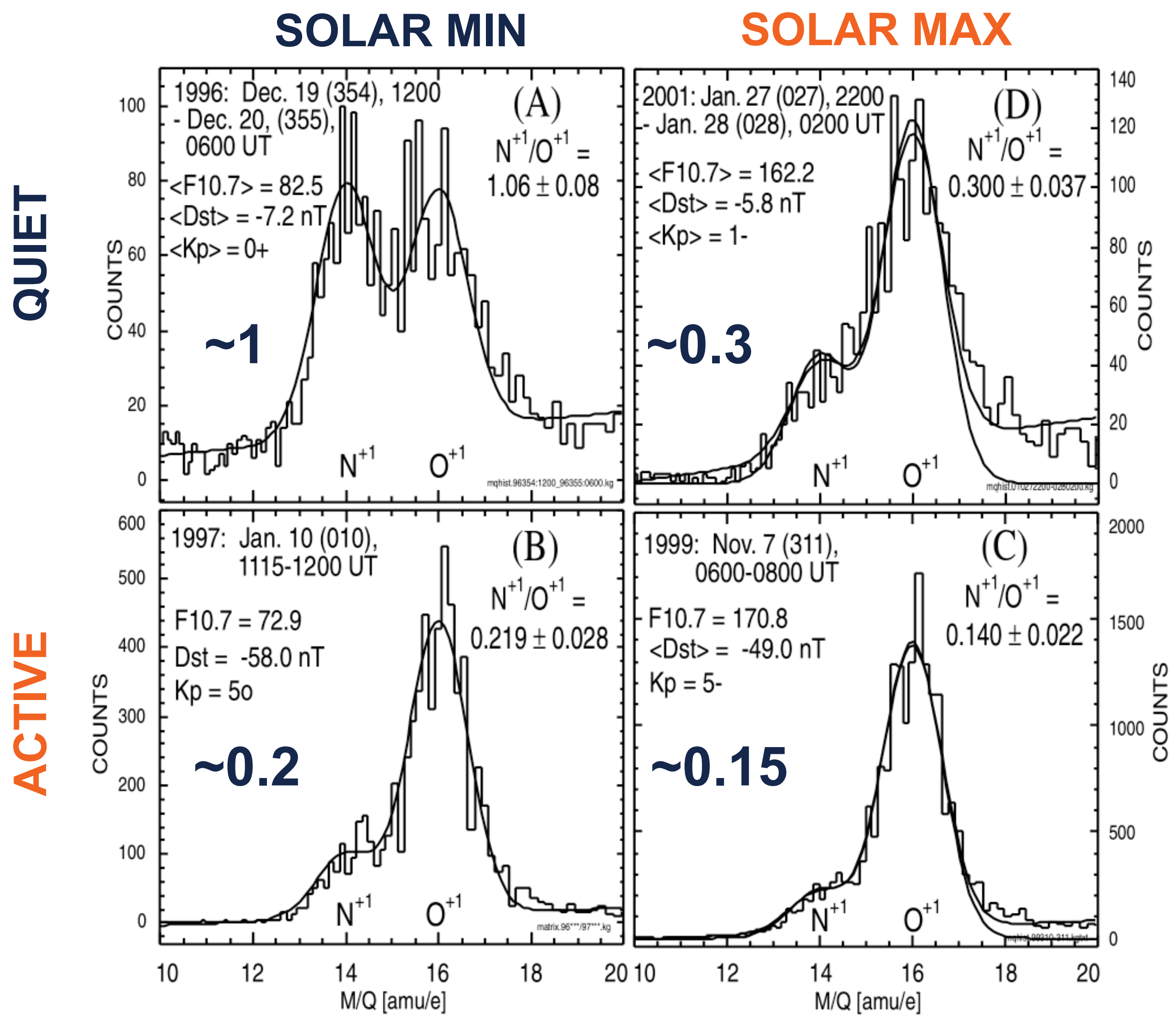


(Hoffman et al., 1974).

N$^+$ Observations in the Magnetosphere

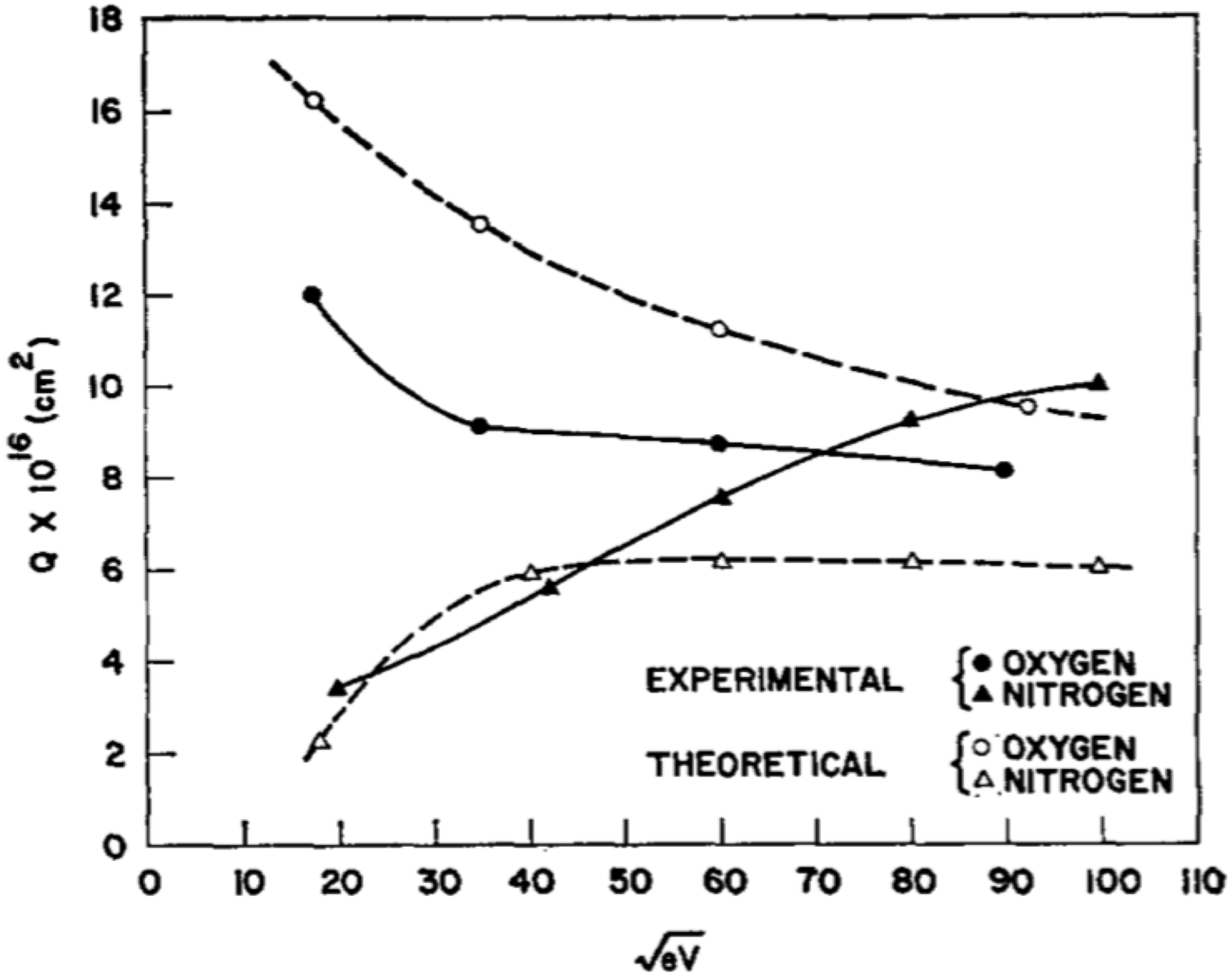


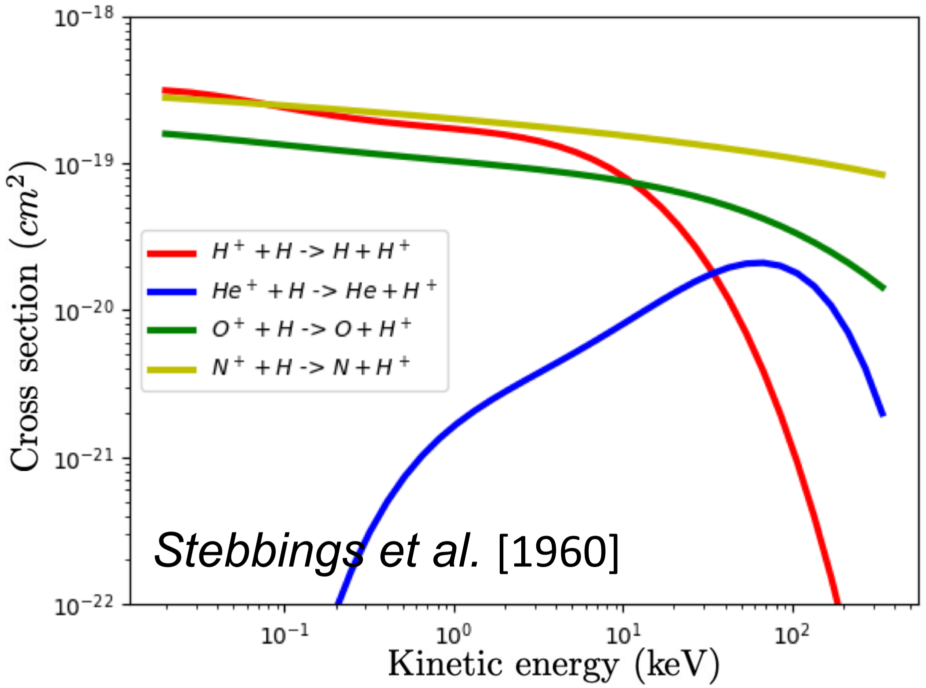
AMPTE measurements (Courtesy of Lynn Kistler).



Christon et al. [2002]

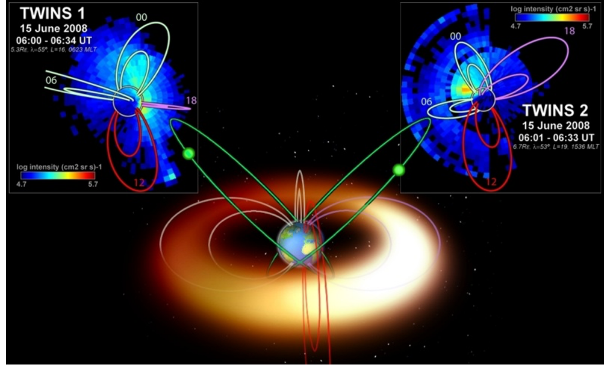
Motivation: Unexplained Fast Decay of O^+ in the Magnetosphere





Closer to the Earth, equatorially mirroring N^+ ions with energies > 10KeV are faster removed from the system than the O^+ ions, and their lifetime is at least one order of magnitude shorter.

Effect of N^+/O^+ ratio in Inner Magnetosphere

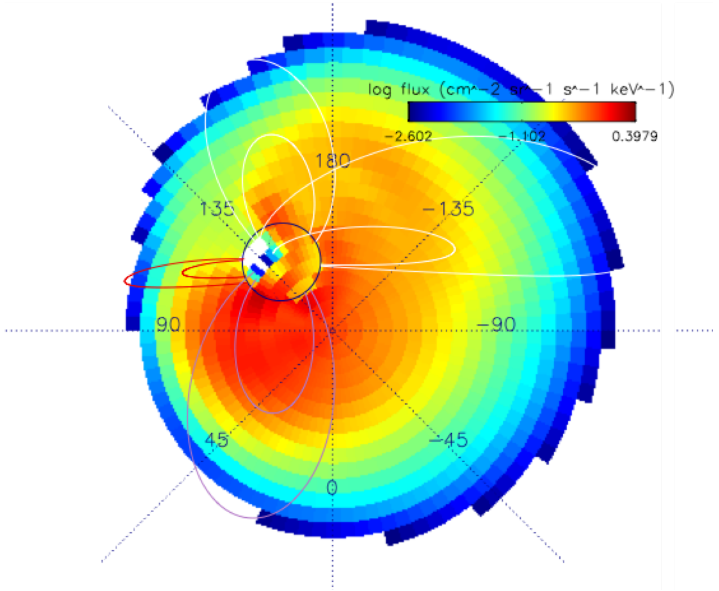


Ilie et al. 2020, GRL

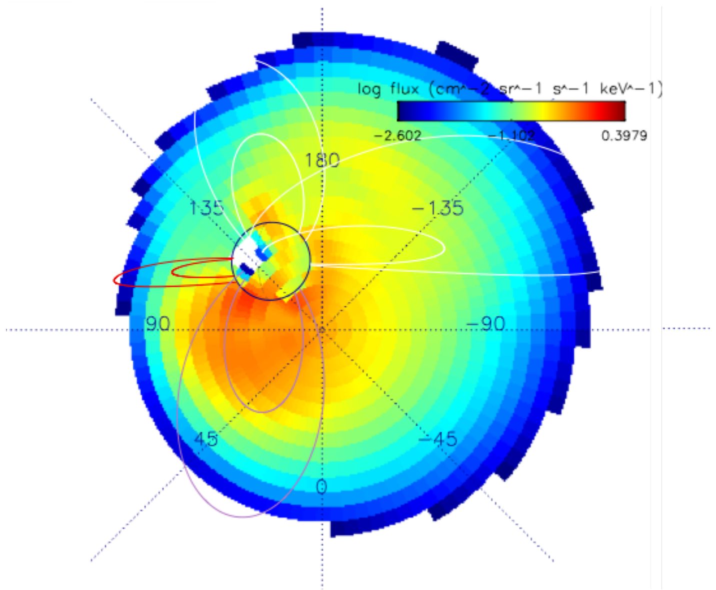
- TWINS-like oxygen ENA fluxes can be calculated from the HEIDI differential fluxes for different ion species. The plots below are extracted at hour 8 during the 12 hour simulation.
- When O^+ and N^+ densities are equal, the peak flux of O ENA is **half** of the O ENA flux when N^+ is absent.

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

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



100% O^+ + 0% N^+



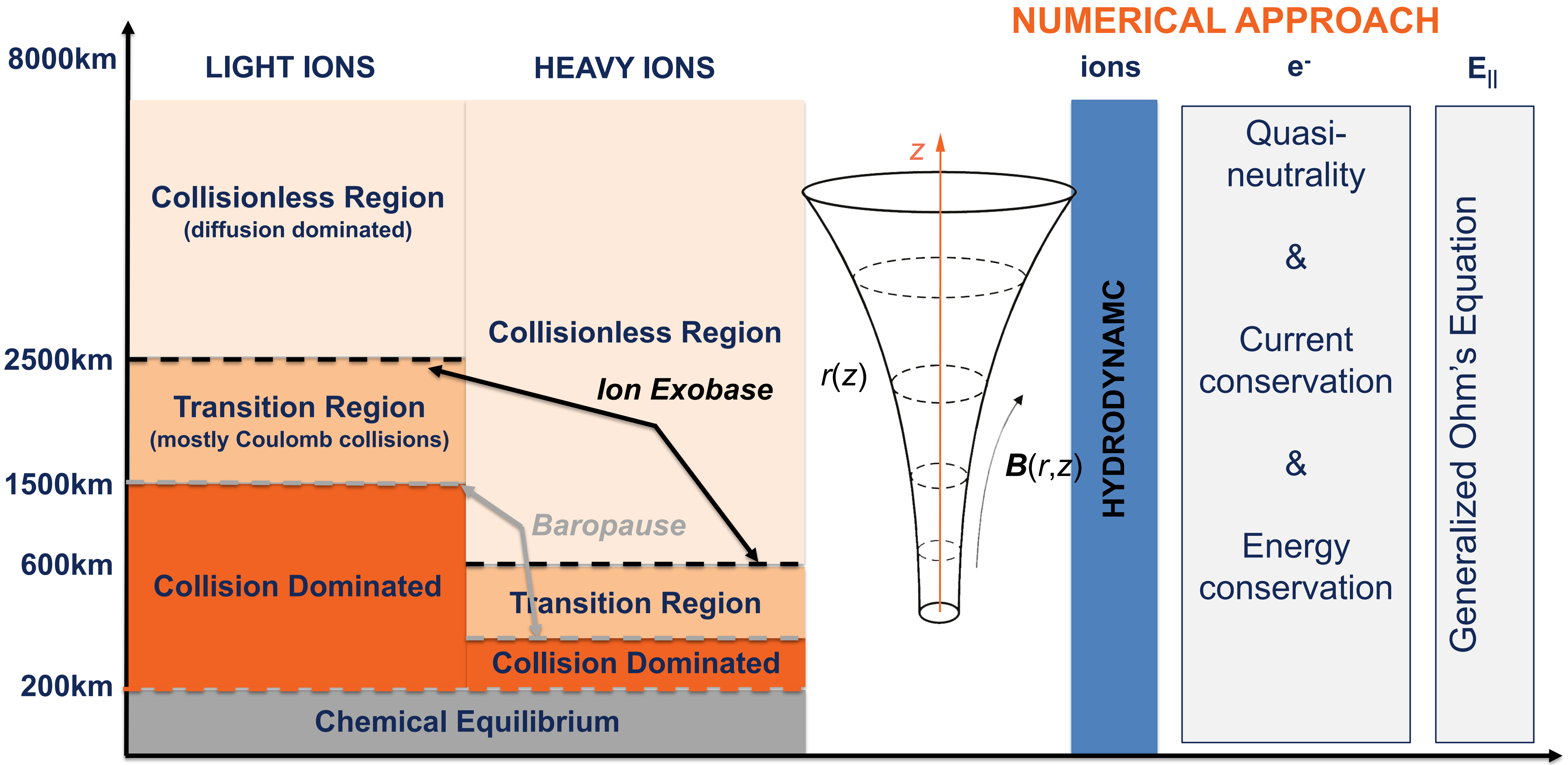
50% O^+ + 50% N^+

NASA TWINS Study

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

How does the ion composition affect the ionospheric outflow?

- 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


NUMERICAL APPROACH
8000km
2500km
1500km
600km
200km
LIGHT IONS
HEAVY IONS
ions
e-
E||
Collisionless Region
(diffusion dominated)
Transition Region
(mostly Coulomb collisions)
Collision Dominated
Collisionless Region
Ion Exobase
Baropause
Transition Region
Collision Dominated
Chemical Equilibrium
z
r(z)
B(r,z)
HYDRODYNAMC
Quasi-neutrality
&
Current conservation
&
Energy conservation
Generalized Ohm's Equation

Continuity Equations

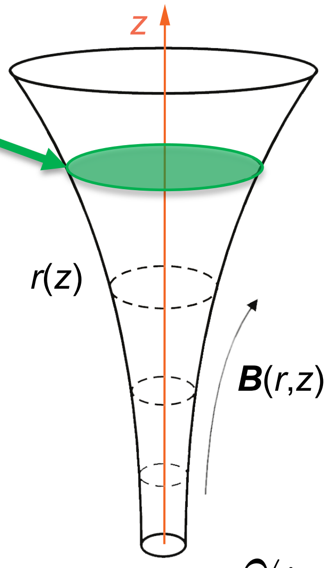
NUMERICAL APPROACH

ions

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

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

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



Flux tube area

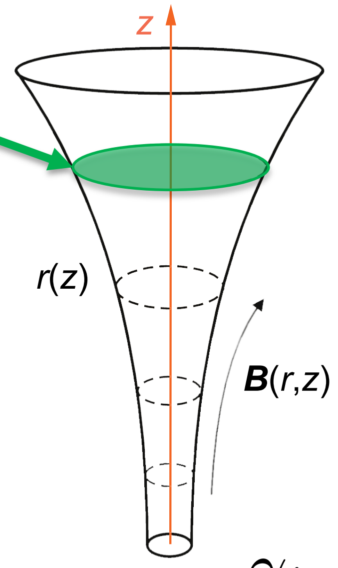
HYDRODYNAMC

Continuity Equations

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

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

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

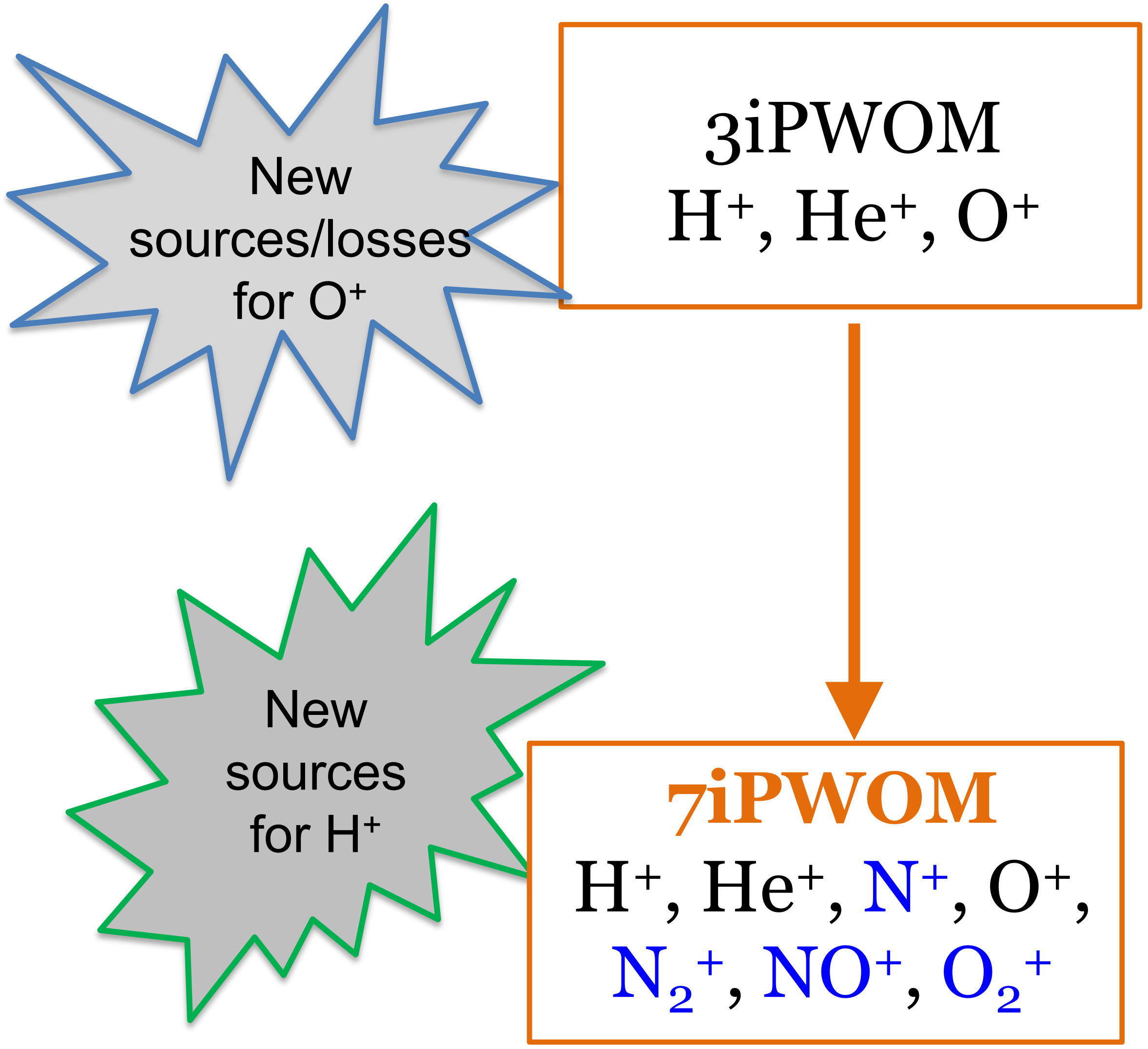


Flux tube area

ions

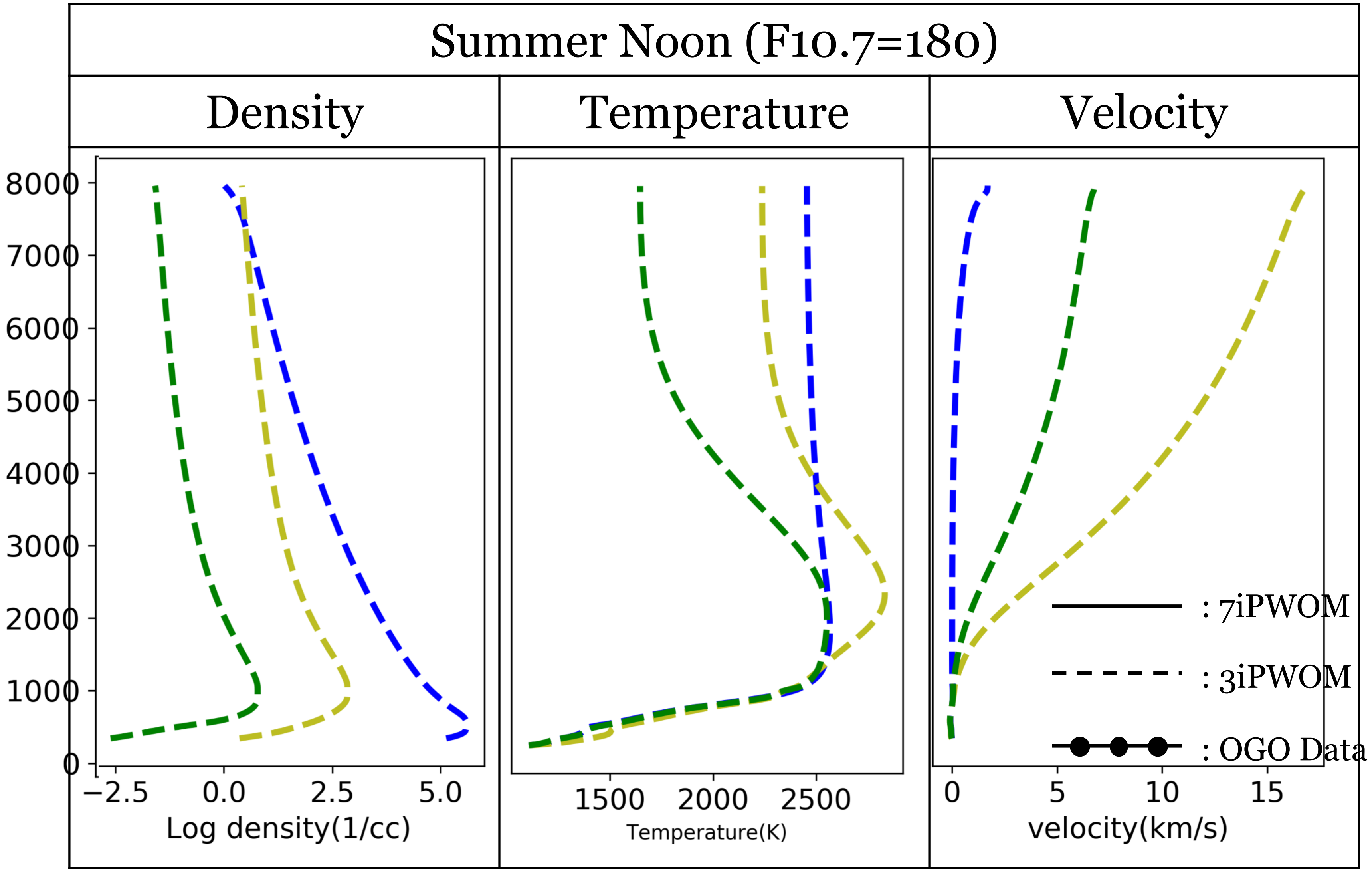
HYDRODYNAMC

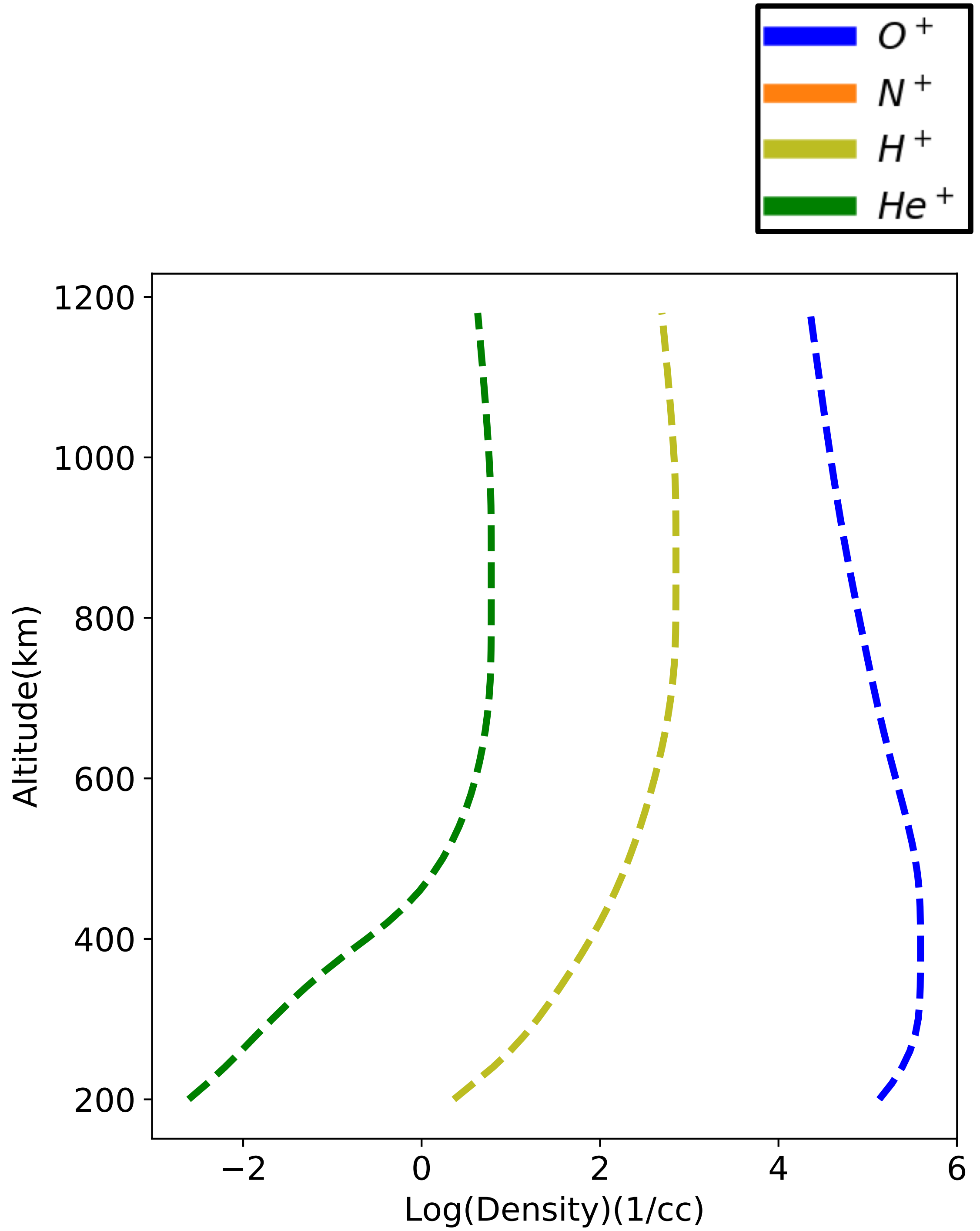
Chemical Scheme



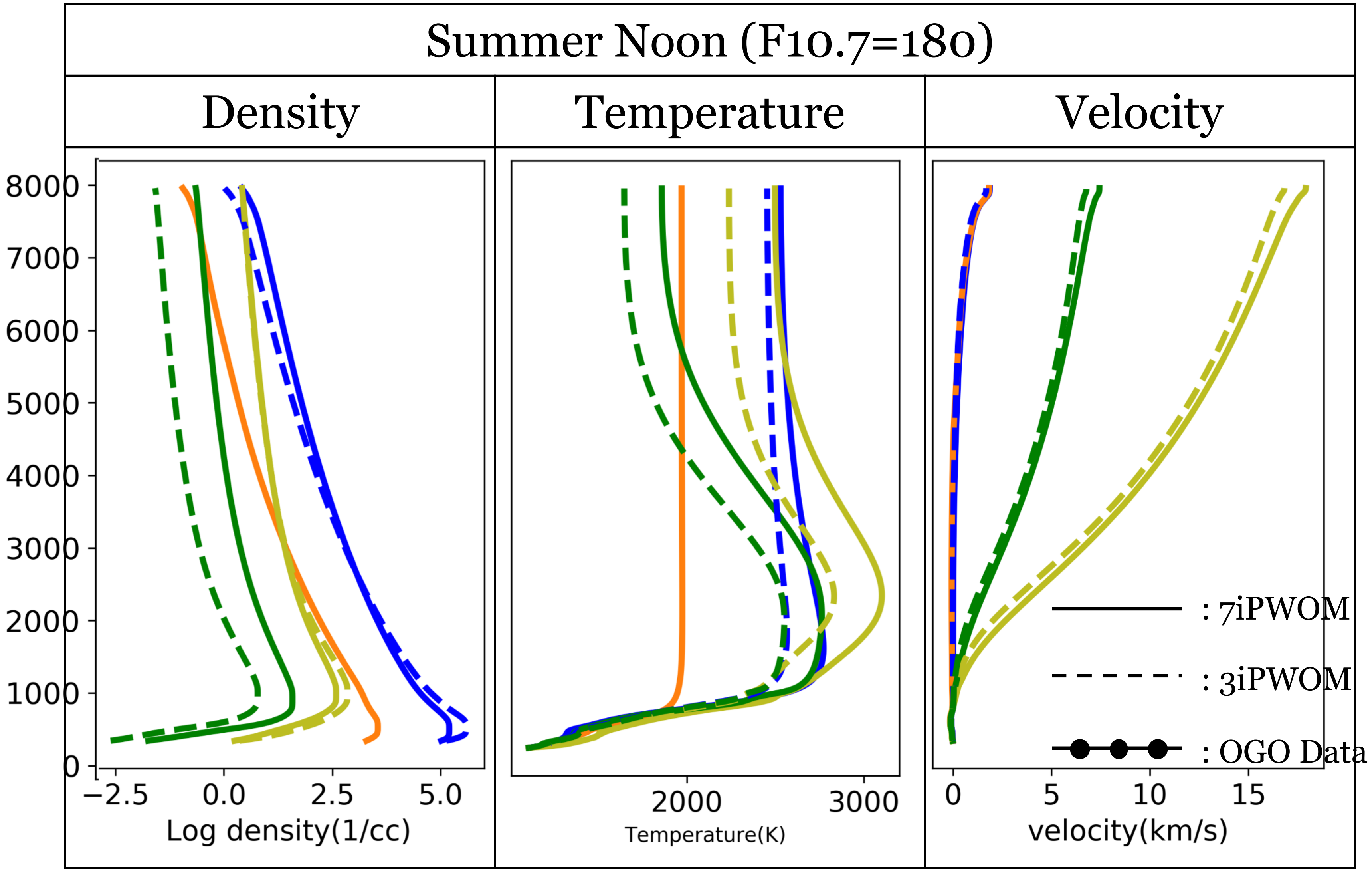
Chemistry reaction	Chemistry process	Reaction rate
Ion atom interchange	$N_2 + O^+ \longrightarrow NO^+ + N$	1.2×10^{-12}
Charge exchange	$O^+ + O_2 \longrightarrow {O_2}^+ + O$	2.1×10^{-11}
Dissociative charge transfer	$He^+ + O_2 \longrightarrow O^+ + O + He$	9.7×10^{-10}
Charge exchange	$He^+ + N_2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

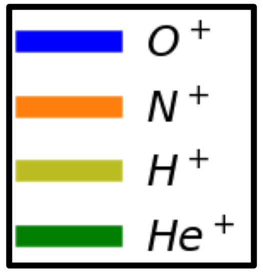
Solar Maximum Summer Noon

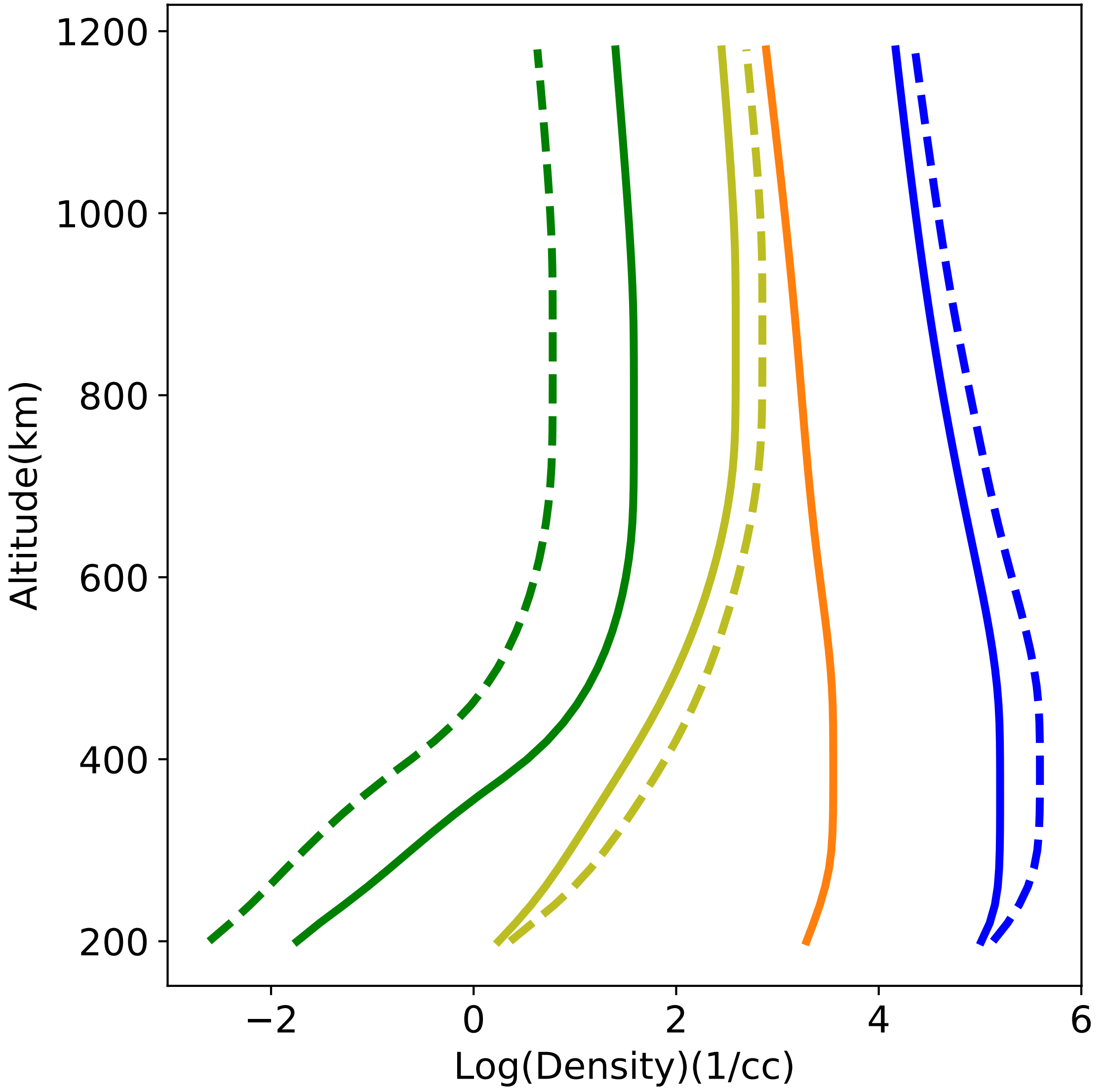




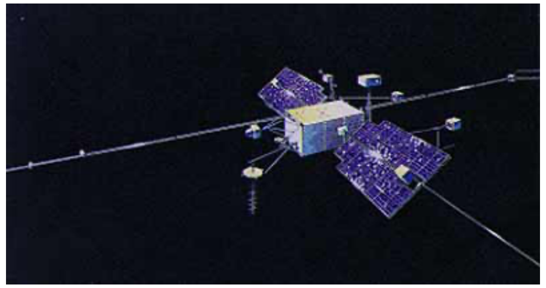
Solar Maximum Summer Noon

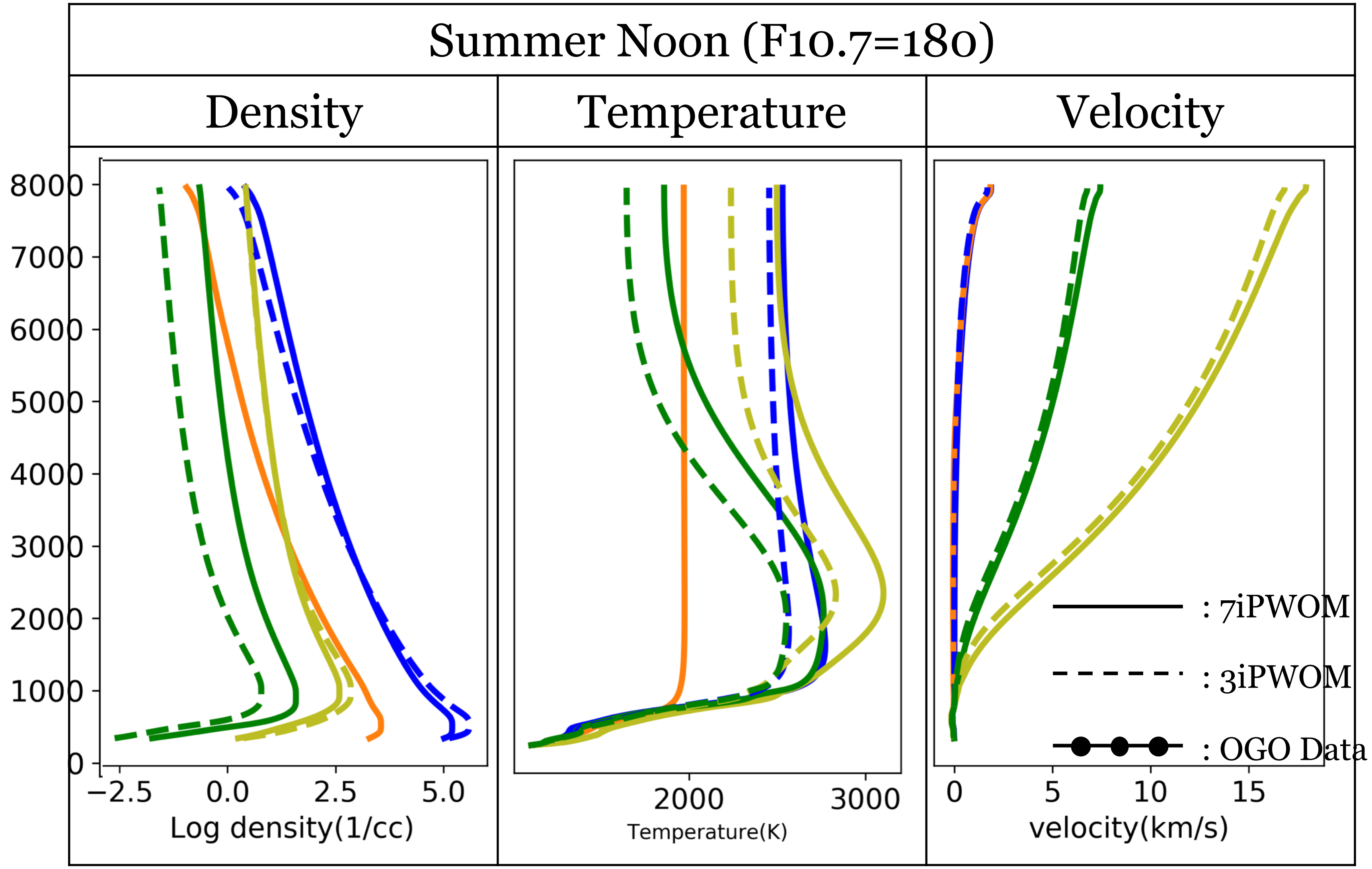


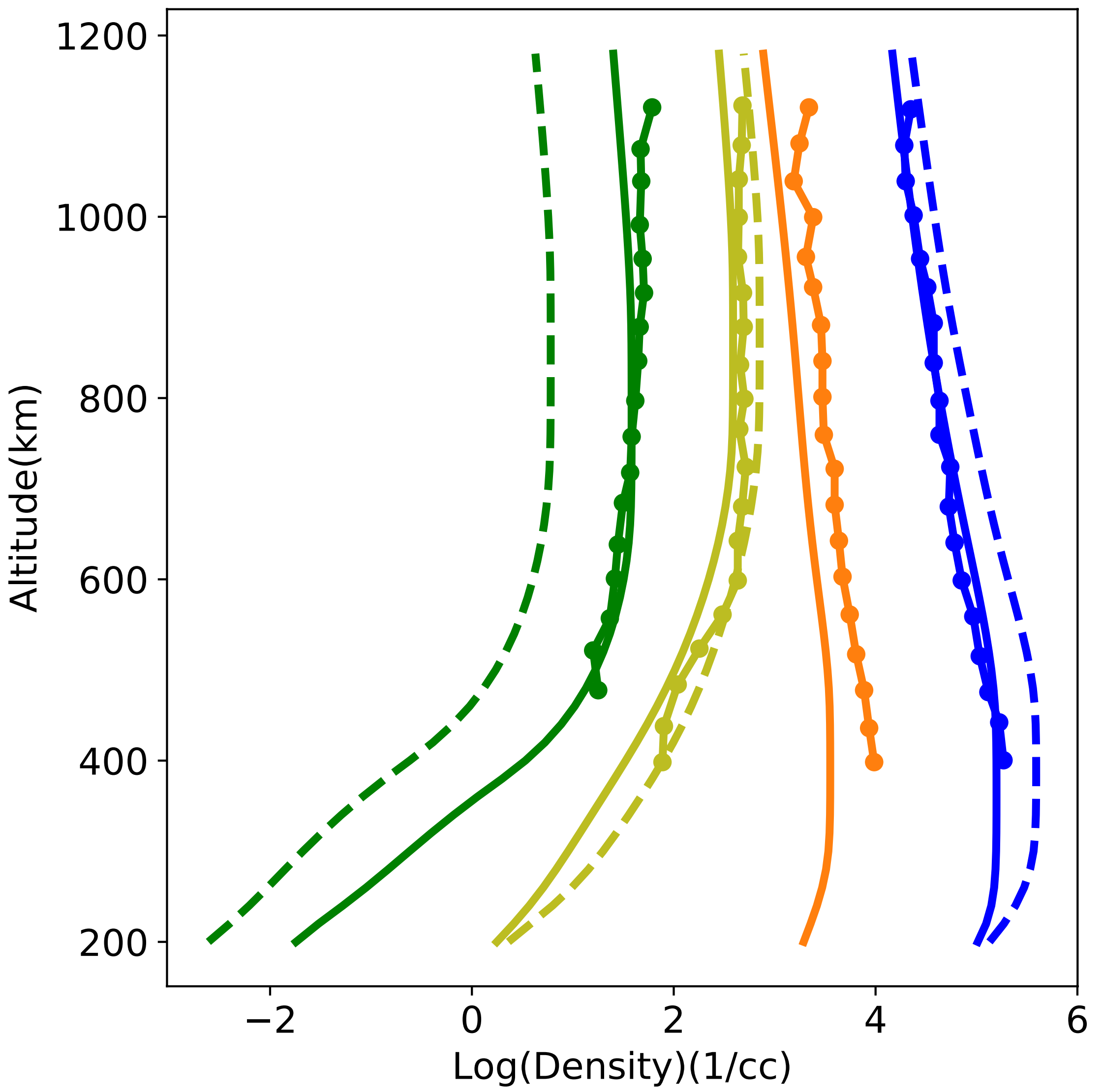




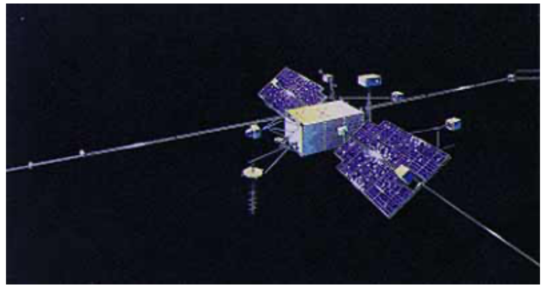
Solar Maximum Summer Noon

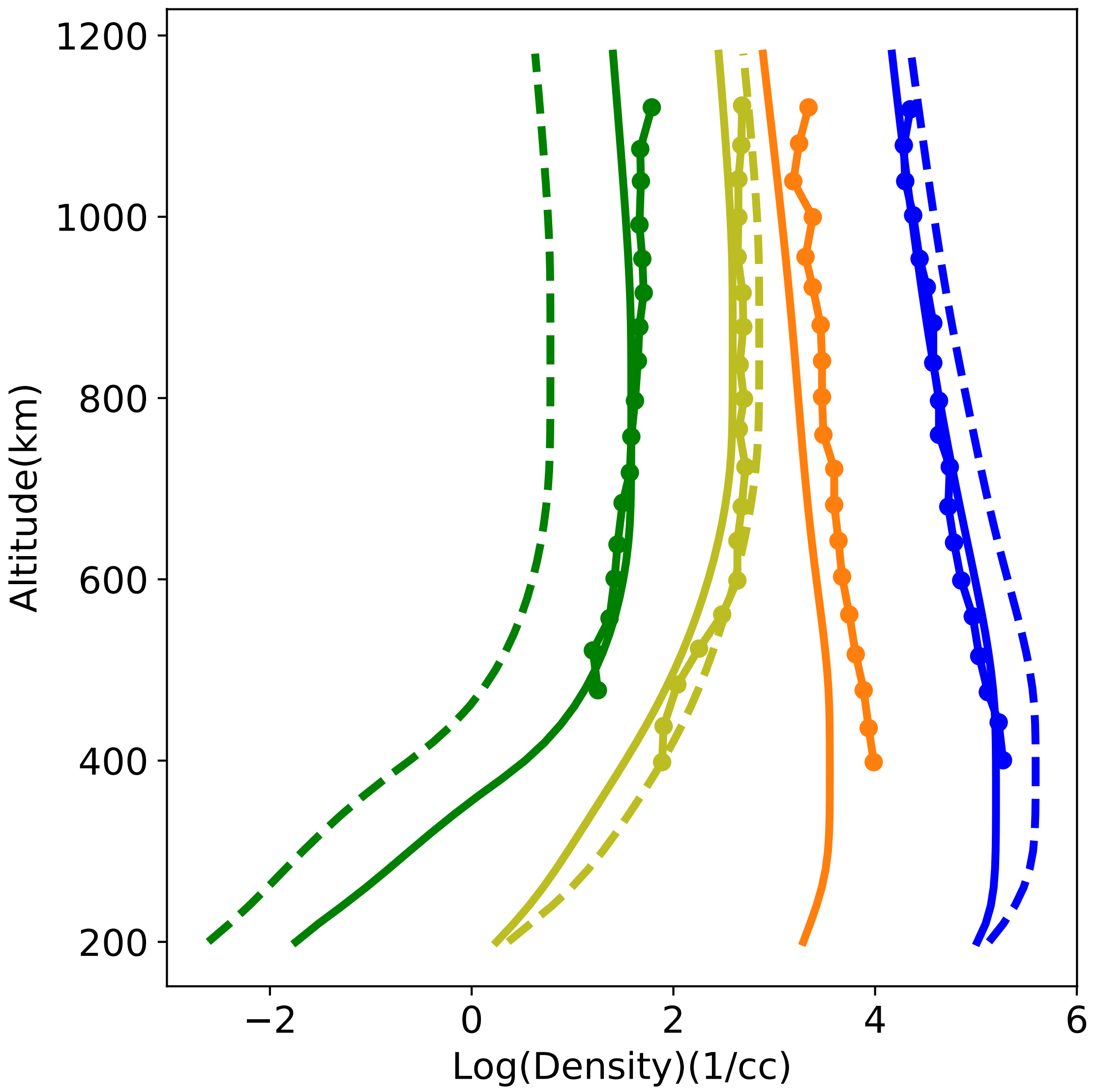






Solar Maximum Summer Noon

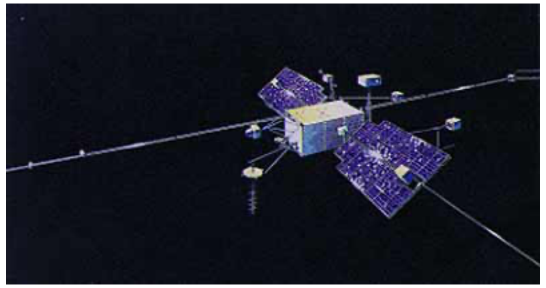


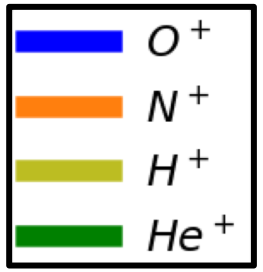


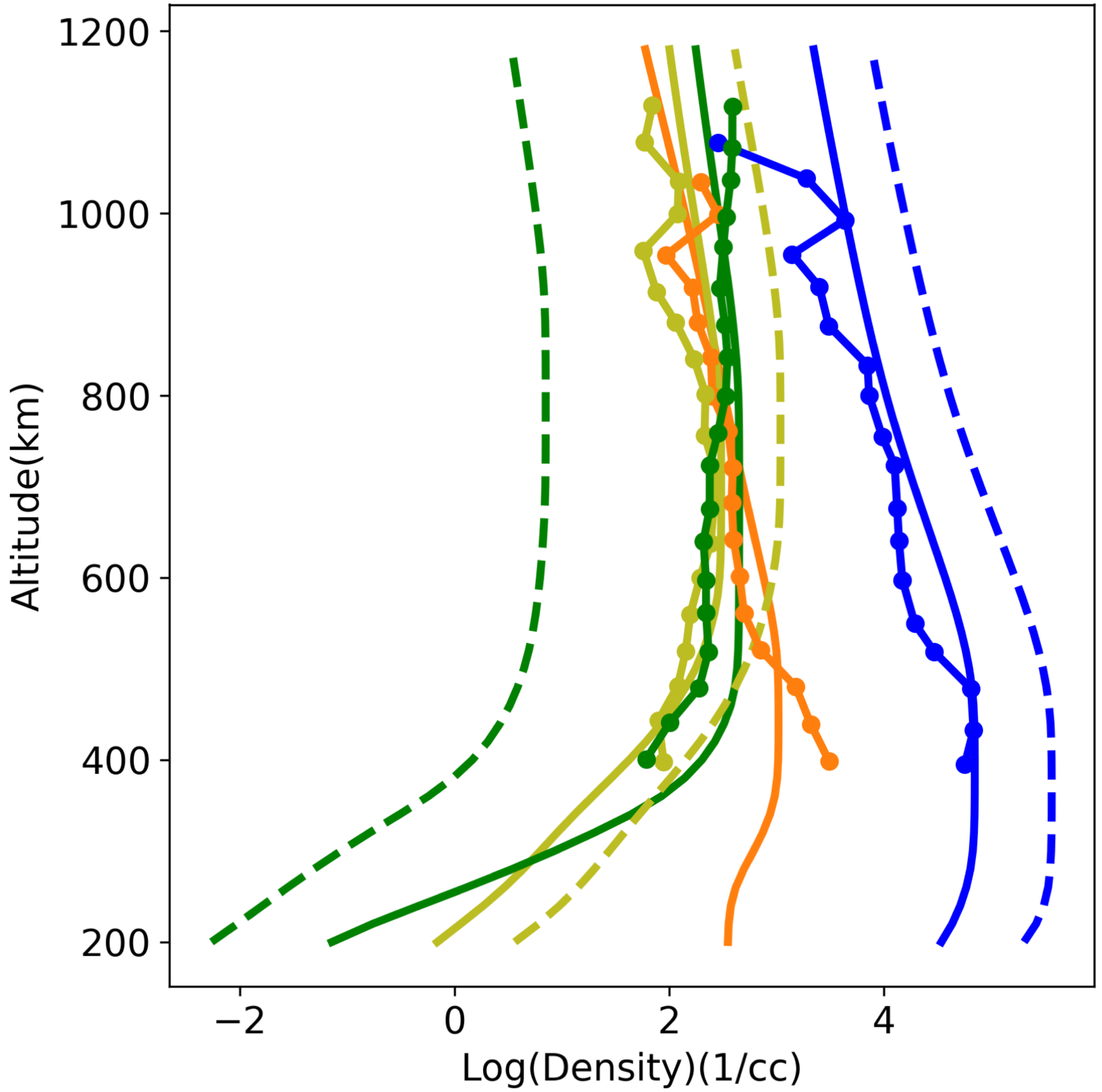
Presence of N^+ and molecular species leads to :

- 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.***

Solar Maximum Winter Noon



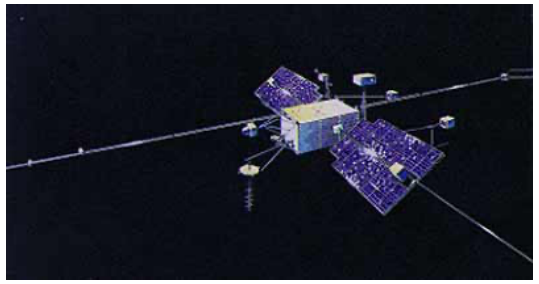
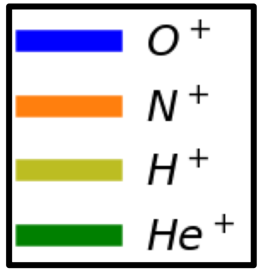


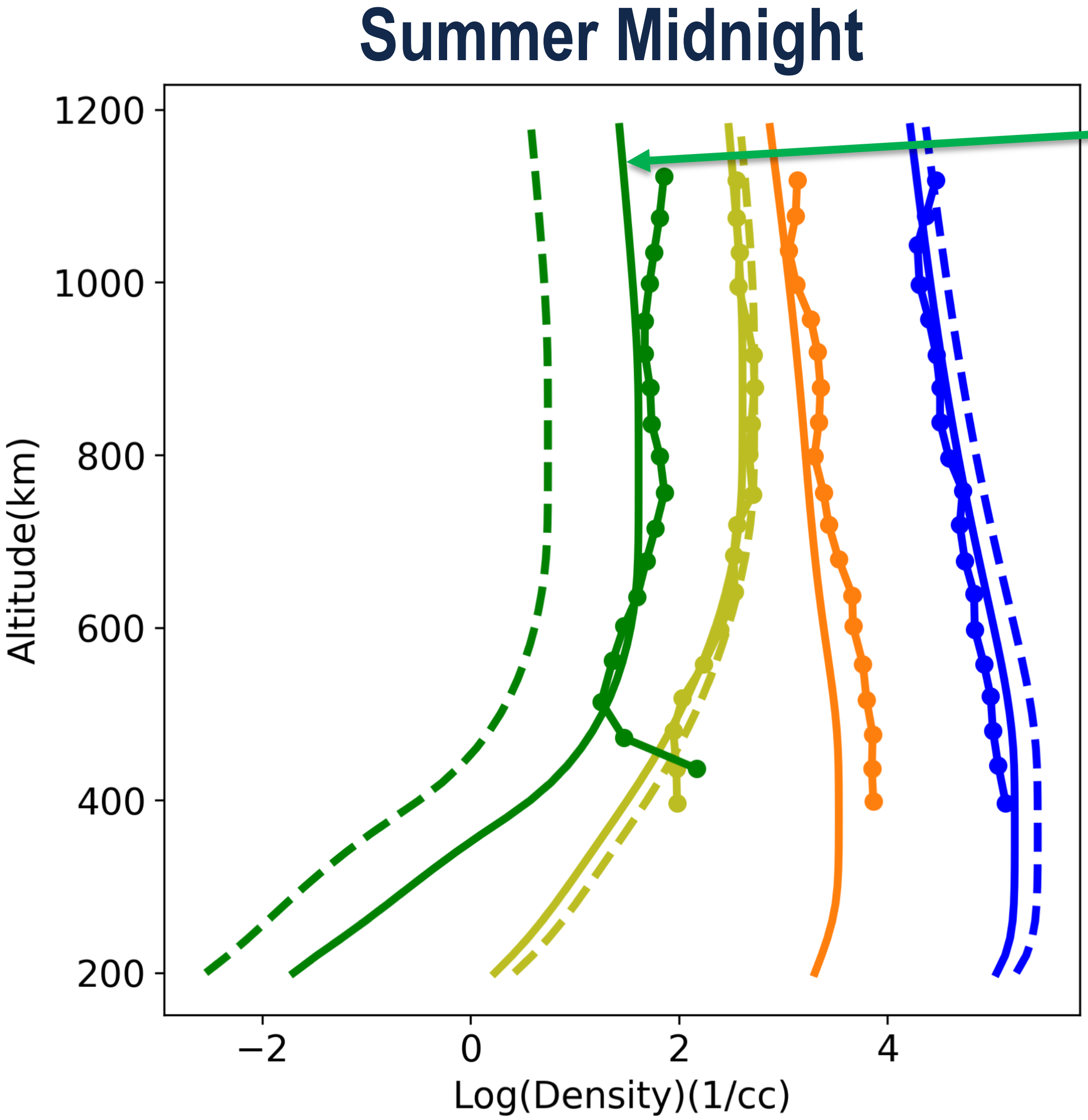


Presence of **N^+** and molecular species leads to :

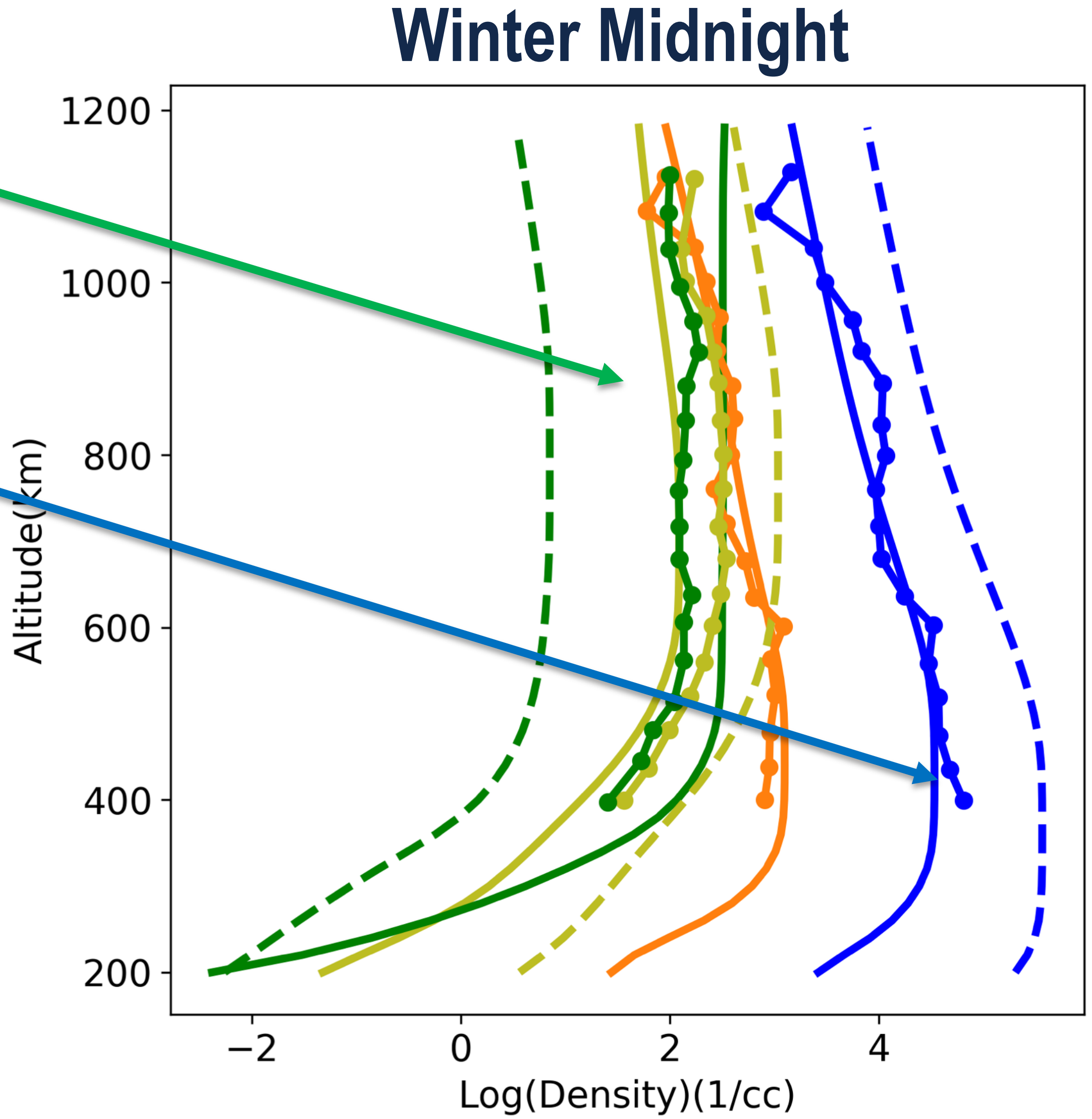
- A significant increase (~2 orders of magnitude) in **He^+** density.
- **H^+** solution improves as compared with measurements
- **O^+** density profile better matches the data, and the density is a factor ~5 larger.
- **N^+** profile matches observations
- ***All species show an increase in temperature/energy.***

Nightside Seasonal Variation

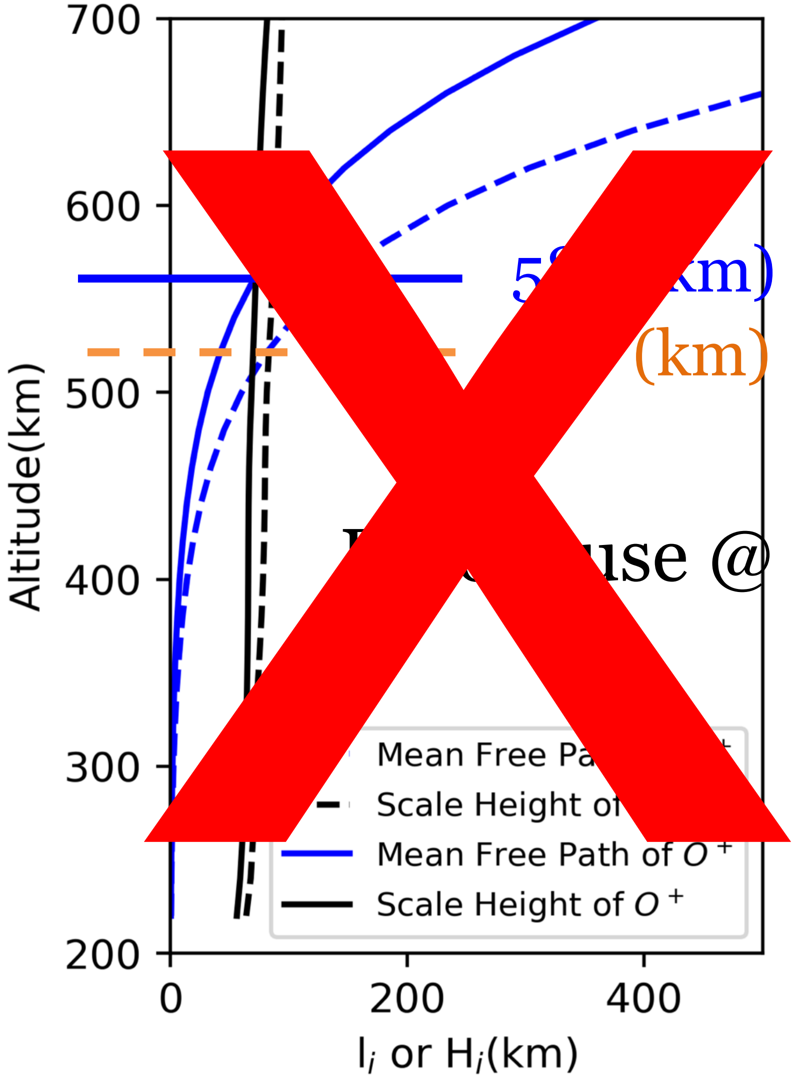





- ~2 orders of magnitude change in **He⁺** density.
- ~1 order of magnitude change in **O⁺** solution
- All species solutions are improved as compared with measurements



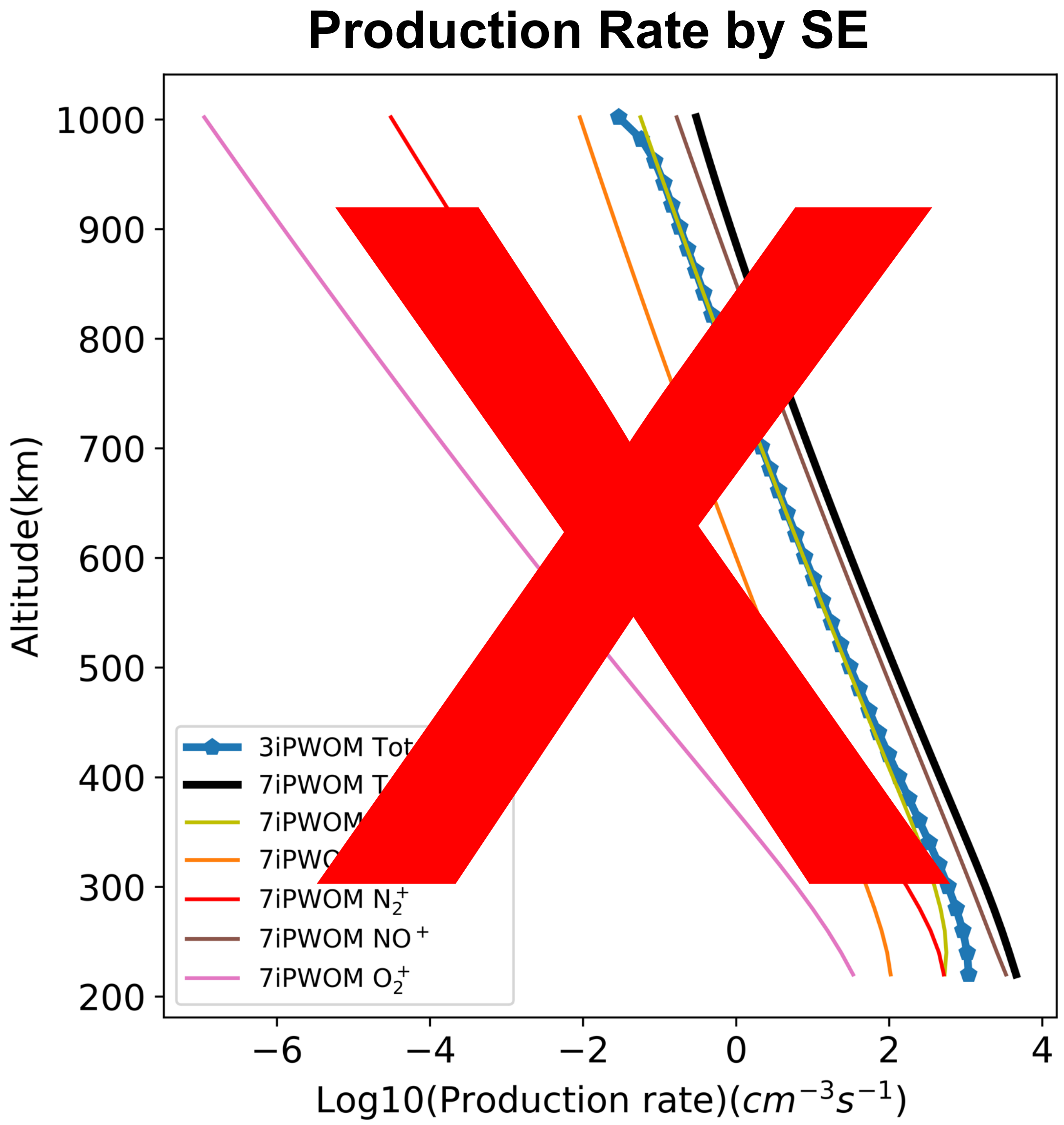
What causes these differences?



$$l_i = (v_i^2 + \frac{3kT_i}{m_i})^{0.5} \nu_{i,j}$$

$$H = \frac{kT_i}{m_i g}$$

use @ l_i = H



What causes these differences?

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^+		
N_2^+		
NO^+		6.2E04
O_2^+		9.7E03
Total number density	**1.17E05**	**1.21E05**

Chemical scheme might explain the differences in density profiles

O^+ decreases by 43%

Total number density doesn't really change

Summary

- **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, etc.**
- 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.