

Refilling the plasmasphere: the role of ring current charge exchange



HELIOPHYSICS RESEARCH AND APPLICATIONS



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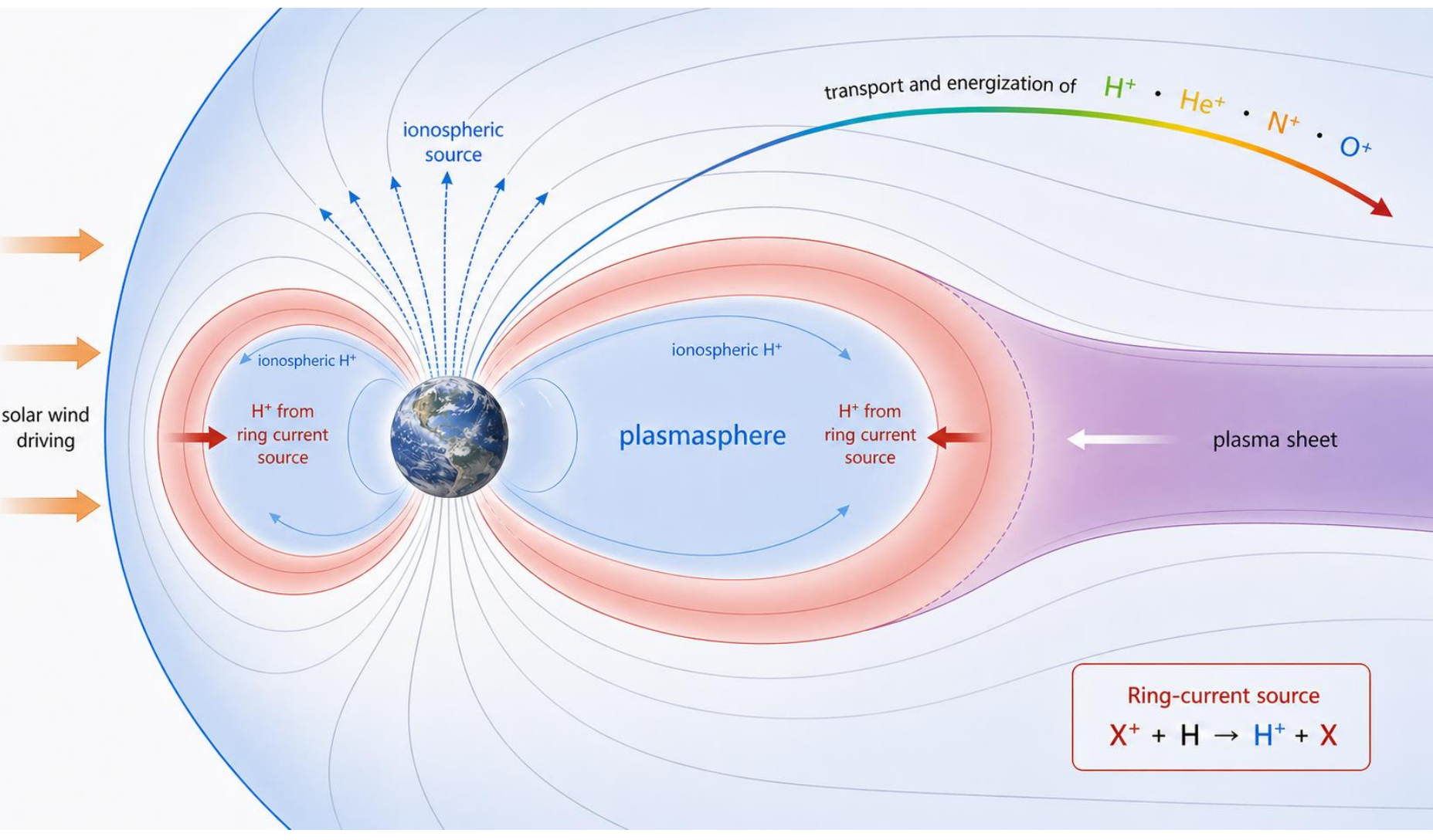
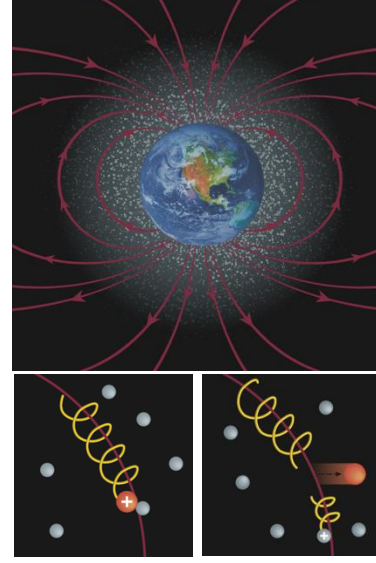
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MAIN FINDING

Ring current charge exchange provides a localized and measurable cold H⁺ source during early plasmaspheric recovery. The contribution is modest relative to the total plasmaspheric reservoir, but it produces structured density enhancements and slightly shifts the plasmapause outward.

1. INTRODUCTION

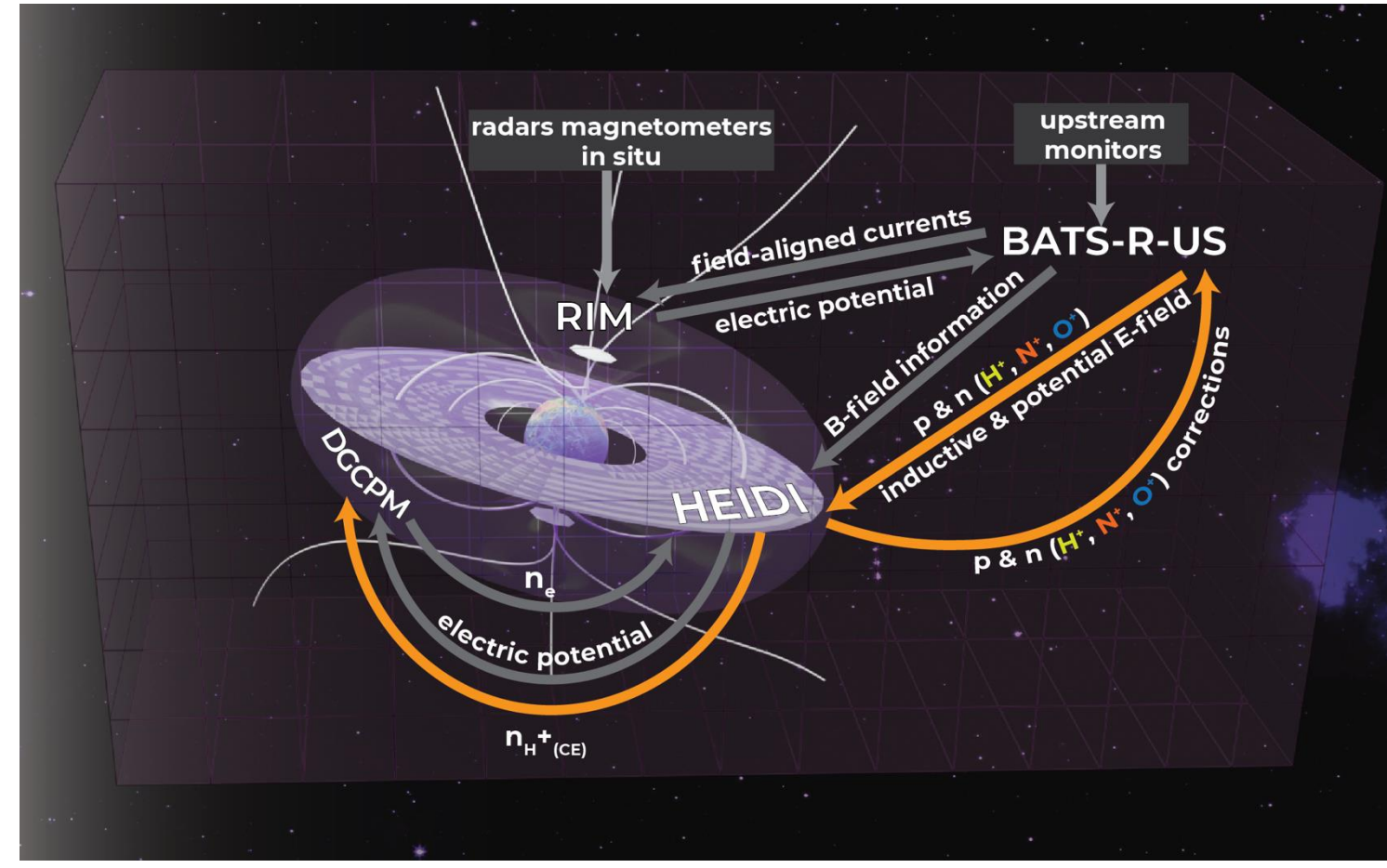
Plasmasphere refilling is usually attributed to ionospheric outflow following storm-time erosion, but modeling descriptions may underestimate the cold plasma content recovered during the early recovery phase (Gallagher et al, 2020) when compared to observations. Recent work has suggested that an additional source of cold H⁺ is its production through charge exchange (CE) between energetic ring current ions and neutral hydrogen in the geocorona (Liu et al, 2022), as illustrated in the figure below.



Conceptual overview of charge-exchange-driven cold H⁺ production. Energetic ring current ions interact with neutral hydrogen in the geocorona, producing cold H⁺ that can contribute to plasmaspheric recovery in addition to standard ionospheric refilling.

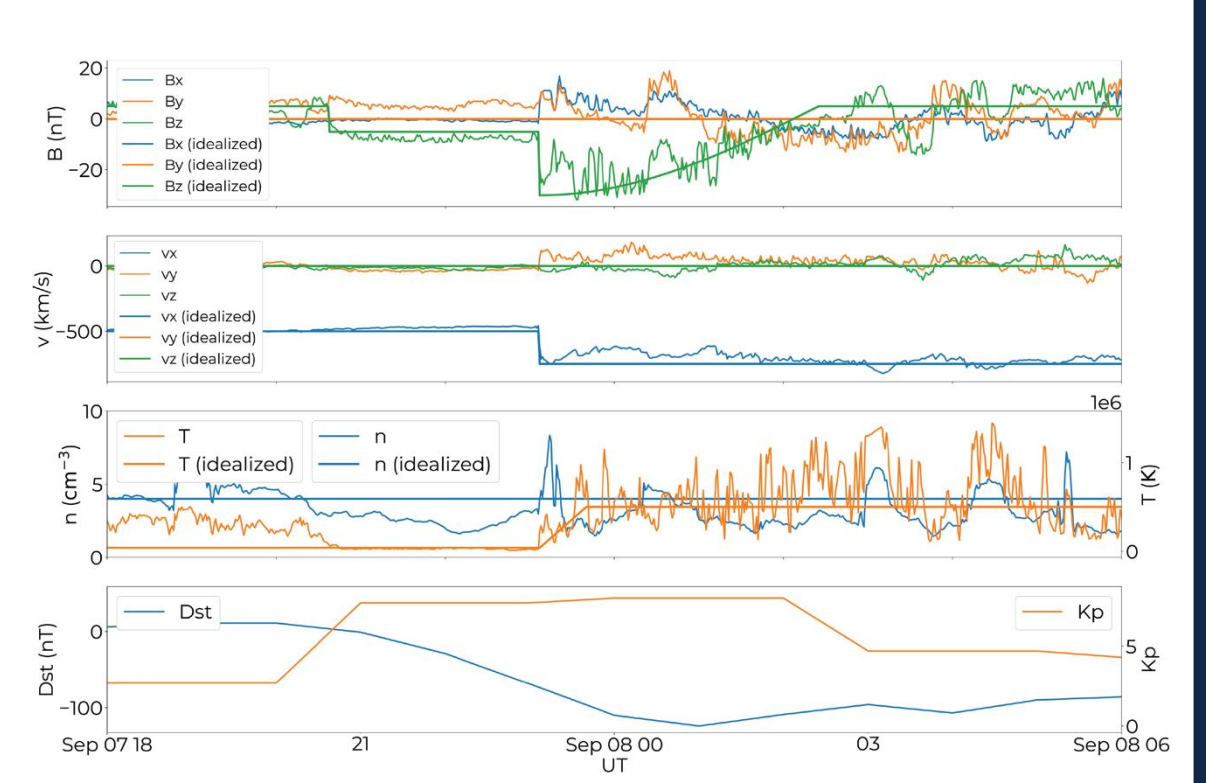
2. METHODOLOGY

- We analyze SWMF simulations coupling BATS-R-US, HEIDI, and DGCPM for two configurations:
- Ionosphere + charge exchange:** includes standard ionospheric refilling and local cold H⁺ production from ring current charge exchange.
- Ionosphere only:** uses standard DGCPM ionospheric refilling and serves as the noCE baseline.
- BATS-R-US provides the global storm-time magnetosphere and multifluid ion populations. HEIDI resolves ring current transport and charge-exchange source terms. DGCPM represents the cold plasmasphere and ionospheric refilling.



3. EVENT AND SIMULATION SETUP

- An idealized version of the **September 7, 2017, storm** was used to drive the simulations for 12 hours.
- To assess composition effects, we varied the imposed heavy-ion composition using five O⁺/N⁺ mixtures: **0%, 20%, 50%, 80%, and 100%**.
- The total heavy-ion density at the inner MHD boundary was kept fixed: $n_{O^+} + n_{N^+} = 30 \text{ cm}^{-3}$
- A CPCP-dependent outflow boundary condition was used to capture storm-time ion fluence variability. The Rairden model was used for the geocoronal H background in all simulations.



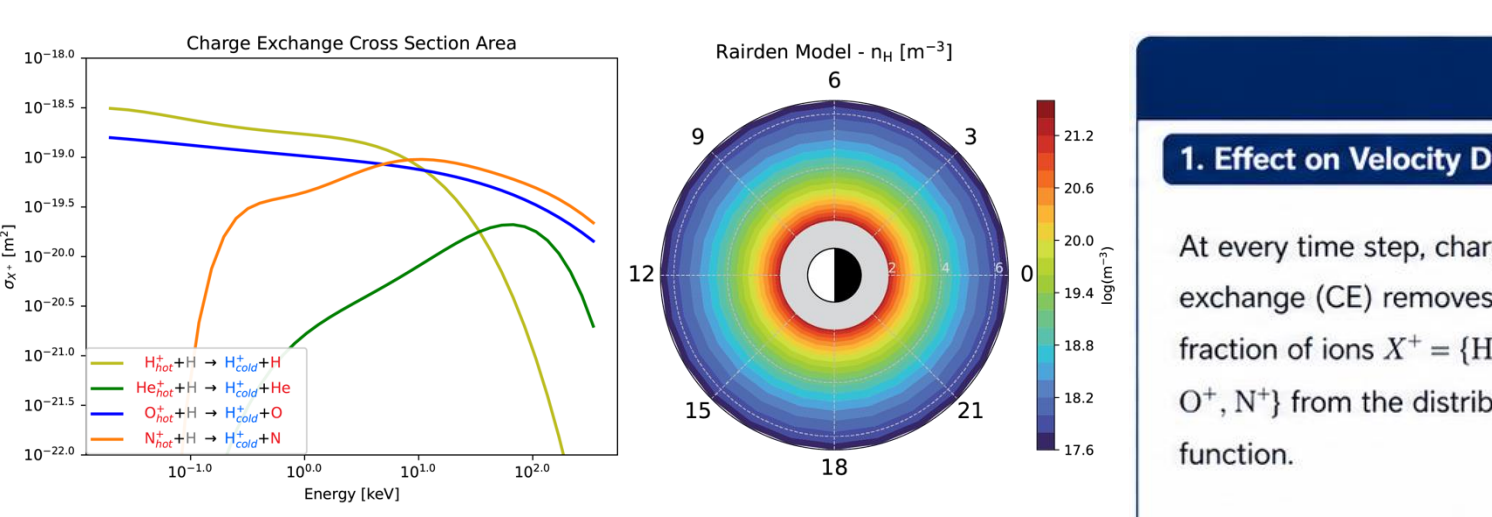
4. PLASMAPAUSE IDENTIFICATION

- At each magnetic local time and time step, we identify the plasmapause using the Carpenter and Anderson (1992) density-drop criterion:

$$\frac{n(L)}{n(L + \Delta L)} \geq 5, \quad \Delta L \leq 0.5$$

- When a sharp density drop is not present, we use a fallback threshold crossing at $n_{H^+} = 100 \text{ cm}^{-3}$. The resulting time-dependent plasmapause boundary is used to isolate the plasmaspheric H⁺ population. Density changes are computed using an overlap-mask approach to reduce apparent variations caused only by plasmapause motion.

5. QUANTIFYING CHARGE EXCHANGE SOURCE



Charge Exchange Loss of Ring Current Ions with Neutral Hydrogen

1. Effect on Velocity Distribution Function

At every time step, charge exchange (CE) removes a fraction of ions $X^+ = \{H^+, He^+, O^+, N^+\}$ from the distribution function.

$F_{X^+(t)}(t, R_0, \phi_0, W, \mu_0) = F_{X^+(t)}(t, R_0, \phi_0, W, \mu_0) \cdot \eta_{X^+(CE)}(R_0, \phi_0, W, \mu_0)$ (6)

2. Local Charge Exchange Loss Factor

The local CE loss factor of ion species X^+ is given by:

$$\eta_{X^+(CE)}(R_0, \phi_0, W, \mu_0) = \exp[-\sigma_{X^+}(W) v_{X^+}(W) (n_H)(R_0, \phi_0, \mu_0) \Delta t]$$
 (7)

$\sigma_{X^+}(W)$: CE cross section between X^+ and neutral H (depends on W)
 $v_{X^+}(W)$: speed of X^+ (depends on W)
 $(n_H)(R_0, \phi_0, \mu_0)$: bounce-averaged neutral H density
 Δt : timestep

3. Physical Picture

Hot (energetic) ring current ion (X^+) + Neutral hydrogen (exosphere) → Charge exchange → X^+ removed (lost from distribution) + Cold H⁺ produced (becomes part of cold plasma population)

Definitions

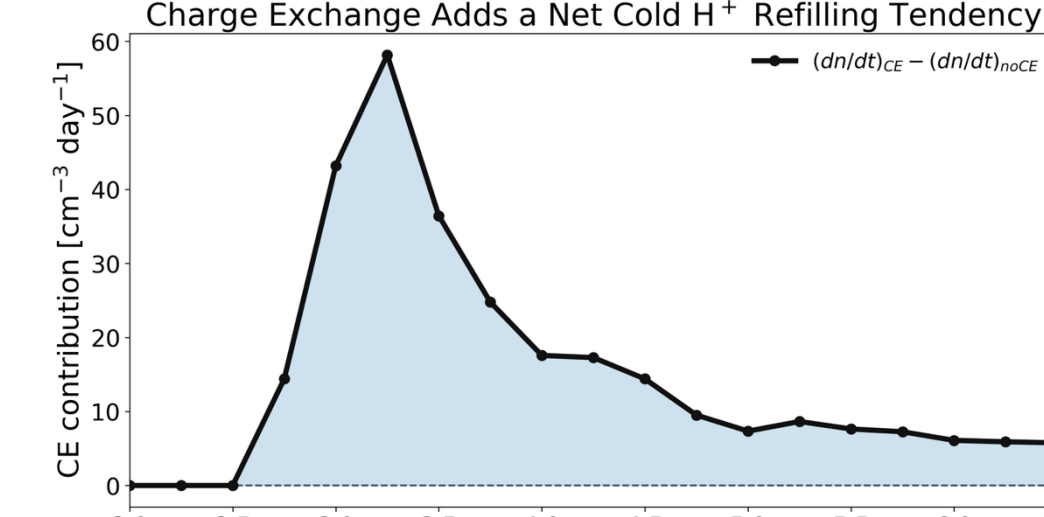
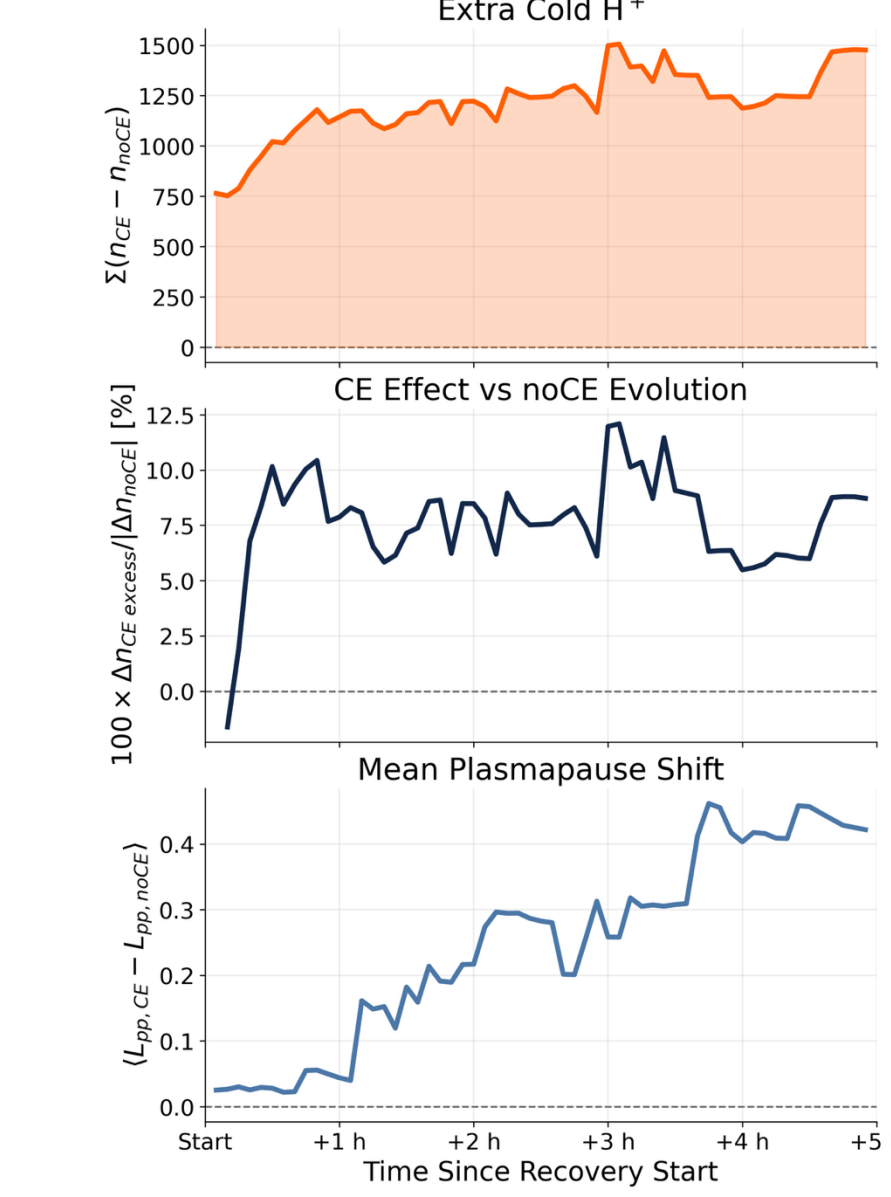
t : time
 R_0 : radial distance
 ϕ_0 : azimuthal angle (MLT)
 W : kinetic energy of parent hot ion
 μ_0 : cosine of pitch angle
 F : velocity distribution function
 X^+ : ion species = $\{H^+, He^+, O^+, N^+\}$
 $\sigma_{X^+}(W)$: CE cross section
 $v_{X^+}(W)$: speed of X^+
 (n_H) : bounce-averaged neutral H density
 Δt : timestep
 $\eta_{X^+(CE)}$: local CE loss factor

Because exosphere models are time independent, $\eta_{X^+(CE)}(R_0, \phi_0, W, \mu_0)$ is constant throughout the simulation.

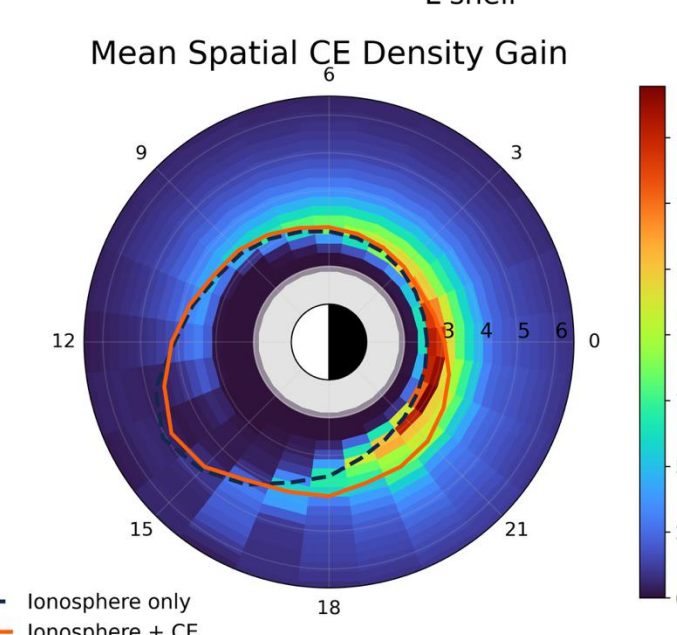
6. CHARGE EXCHANGE SOURCE ADDS COLD H⁺ DURING RECOVERY

- Charge exchange produces a persistent cold H⁺ enhancement relative to the ionosphere-only case. The integrated CE contribution is computed as $\Delta n_{H^+}^{CE} = n_{H^+}^{iono+CE} - n_{H^+}^{iono}$. The normalized enhancement compares this additional cold H⁺ content with the ionosphere-only recovery-time evolution: $\frac{\Delta n_{H^+}^{CE}}{n_{H^+}^{iono}}$. The plasmapause response is measured as: $\Delta L_{pp} = L_{pp}^{iono+CE} - L_{pp}^{iono}$

Integrated Charge-Exchange Contribution During Recovery



Radial structure of the CE-driven enhancement.
The charge exchange contribution is localized in radial distance, with the strongest positive cold H⁺ enhancement near $L \sim 3.25$, where the recovering plasmasphere overlaps the decaying ring current.



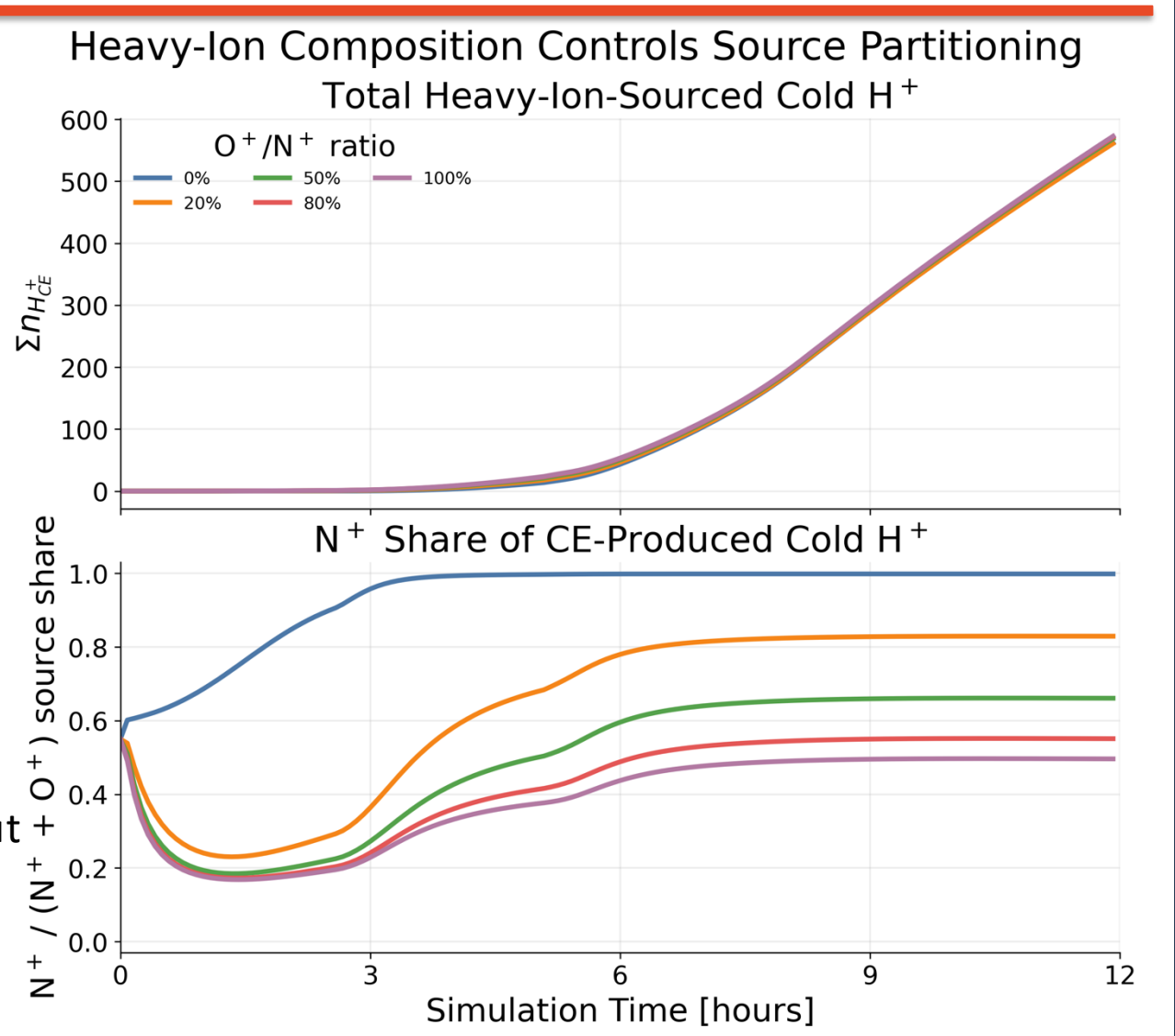
Spatial distribution of the CE density gain.
The time-mean cold H⁺ enhancement is concentrated in localized MLT-L regions, indicating that charge exchange acts as a structured in-situ source rather than a uniform refilling term.

Integrated charge exchange contribution to recovery.

Including charge exchange increases the total cold H⁺ content relative to the ionosphere-only case, produces a measurable recovery-phase enhancement, and slightly shifts the mean plasmapause outward.

7. COMPOSITION DEPENDENCE

- Heavy ion composition controls which parent ion produces the cold H⁺ source.
- Both N⁺ and O⁺ contribute during early recovery, but their relative roles evolve differently in time and space. Changing the O⁺/N⁺ ratio alters the source attribution more strongly than the total cold H⁺ enhancement.
- Overall, composition affects where and from which parent ion cold H⁺ is produced, while the total heavy-ion-sourced contribution remains comparatively weakly affected in this setup.



Effect of heavy ion composition.

Changing the imposed O⁺/N⁺ ratio modifies which parent ion produces cold H⁺, but the total charge-exchange-driven cold H⁺ enhancement remains comparatively similar across the tested compositions.

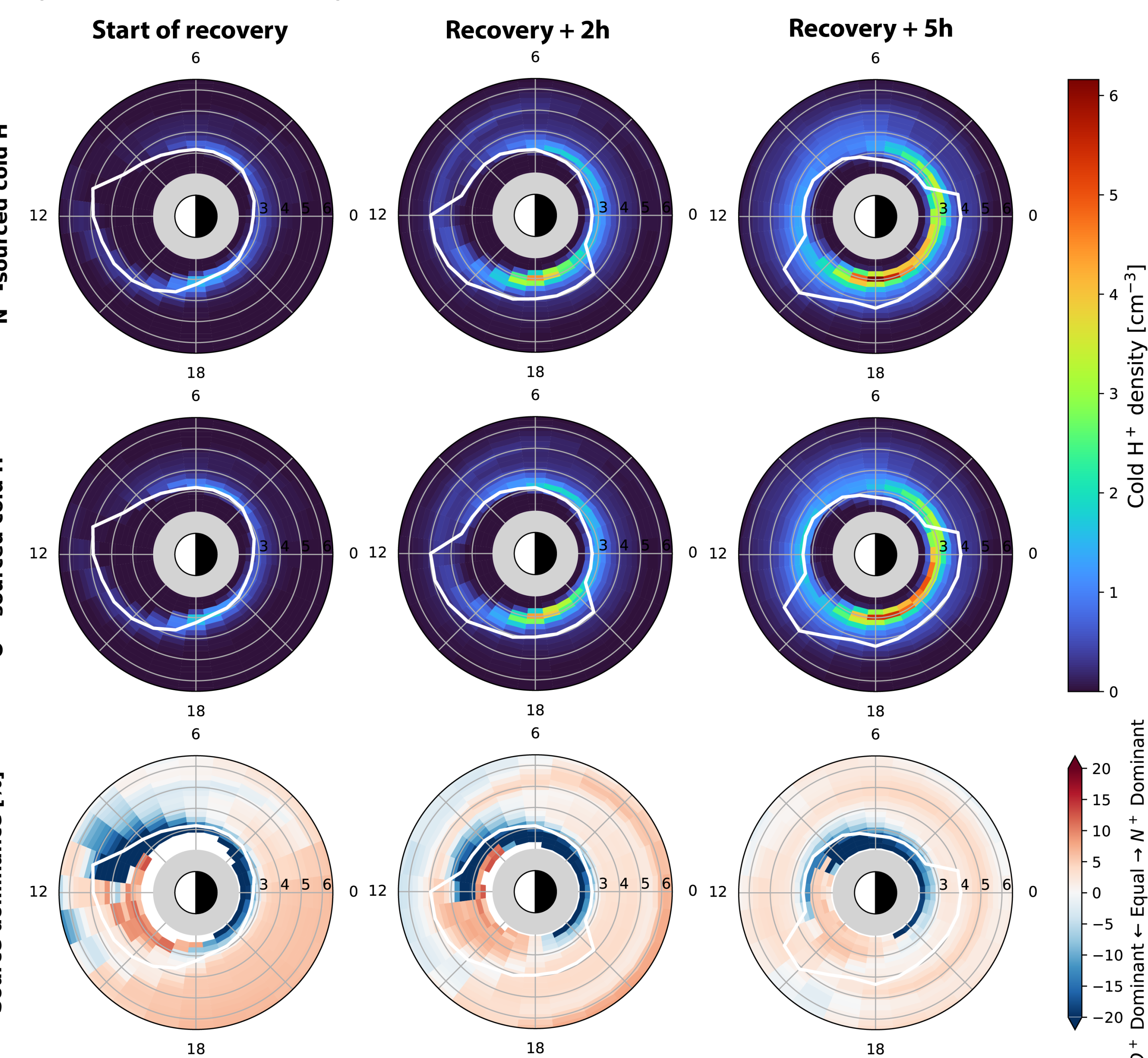
8. SPATIAL EVOLUTION

- The CE-driven cold H⁺ enhancement is not spatially uniform. It is concentrated in localized MLT-L regions where the recovering plasmasphere overlaps the decaying ring current.
- The strongest enhancement occurs near low to moderate L shells, where charge exchange can act as an in-situ source of cold H⁺ during early recovery.

Parent-ion contribution to cold H⁺ production.

Top row: cold H⁺ produced by charge exchange involving N⁺ parent ions. Middle row: cold H⁺ produced by charge exchange involving O⁺ parent ions. Bottom row: source dominance, shown as the N⁺-sourced fraction relative to an equal 50/50 split. Positive values indicate N⁺-dominated production, while negative values indicate O⁺-dominated production.

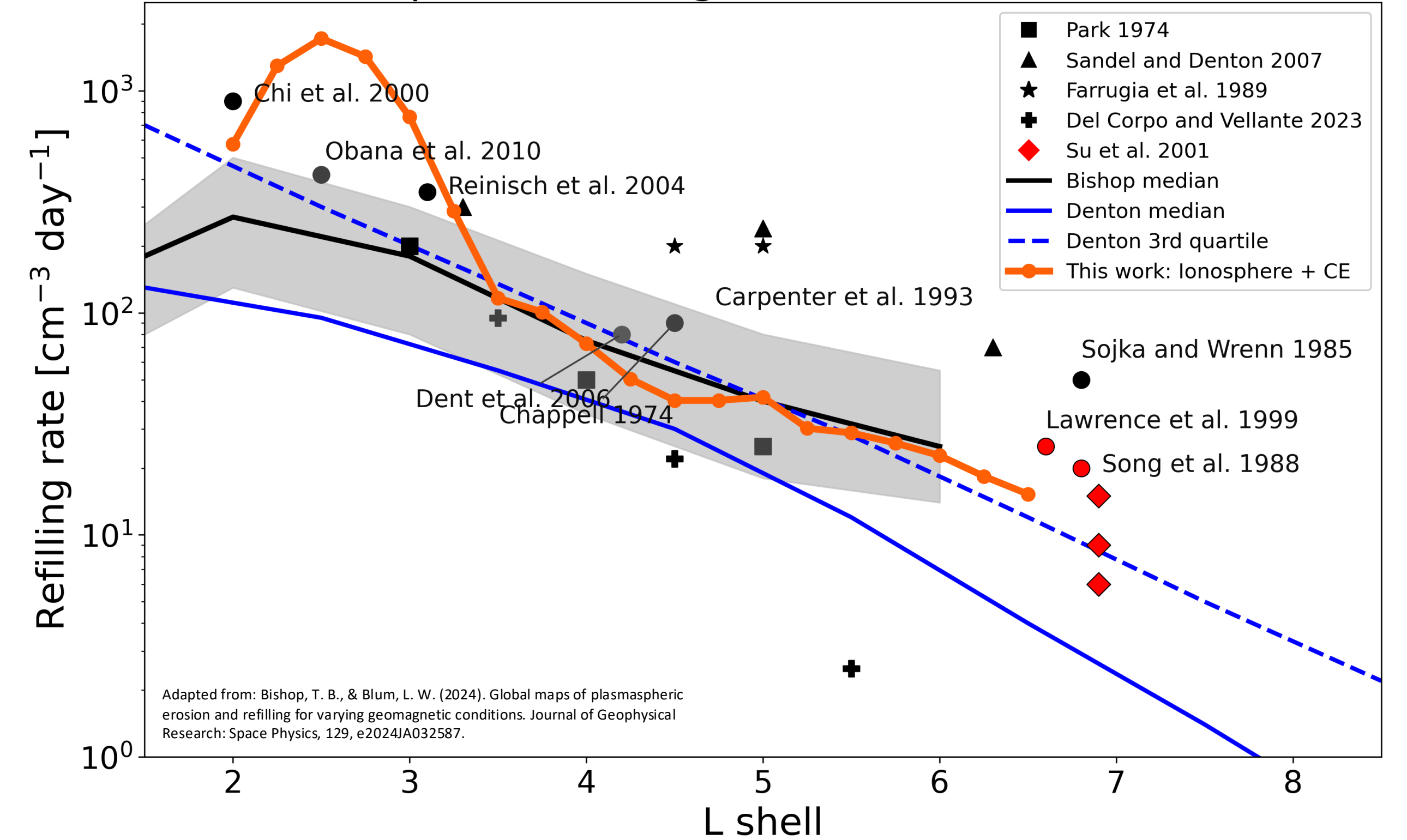
Spatial Evolution of Species-Resolved Sources of CE-Produced Cold H⁺



9. REFILLING CONTEXT

- We compare simulated recovery phase refilling rates with published observational and empirical estimates.
- The literature range is broad because refilling depends on geomagnetic activity, local time, L shell, and the method used to identify the recovering plasmasphere.
- The ionosphere + CE simulation remains broadly consistent with published refilling rate estimates across much of the inner magnetosphere. This comparison is a consistency check, not an event-specific validation.

Plasmaspheric Refilling Rates in Literature Context



Comparison with published refilling estimates.

Simulated recovery phase refilling rates remain within the broad observational range over much of the inner magnetosphere. The ionosphere + CE case shows enhanced refilling at low to moderate L, where charge exchange provides an additional cold H⁺ source.

10. SUMMARY

- Coupled BATS-R-US-HEIDI-DGCPM simulations capture both ionospheric refilling and local cold H⁺ production from ring current charge exchange.
- Charge exchange adds a measurable but modest cold H⁺ source during early recovery.
- The CE-driven enhancement is spatially structured and concentrated where the recovering plasmasphere overlaps the decaying ring current.
- Including CE produces a small outward shift of the mean plasmapause.
- O⁺/N⁺ composition controls parent-ion attribution more strongly than the total cold H⁺ enhancement.
- Simulated refilling rates fall within the broad observational range, but longer recovery intervals are needed for event-specific validation.

ACKNOWLEDGMENTS

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