Erosion of Earth's atmosphere by ion escape: observations, a consistent model, and implications to the atmospheric evolution

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Key Point

(1) ***Slapak et al*. (Ann. Geo. 2017):** O^+ Loss Rate from the Earth for $Kp < 7$:

$F_{loss} \propto \exp(0.45*Kp) \Rightarrow \int F_{loss} \approx 10^{18}$ kg ≈ atmospheric O_2

(2) ***Yamauchi and Slapak*** **(Ann. Geo. 2018):**

(a) Mass loading of these O^+ extracts solar wind kinetic energy:

$\Delta E \propto (m_O/m_H) \cdot (n_O/n_H) \sim$ substantial

$\propto F_{loss} \cdot v_{SW}^2$

where F_{loss} is the total O^+ flux into the solar wind.

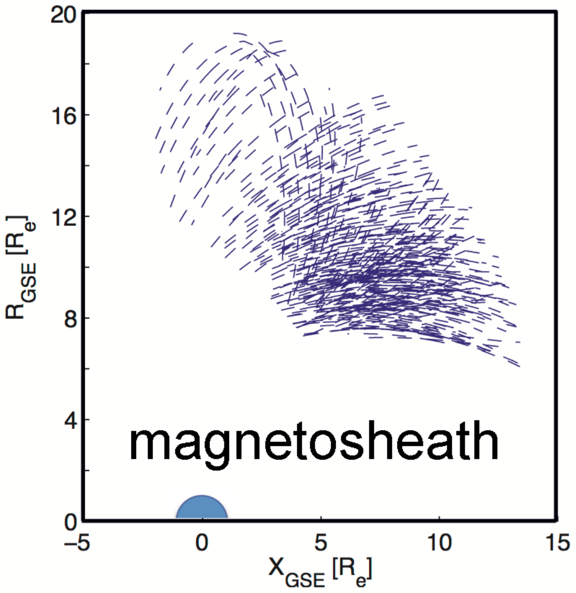
(b) Positive feedback between ΔE into the ionosphere and O^+ energization by ΔE ⇒ non-linear Kp dependence

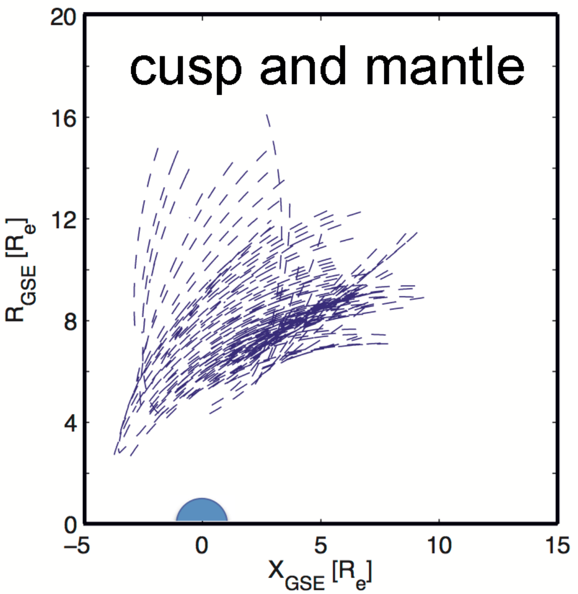
(3) ***Schillings et al*. (Ann. Geo. 2017):** For large $Kp \geq 7+$ (ancient condition) :

F_{loss} (and ΔE) >> prediction by $\exp(0.45*Kp)$

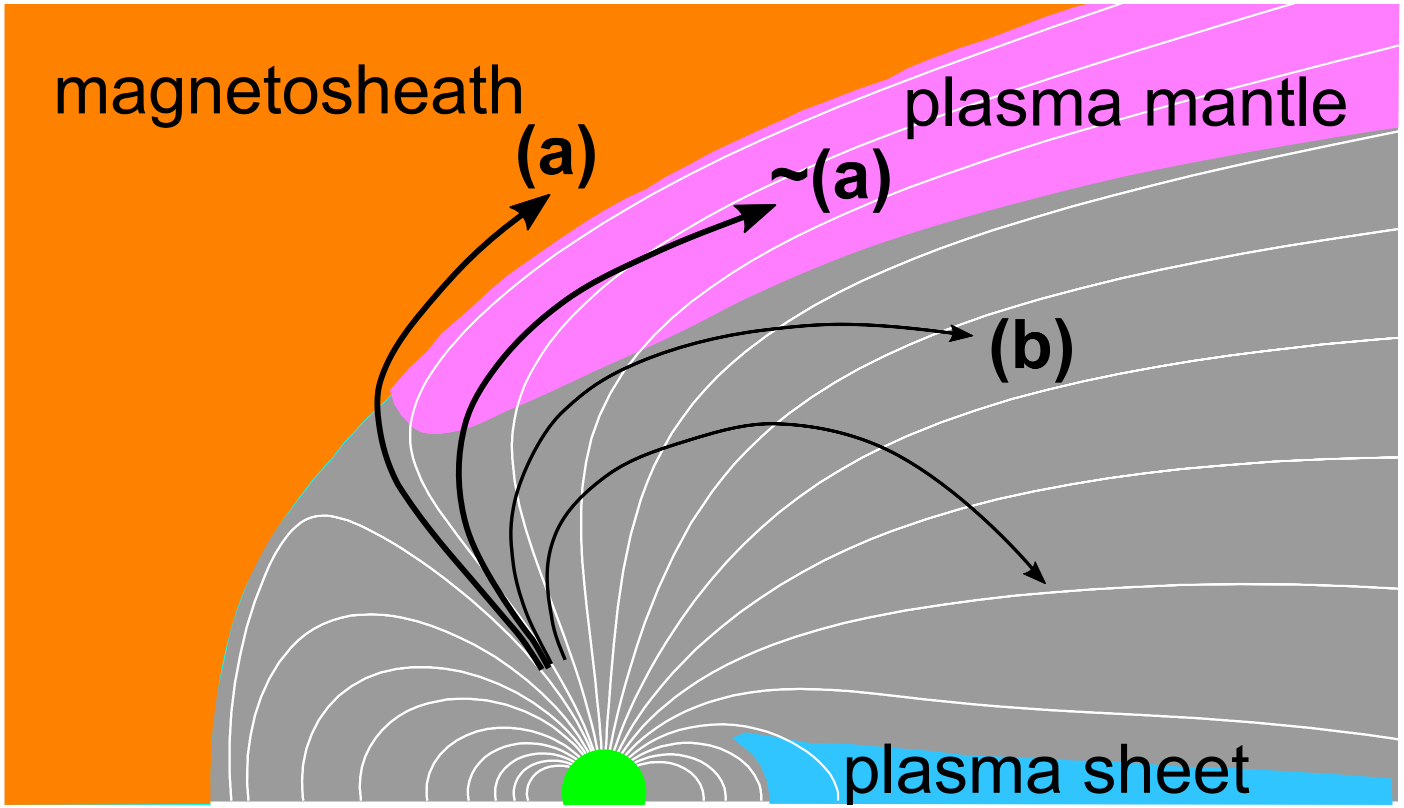
⇒ **O^+ escape can no longer be ignored in the evolution of the atmosphere**

(1) O^+ escape vs. Kp: Cluster/CIS





Cluster could distinguish
(a) loss to the space
(b) flowing into the magnetotail



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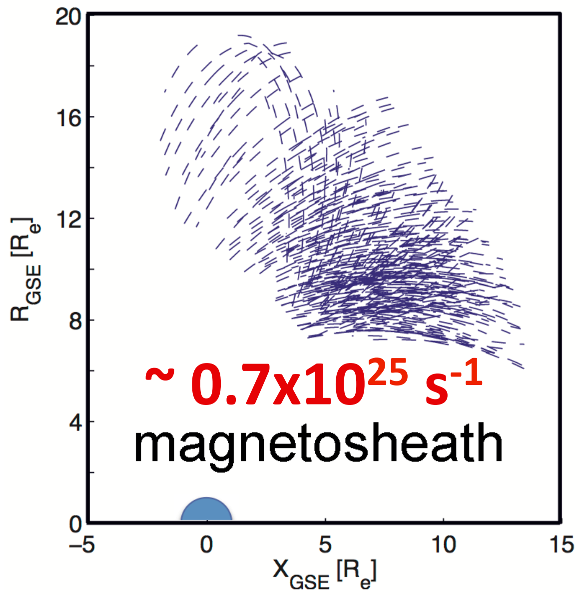
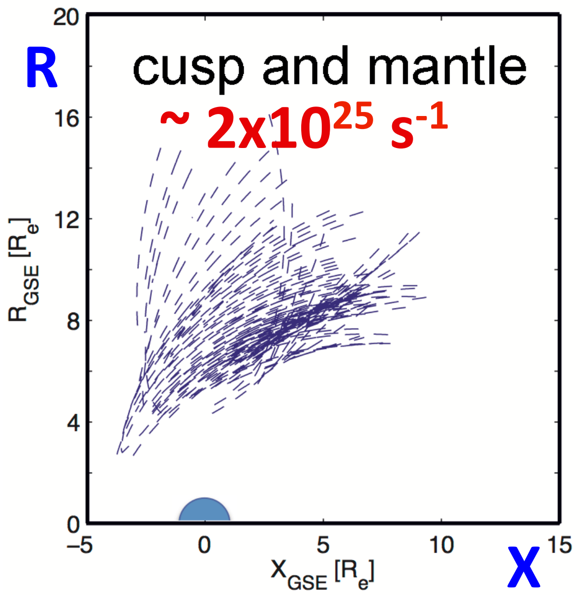
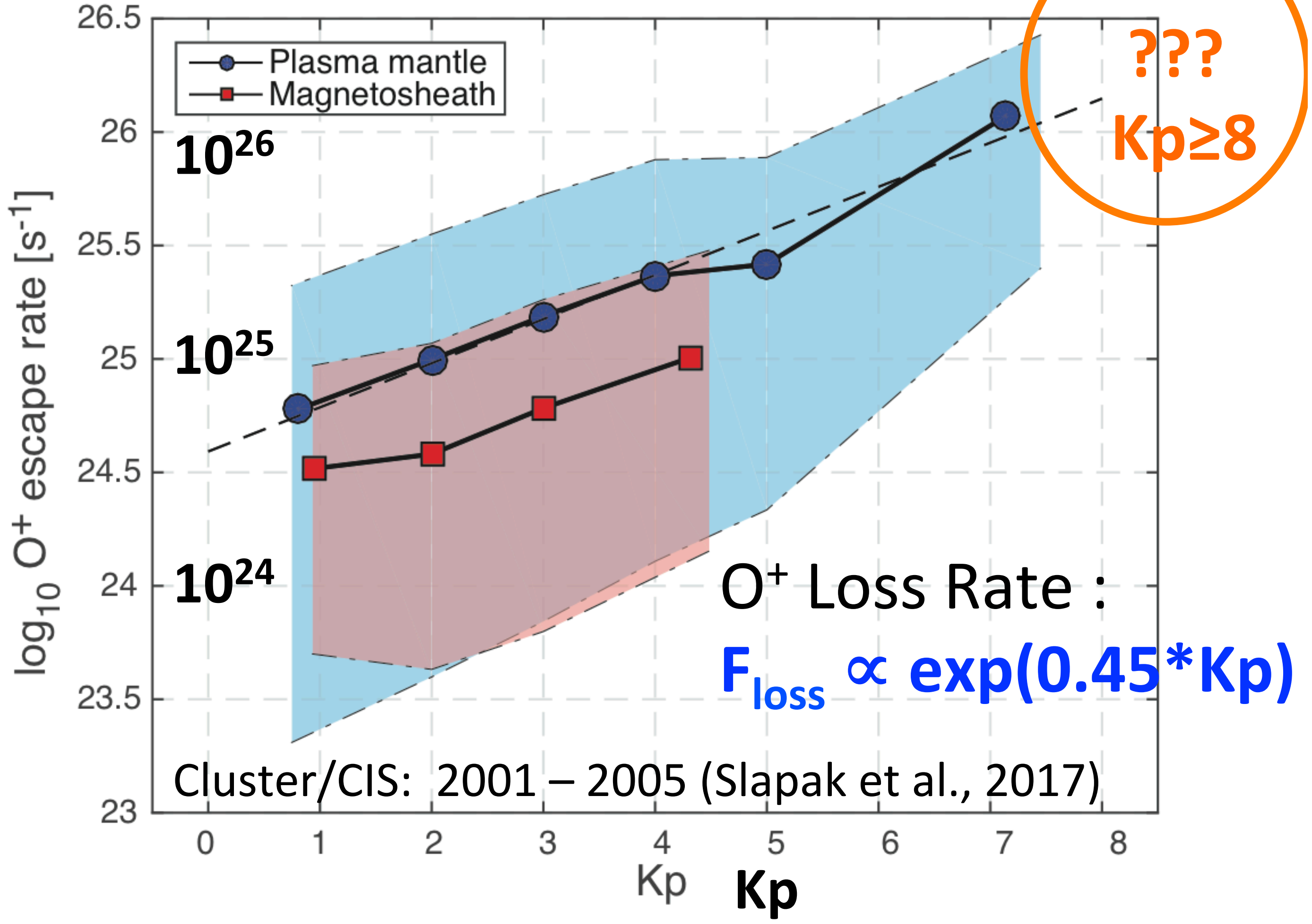
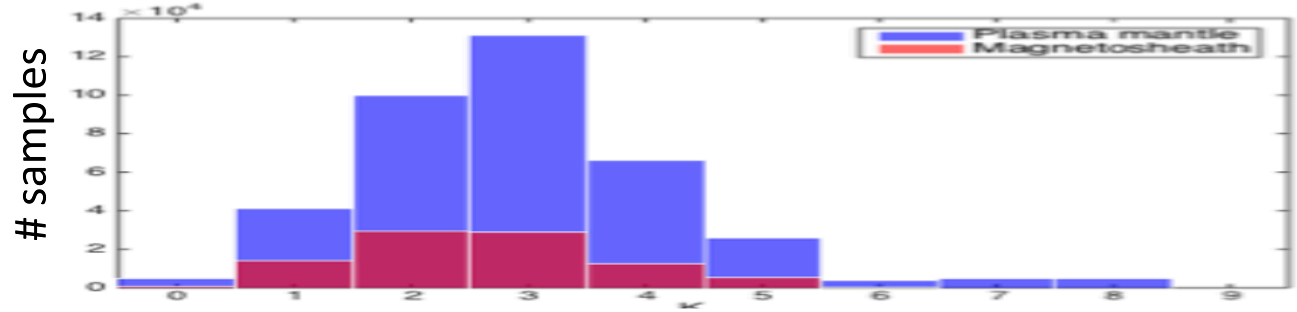
Cluster/CIS hot O^+ obs. of direct escape

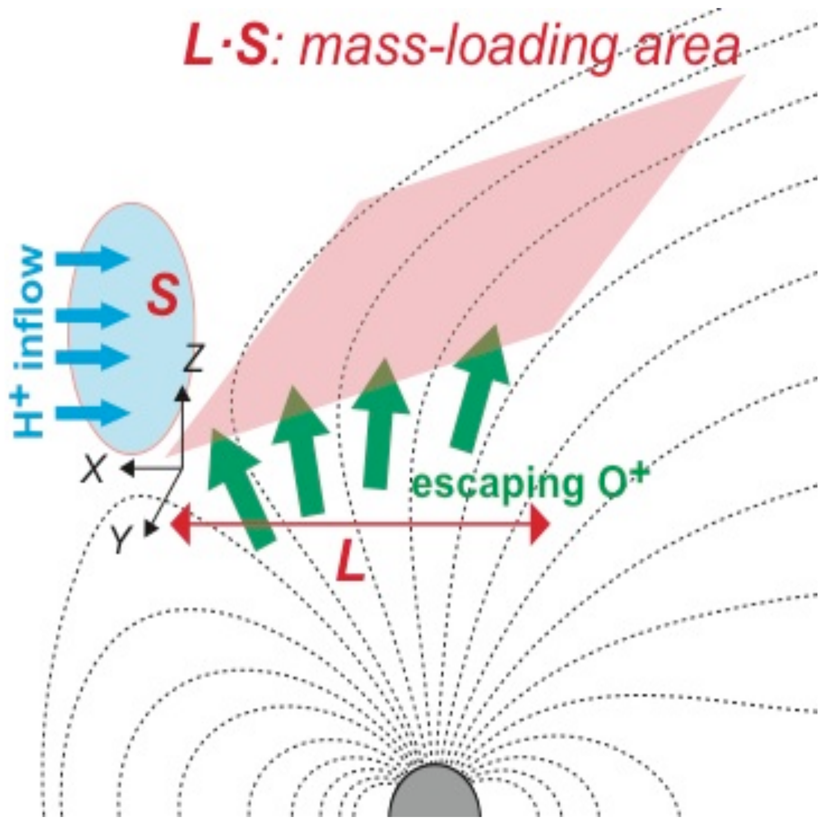


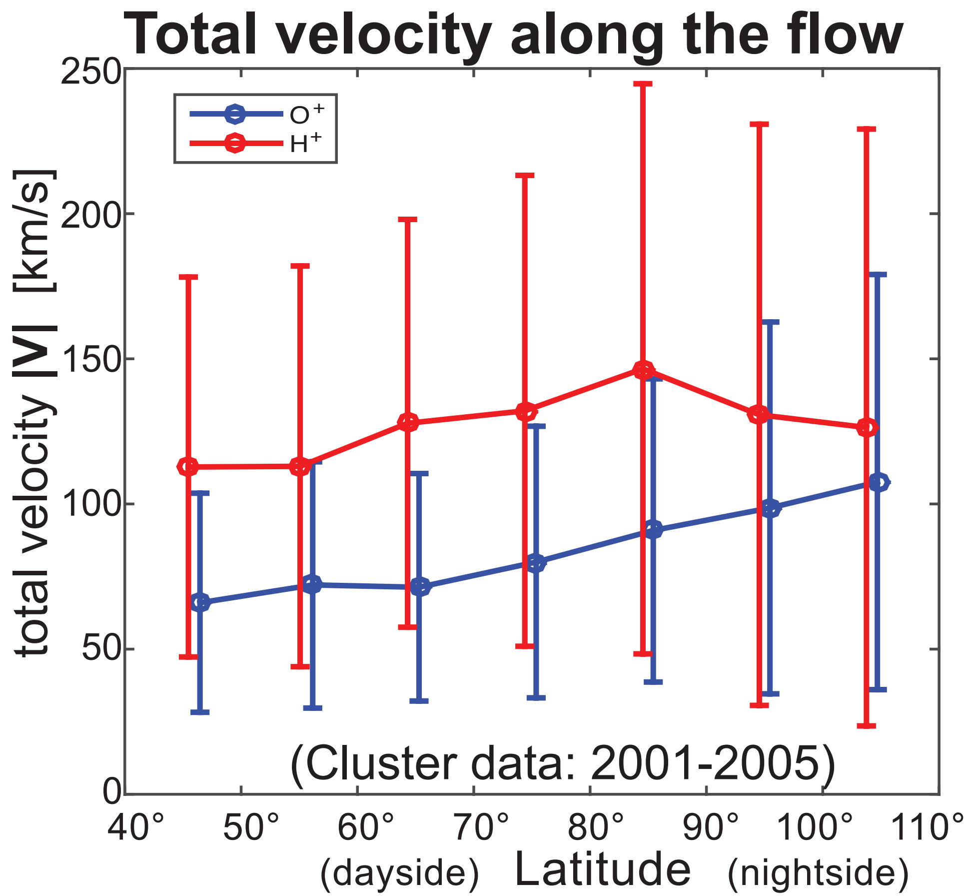






(2) Feedback from escaping ions





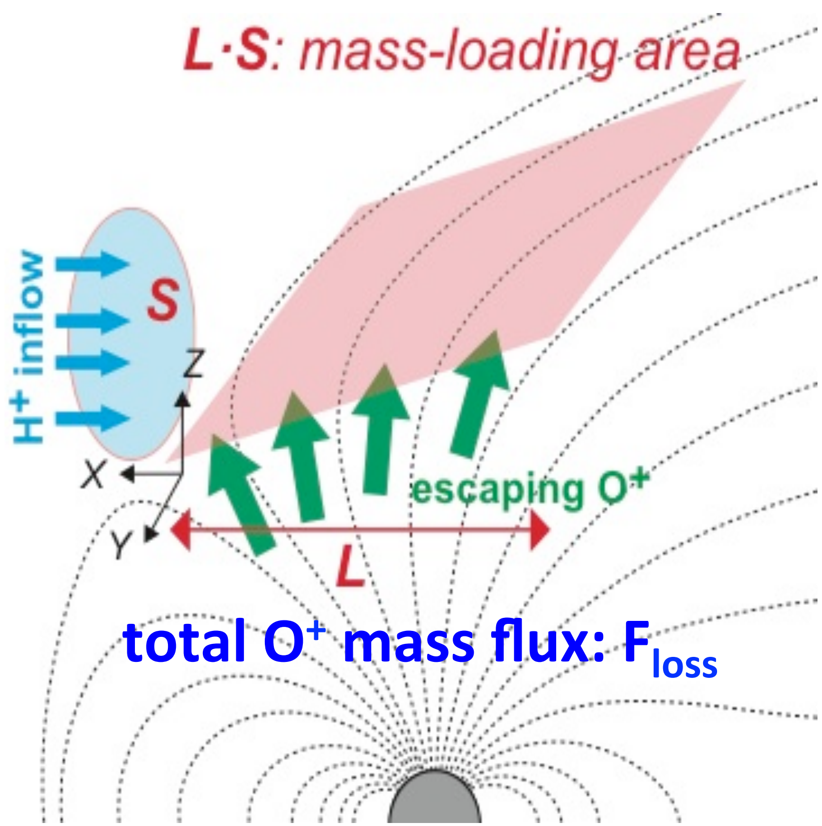
V_{O+} increases while V_{H+} decreases

⇒ Mass loading

⇒ inelastic momentum conservation

⇒ **Extraction of kinetic energy**

(2a) Energy extraction by O^+ mass-loading ≠ 0



(1) Momentum conservation in the –x direction:

$\Delta P = (\rho+d\rho)\cdot(v+dv)^2 - \rho u^2 = 0$

and dF_{loss} (O^+ supply from –z) plays as dρ

$\Rightarrow \quad d\rho/\rho \approx (dF_{loss}/dx)\cdot dx/\rho v\cdot S$

(2) "inelastic" mixing means

$\Delta E = (\rho+d\rho)\cdot(v+dv)^3/2 - \rho u^3/2 < 0$

$\Rightarrow$ ΔE (extracted energy) $\approx F_{loss}\cdot v_{SW}{}^2/4$

(3) Amount is substantial:

n_{O+}/n_{SW}~0.01 $\Rightarrow$ ρ_{O+}/ρ_{SW}~0.16

$\Rightarrow$ extract 7% of kinetic energy E

$\Rightarrow$ $\Delta E \approx 10^{9\text{-}10}$ W to $J_{//}$ through B

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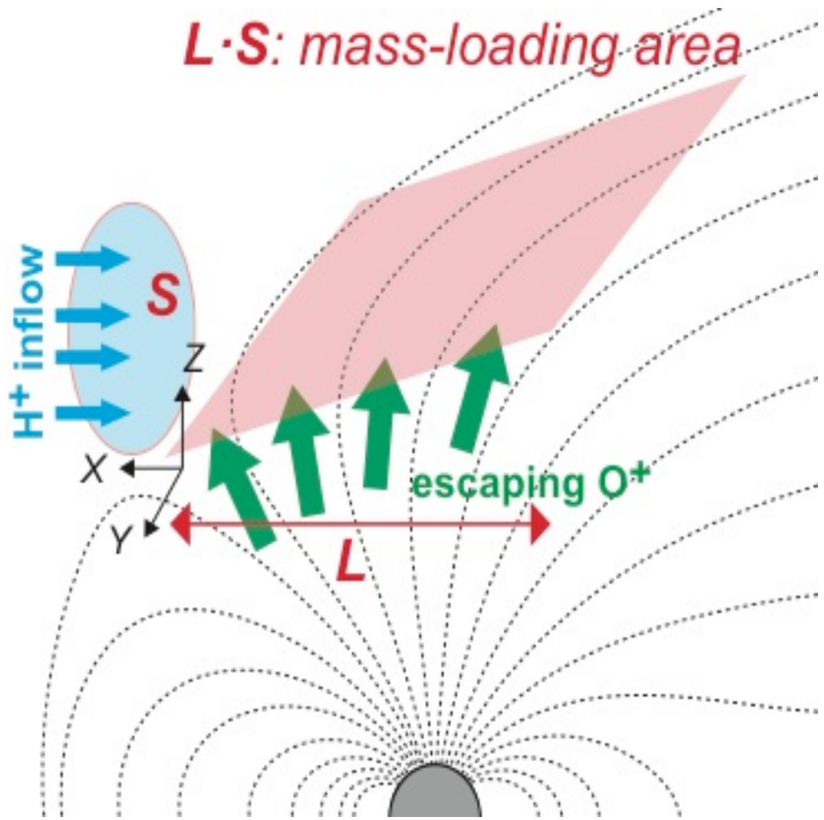
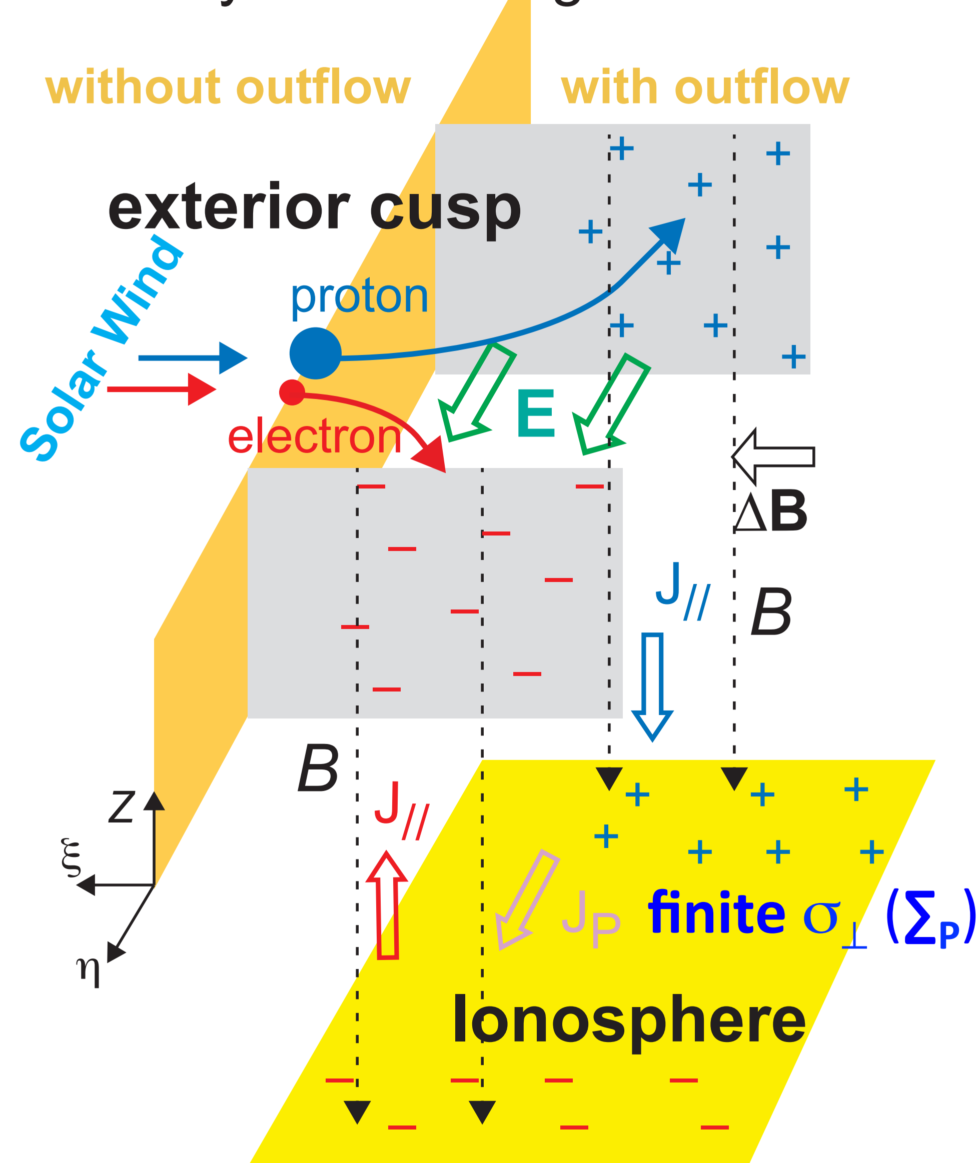
If "ionosphere" is connected to mass-loading region



MHD dynamo during deceleration



If $\Sigma_P = \infty$, charges are canceled & $E = 0$

If $\Sigma_P = 0$, charges cause $E = -UxB$

If Σ_P = finite, E = finite & $I_P \cdot \Sigma_P$ = finite $\propto \Delta E$

(2b) Combine with feedback to ion escape

Energy to ionosphere by mass-load:

$\Delta E \propto F_{loss} \cdot v_{SW}^2$

Assume **escape ∝ energy loss in the ionosphere**: $F_{loss} \propto \Delta E$

⇒ **Positive feedback !**

Add two empirical relations

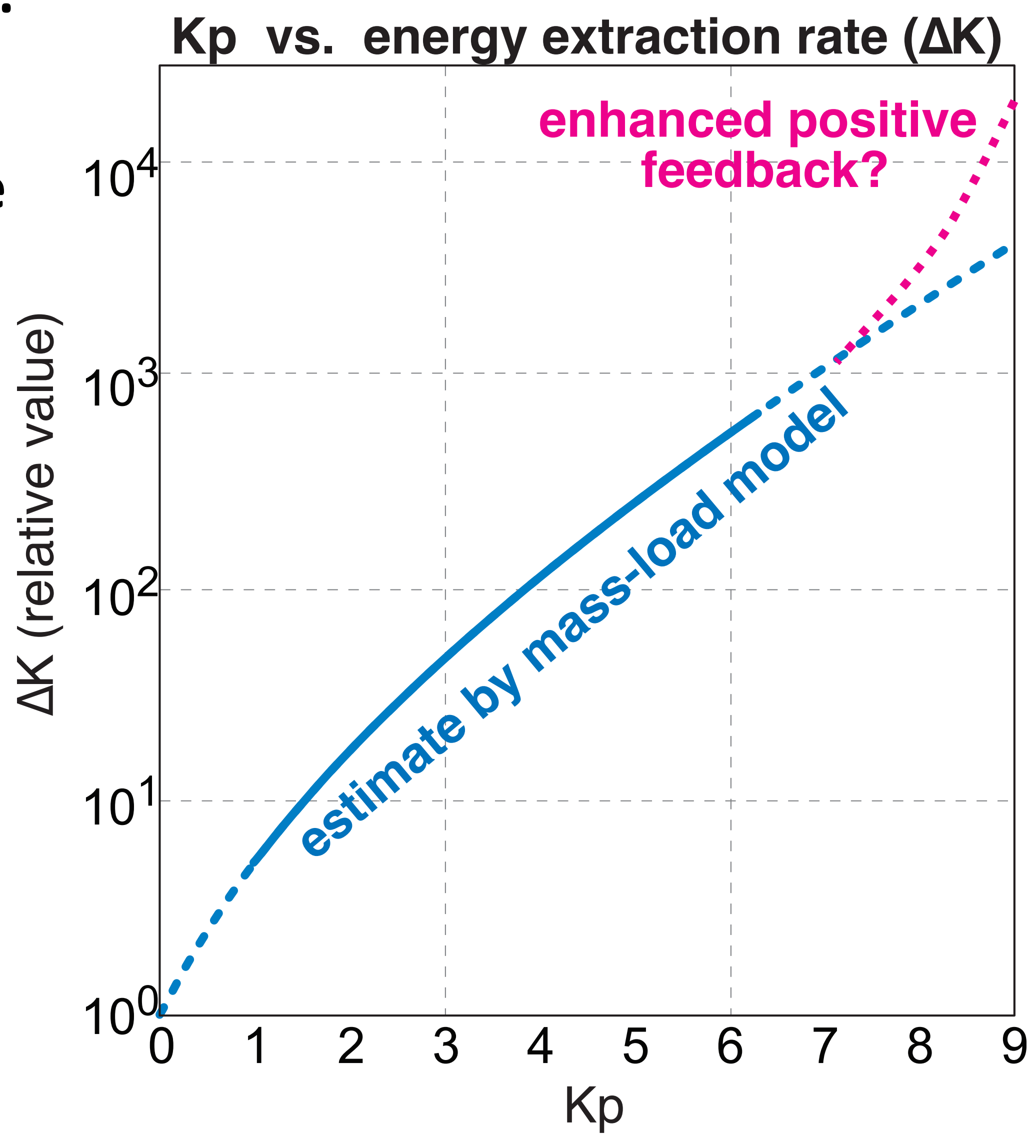
(1) Ion Loss Rate (Cluster):

$F_{loss} \propto \exp(0.45 * Kp)$

(2) Kp and V_{SW} :

$V_{SW} \propto 135 \cdot (Kp+1.2)$

⇒ $\Delta E \propto Kp^2 \cdot \exp(0.45 * Kp)$



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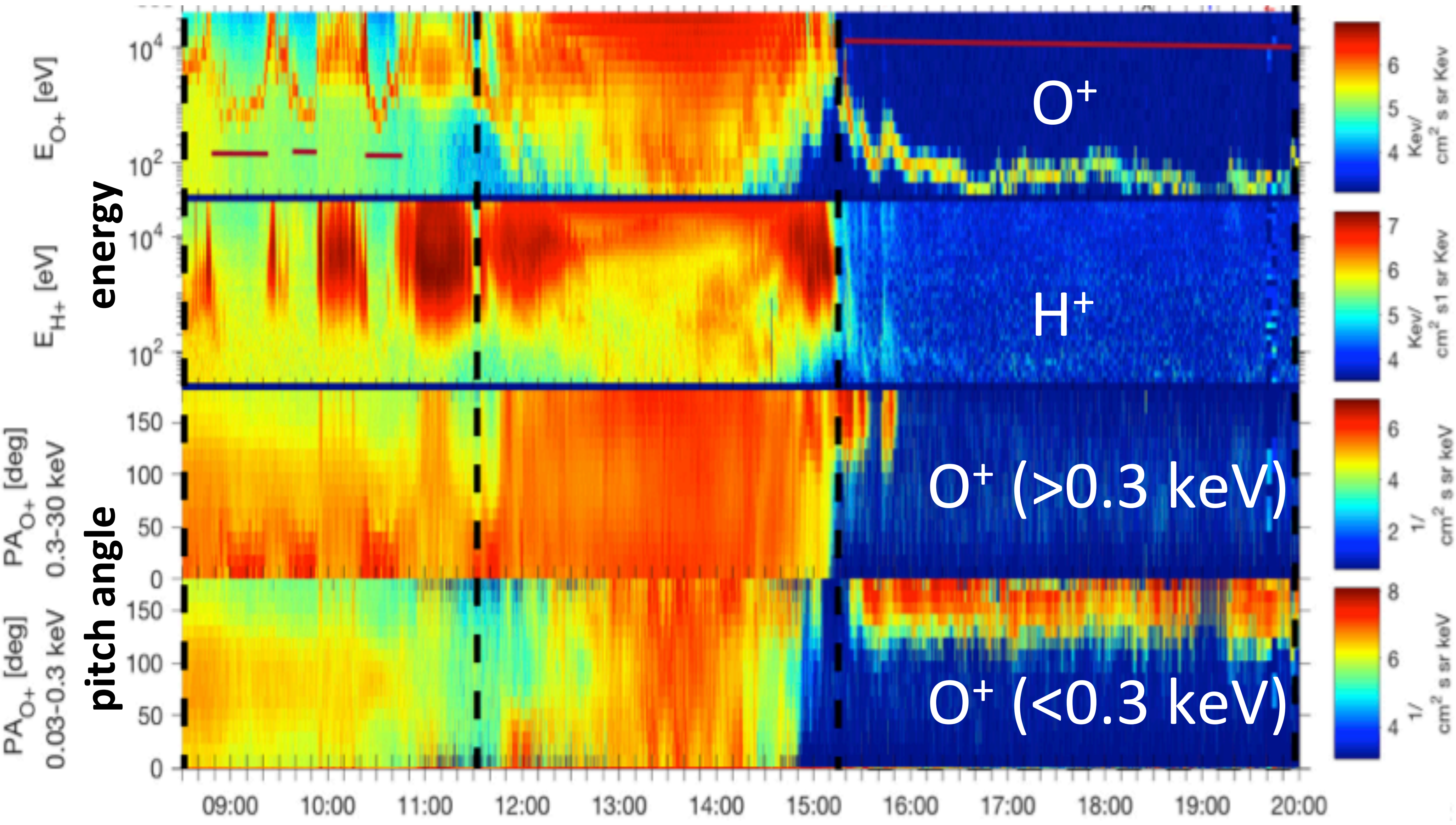
(3) Non-linearity for Kp>7

example: Halloween event (2003-10-29)



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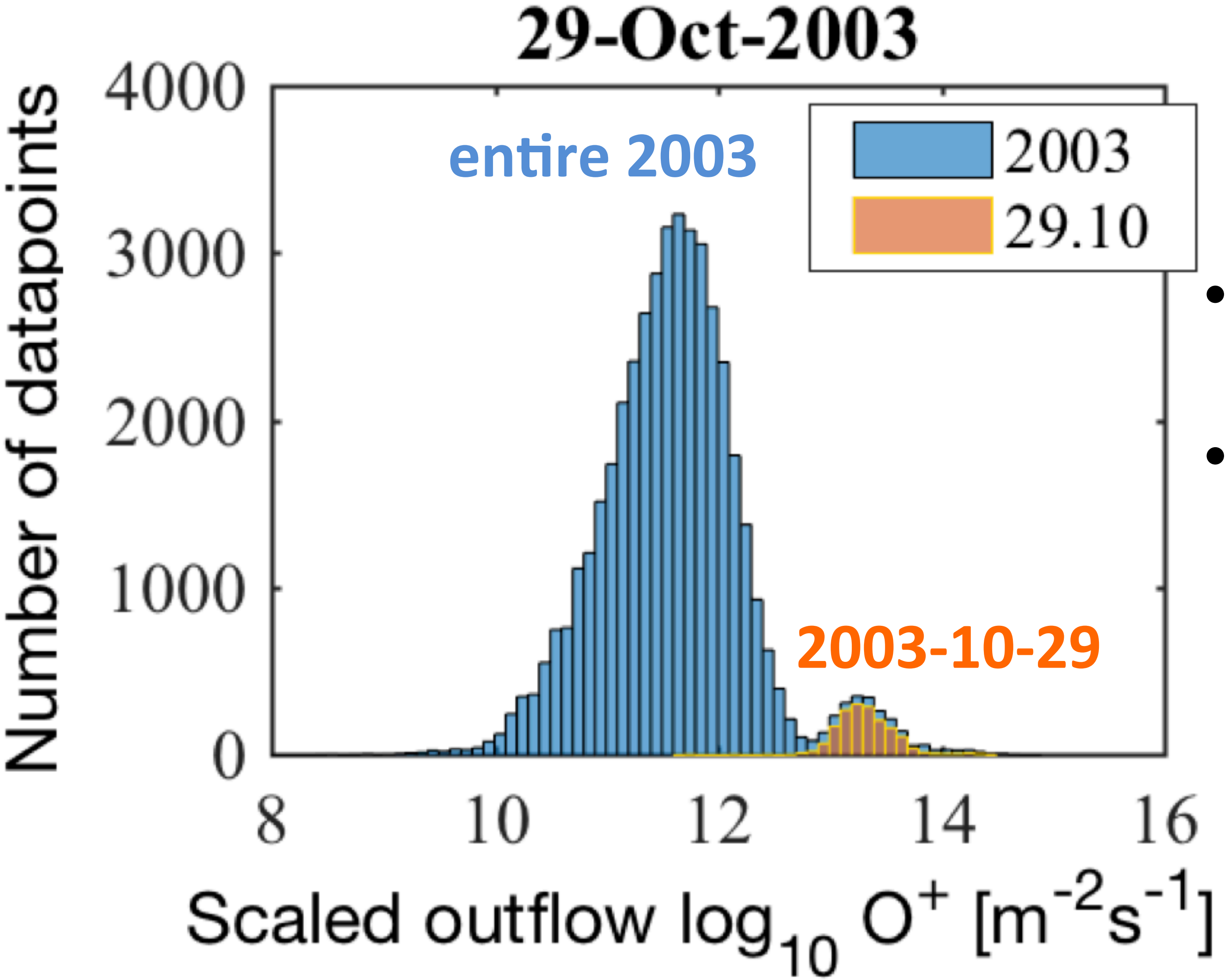

- Flux after scaling to the ionosphere
- Reference: 1-year data in the same region

⇒ higher than extrapolation

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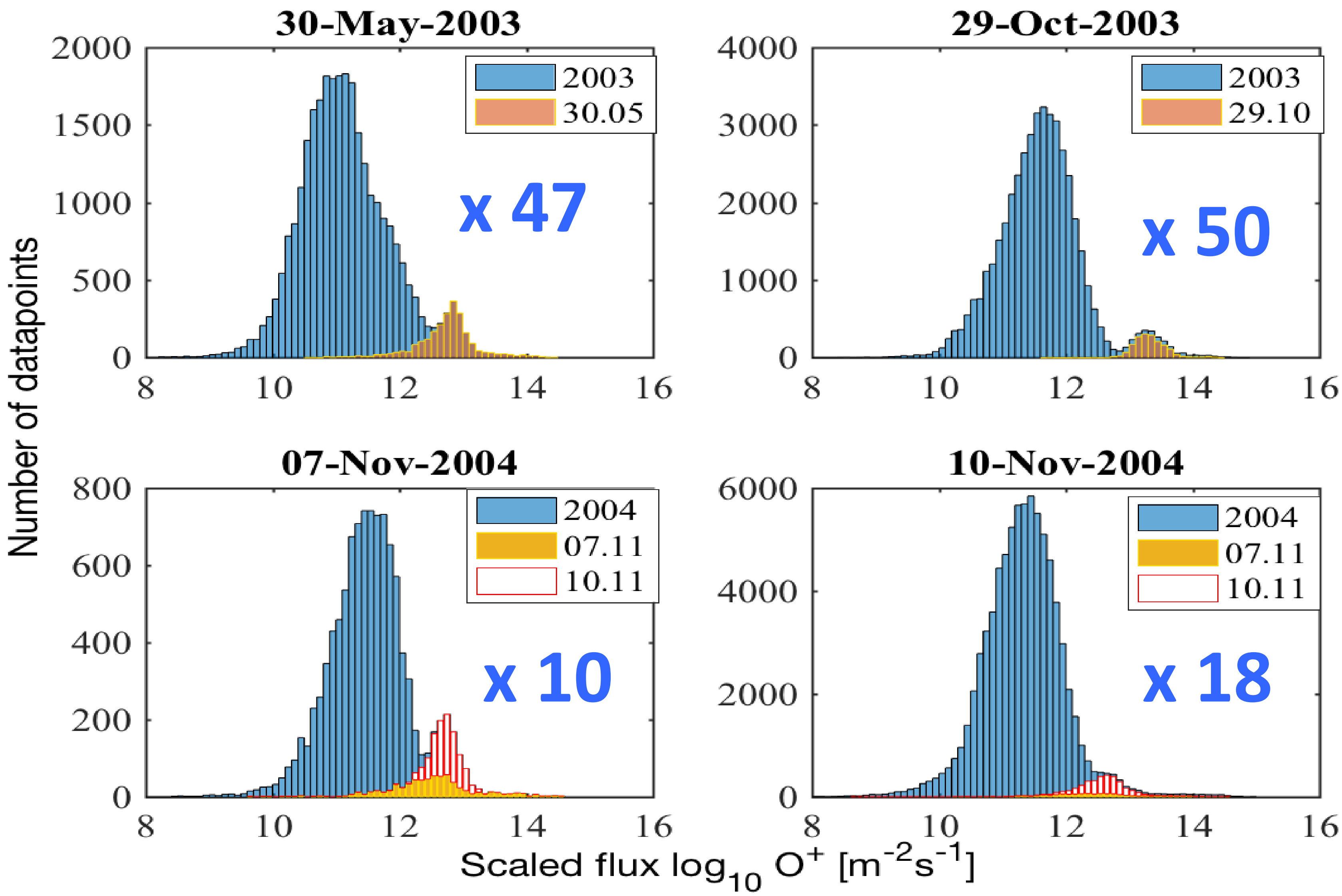
(3) Non-linearity for Kp>7

Examined 6 “extreme” events

Dates	V_{SW}(km/s)	N_{SW} (cm^{-3})	Dst [nT]	Kp
2001-3-31	**~ 720**	**38**	-387	9-
2001-4-12	**~ 720**	**4.4**	-271	7+
2003-5-30	**~ 810**	**52**	-144	7+
2003-10-29	**(2000 ?)**		-350	9
2004-11-7	**~ 700**	**90**	-117	8
2004-11.10	**~ 790**	**18**	-259	9-

(3) Non-linearity for Kp>7

Shift of median flux **(a) Southern hemisphere**



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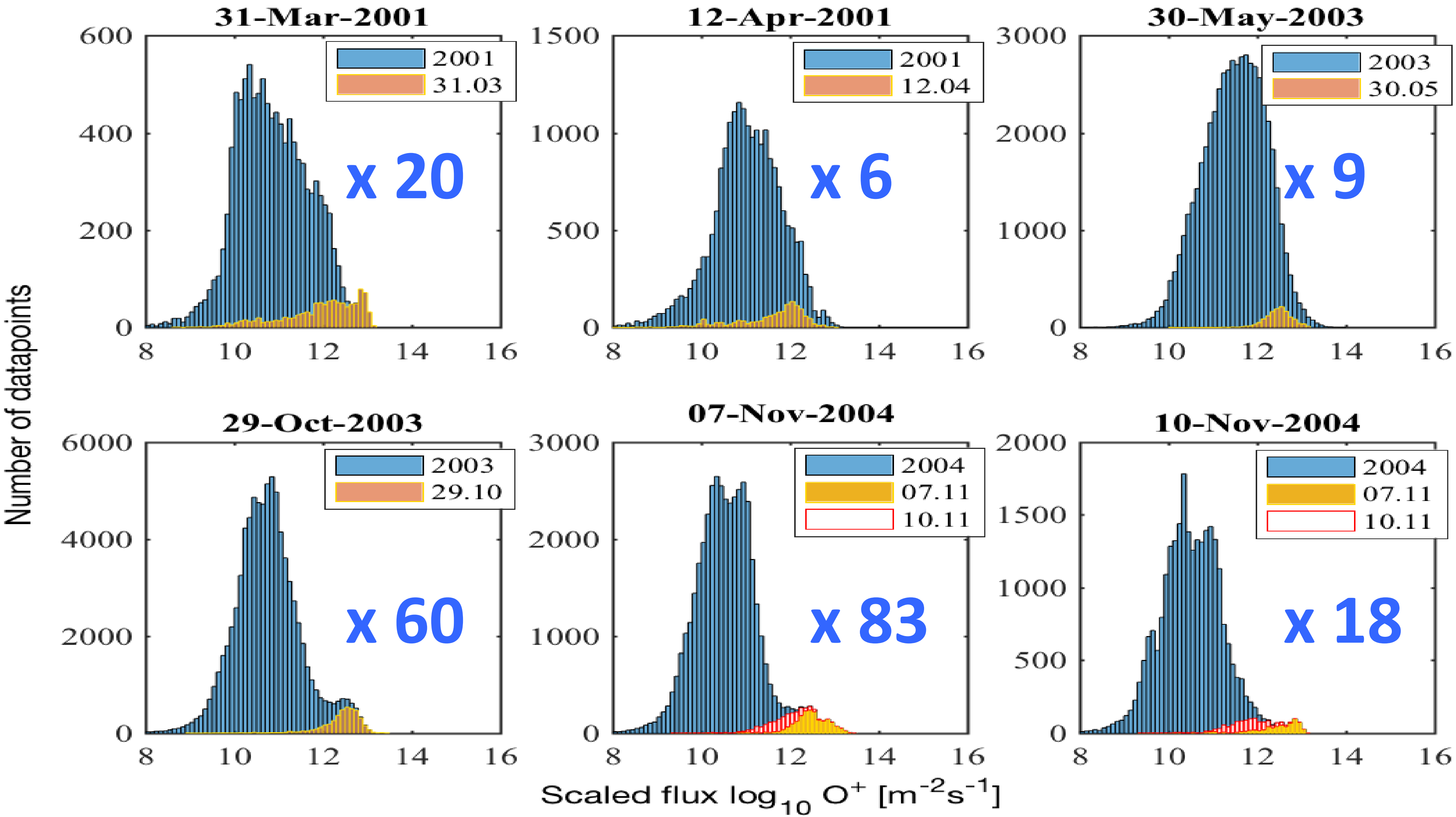
(3) Non-linearity for Kp>7

Shift of median flux **(b) Northern hemisphere**



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(3) Non-linearity for Kp>7

The O^+ outflow during major storms is 1 to 2 orders of magnitude higher than during less disturbed time

Summary and Conclusion

(1) *Slapak et al*. (2017): Ion Loss Rate from the Earth for $Kp < 7$:

$F_{loss} \propto \exp(0.45*Kp) \Rightarrow \int F_{loss} \approx 10^{18}$ kg ≈ atmospheric O_2

(2) *Yamauchi and Slapak* (2017): Extraction of Solar Wind kinetic energy by mass loading :

$\Delta E \propto F_{loss} \cdot v_{SW}^2 \Rightarrow \Delta E \propto Kp^2 \cdot \exp(0.45*Kp)$, for $Kp < 7$

(3) *Schillings et al*. (2017): However, for large Kp ≥ 7+ (condition of ancient time)

F_{loss} (and ΔE) >> prediction by $\exp(0.45*Kp)$

$\Rightarrow \int F >> 10^{18}$ kg (atmospheric O_2 and N_2)

$\Rightarrow$ **O^+ escape can no longer be ignored in the evolution of the atmosphere**

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