

Mass-loading energy extraction from the solar wind to the planetary system and resultant additional ion escape

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Outline

- (1) What is mass loading? / Evidence in the cusp-plasma mantle**
- (2) Mass loading in M-I coupling system / Amount cannot be ignored**
- (3) Formulation and estimate (combining model and observations)**
- (4) Summary and Implications**
- (5) Extra importance for strong CMEs and Earth's evolution**
- (6) Future direction : simulation and Mars/comet application**

(1a) Mass-load = Inelastic mixing

(1) Momentum conservation:

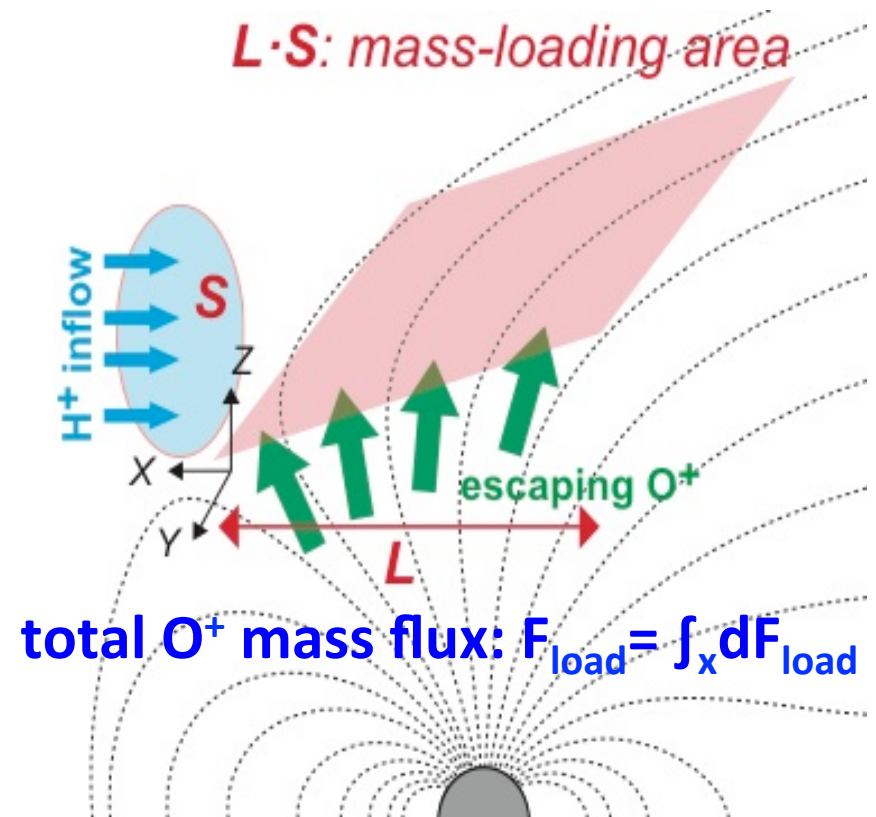
momentum flux in the -x direction = $\rho u^2 S|_{\text{before}} = (\rho + \Delta\rho)(u + \Delta u)^2 S|_{\text{after}}$

(2) Inelastic mixing (final velocity is the same):

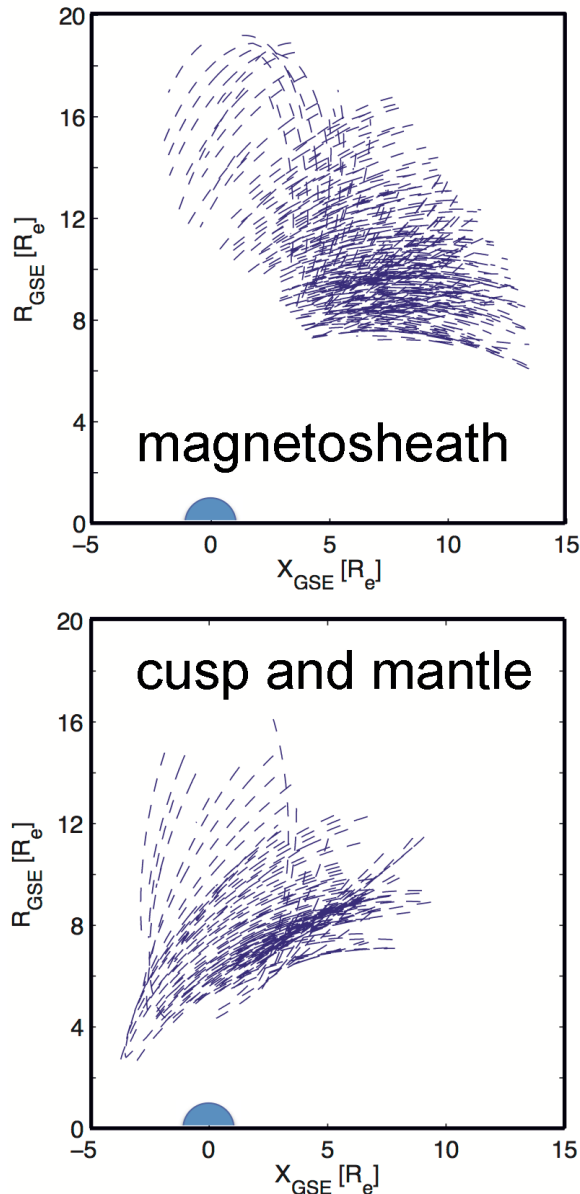
kinetic energy flux $K = \rho u^3 S/2|_{\text{before}} > K + \Delta K = (\rho + \Delta\rho)(u + \Delta u)^3 S/2|_{\text{after}}$

or using (1), $(K + \Delta K)/K = (u + \Delta u)/u$

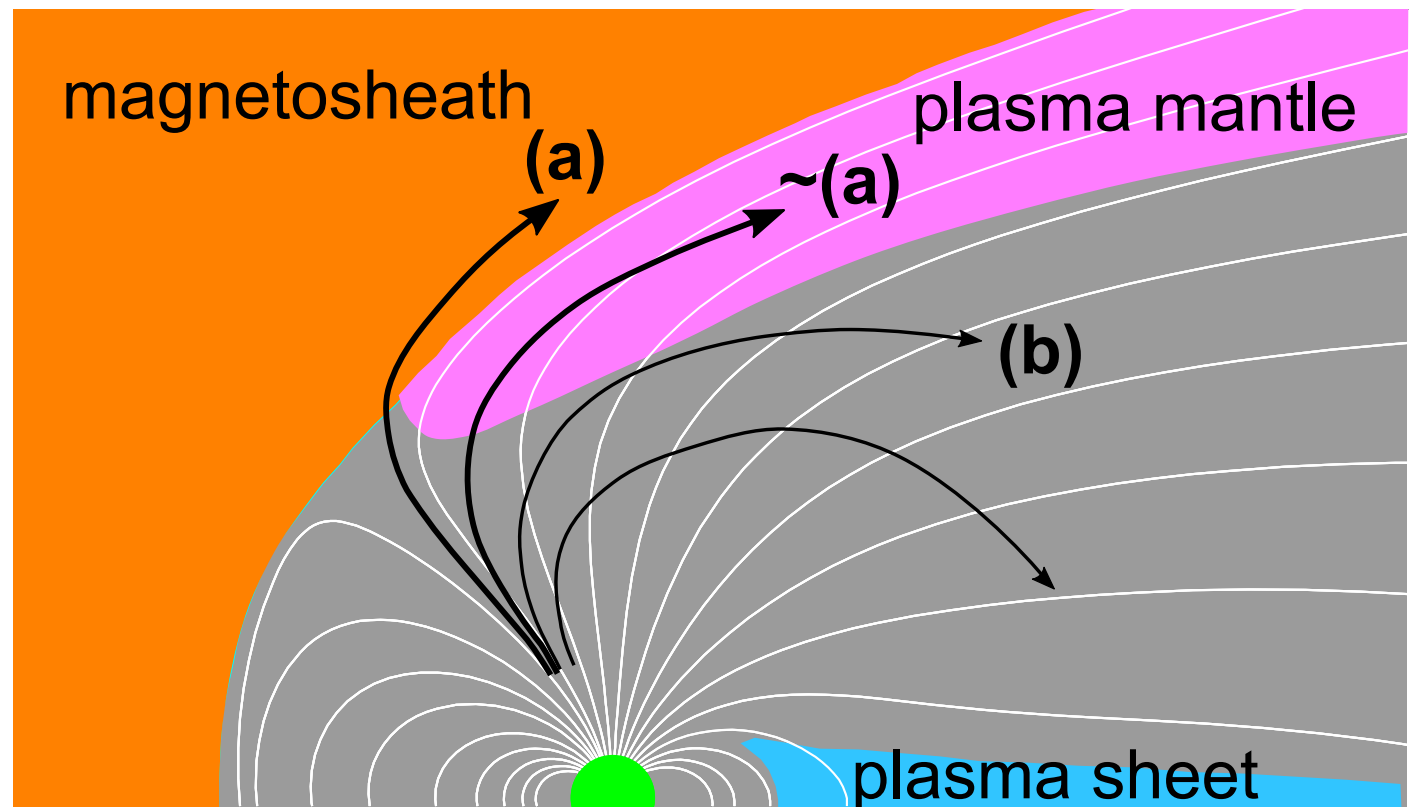
Simplify the mixing
configuration



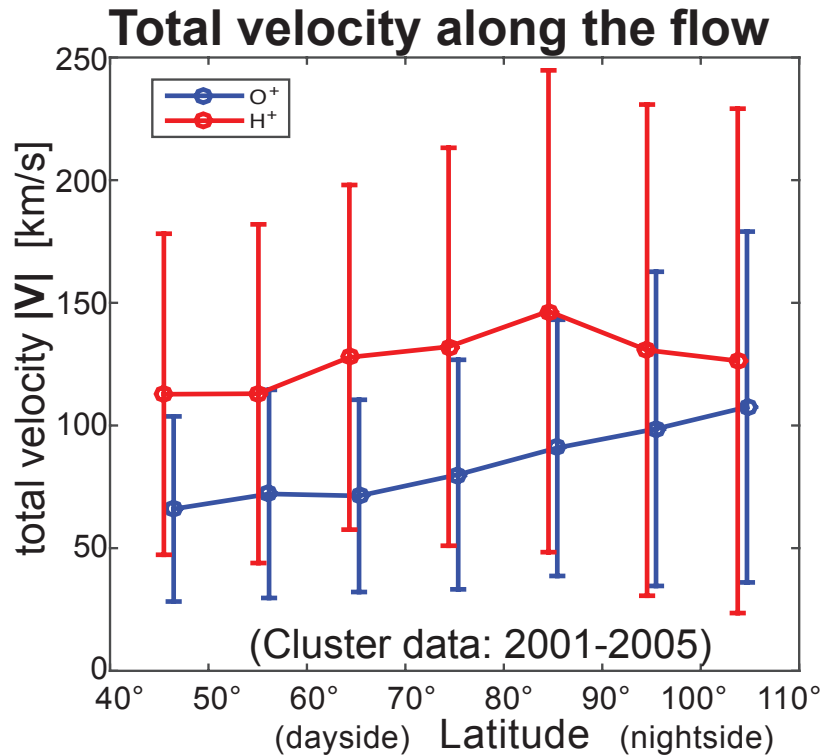
(1b) O^+ observation by Cluster/CIS



**Cluster covers mass-loading area
(we consider only (a) here)**



(1b) O⁺ observation by Cluster/CIS



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

⇒ Mixing is indeed inelastic toward the common velocity

$$\Rightarrow \Delta K/K = \Delta u/u$$

Note: change is gradual in the $-x$ direction

⇒ use integral form of dx distance

$$\Rightarrow \Delta K = \int dK, \text{ where } dK/K = du/u \approx -dp/2\rho$$

(2a) Role of the ionosphere

(3) Destination of extracted energy ΔK :

H^+ and e^- moves in the opposite direction by the solar wind electric field

(3a) unmagnetized planet: used as the kinetic energy of gyromotion

⇒ ΔK is used as temperature (non-laminar motion) increase

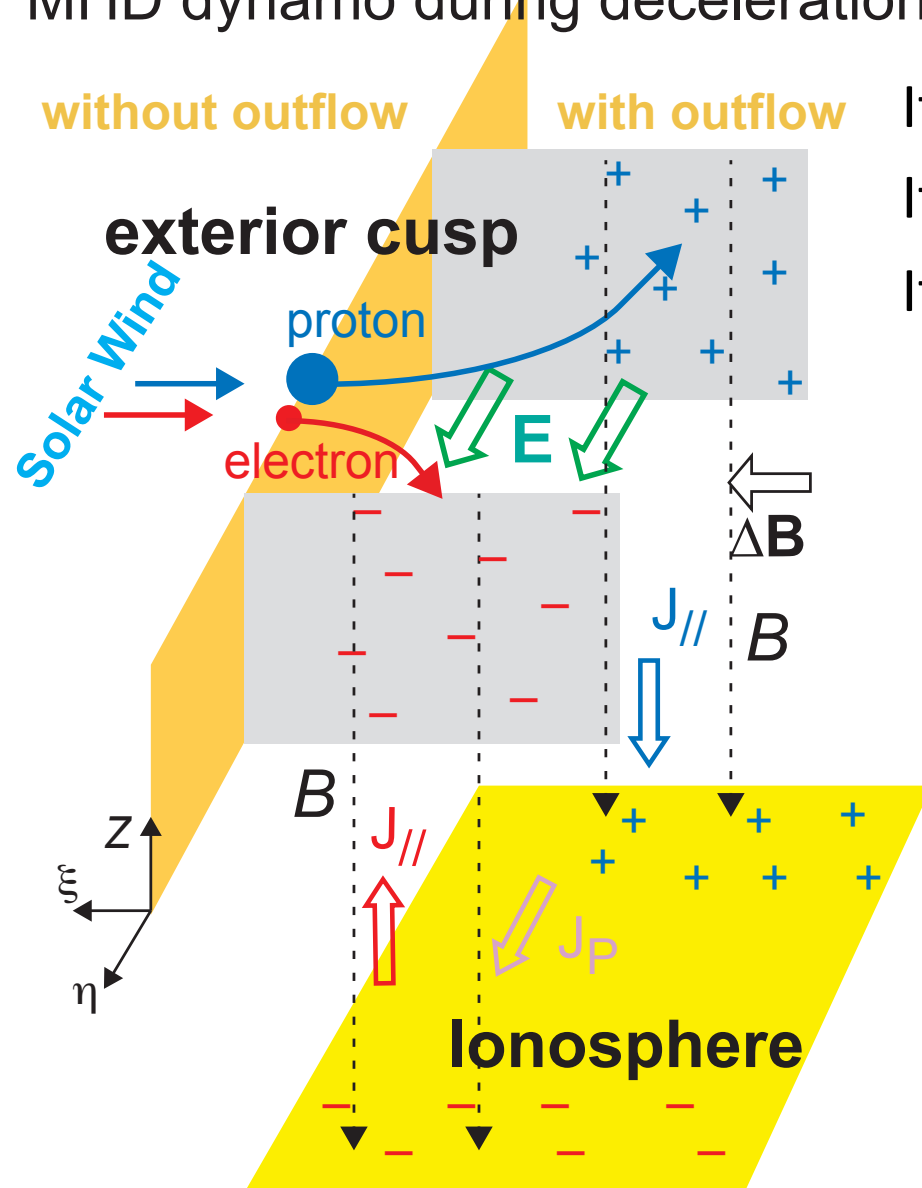
(3b) magnetized planet: mass-loading region is geomagnetically to the ionosphere, a conducting surface

⇒ separated charges can leave toward the ionosphere

⇒ ΔK is first converted to electric energy, and then consumed there

(2a) Role of the ionosphere

MHD dynamo during deceleration



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

If $\Sigma_p = 0$, charges cause $E = -U \times B$

If $\Sigma_p = \text{finite}$, $E = \text{finite}$ & $I_p \cdot \Sigma_p = \text{finite} \propto \Delta E$

(2b) Estimation of amount

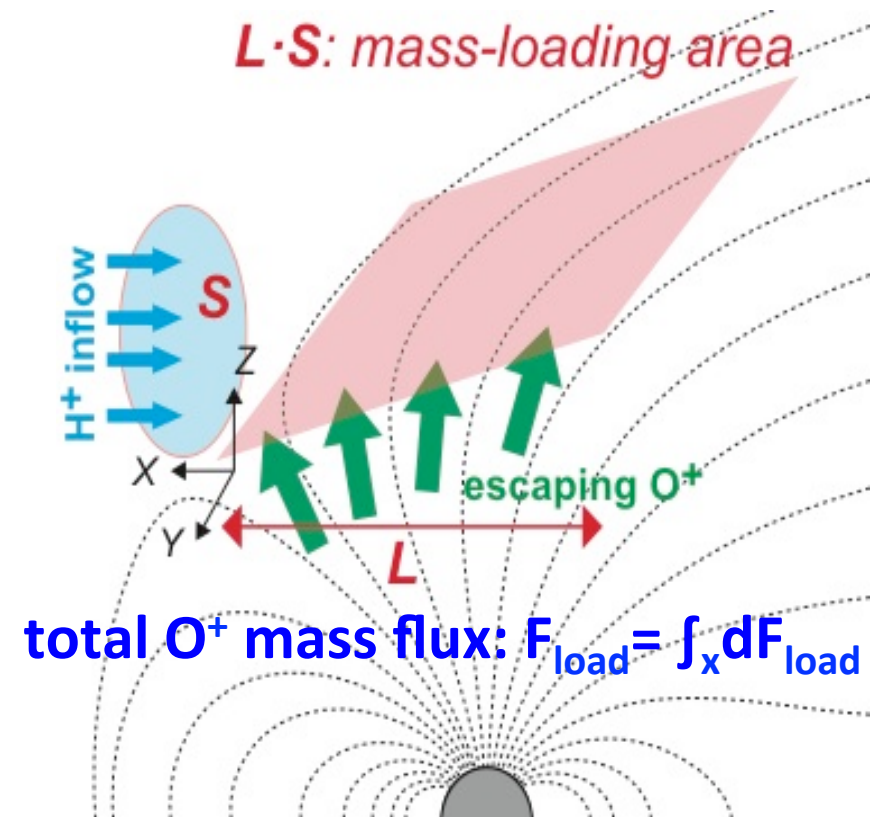
* Using dp = "added mass over dx / volume in dx "

$$= dF_{\text{load}}/uS$$

$$\begin{aligned}\Delta K/K_{\text{in}} &= (-1/2) \cdot \int^L dp(x)/\rho(x) \\ &= (-1/2) \cdot \int^L dF_{\text{load}}(x)u^2(x)/(\rho(x)u^3(x)S(x)) \\ &= (-1/4K_{\text{in}}) \cdot \int^L dF_{\text{load}}(x)u^2(x)\end{aligned}$$

$$\Rightarrow \Delta K \approx (-1/4) \cdot u_{\text{sw}}^2 \cdot F_{\text{load}}$$

where K_{in} is the solar wind kinetic energy flux into the mass-loading area, F_{load} is total mass flux of escaping ions into the mass-loading area.



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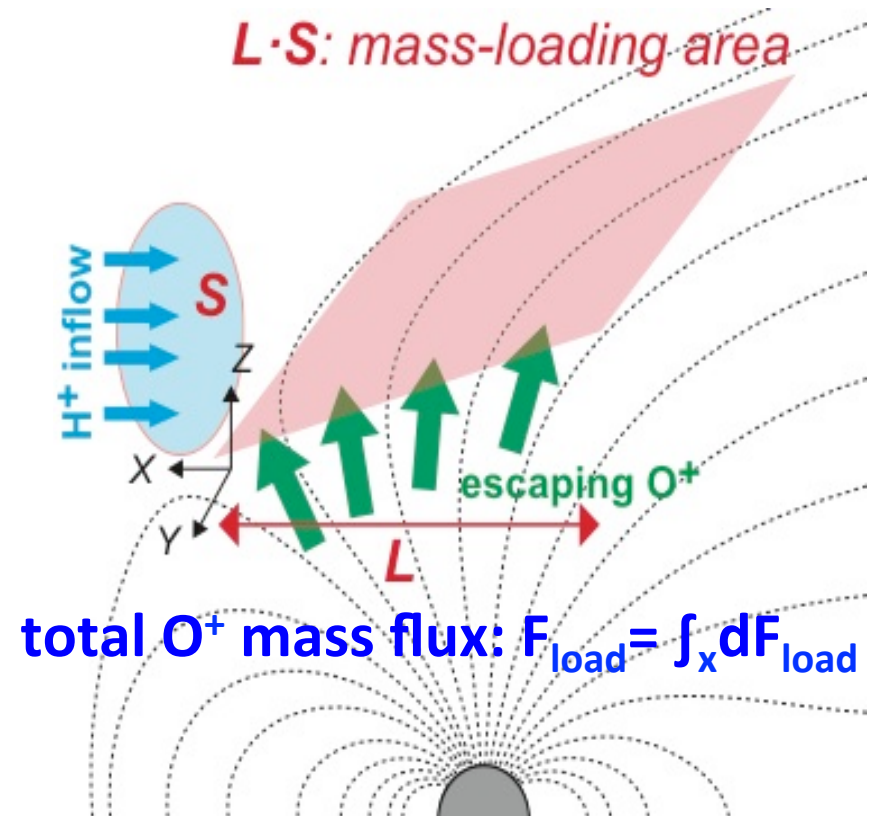
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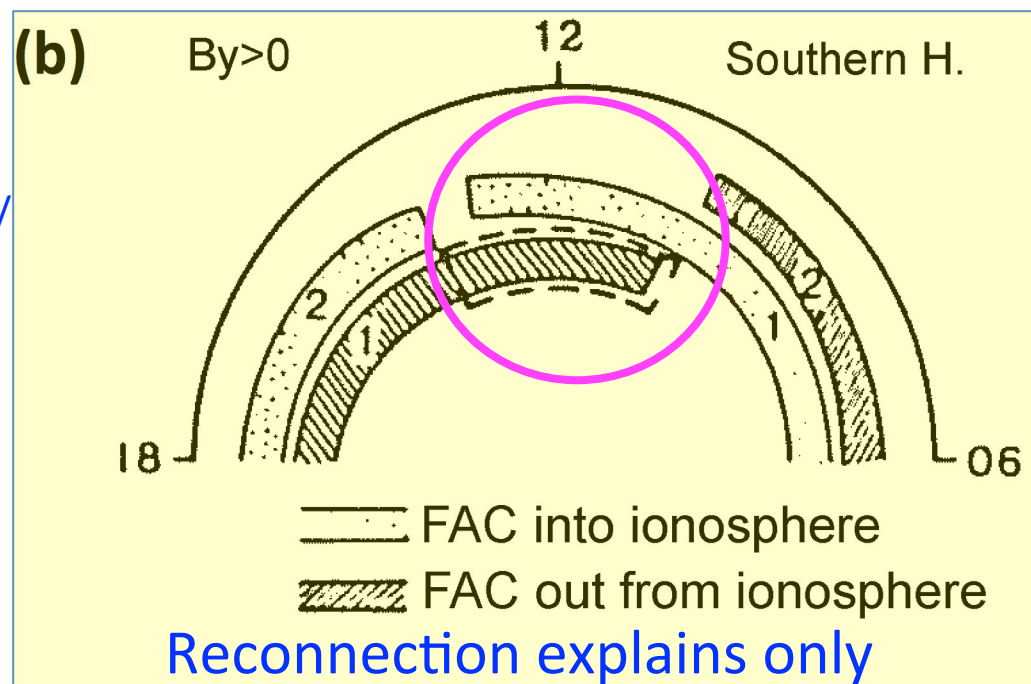
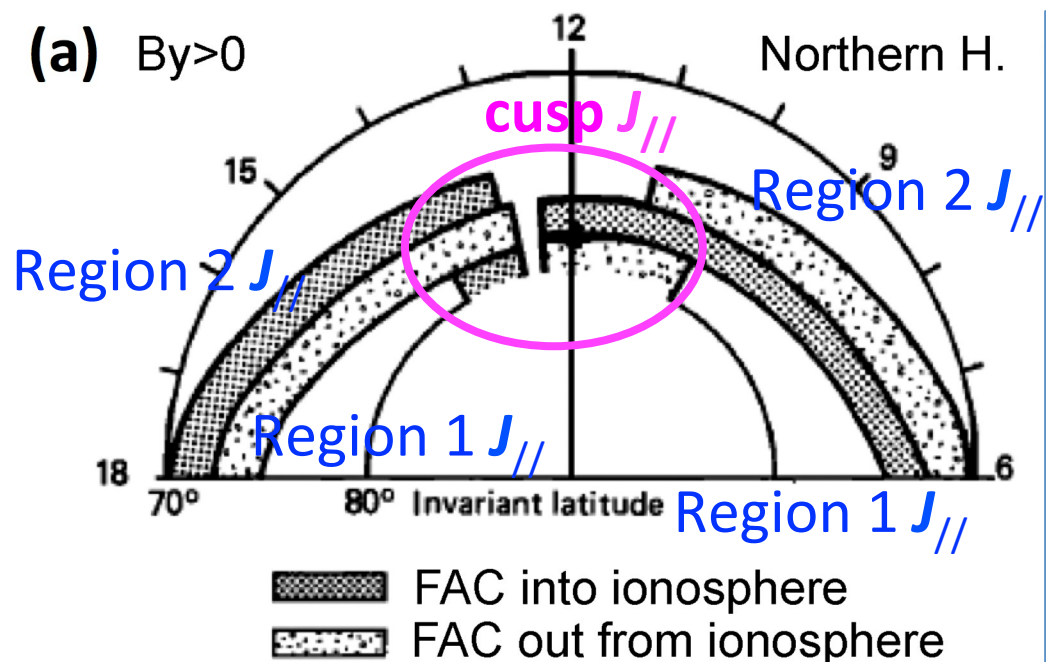
* **Amount is substantial:**

$$n_{\text{O}^+}/n_{\text{SW}} \sim 0.01 \Rightarrow \rho_{\text{O}^+}/\rho_{\text{SW}} \sim 0.16$$

$\Rightarrow$ extract 7% of kinetic energy E

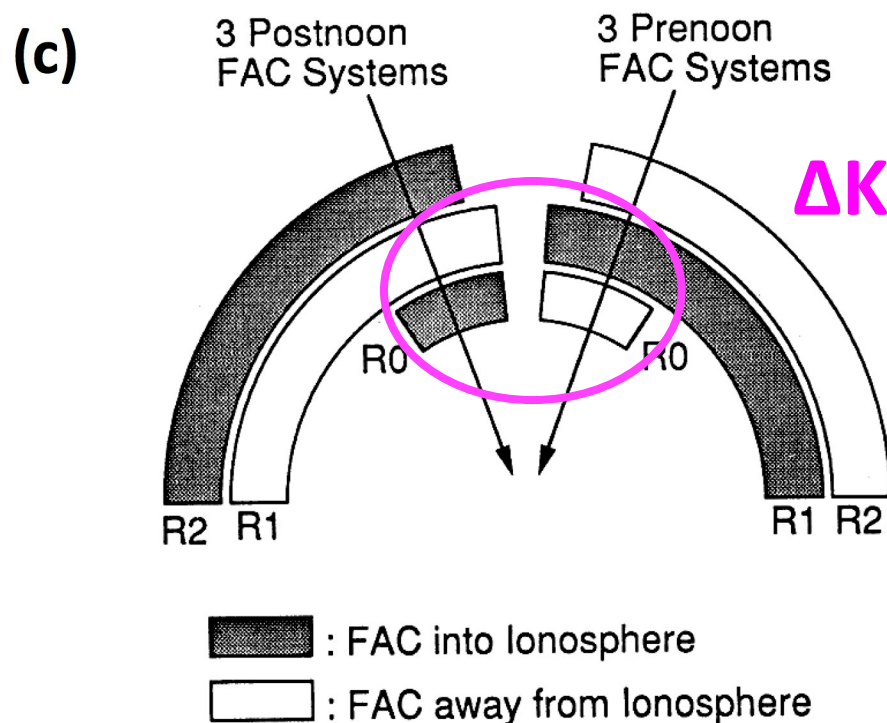
$$\Rightarrow \Delta K \approx 10^{9-10} \text{ W into the ionosphere}$$





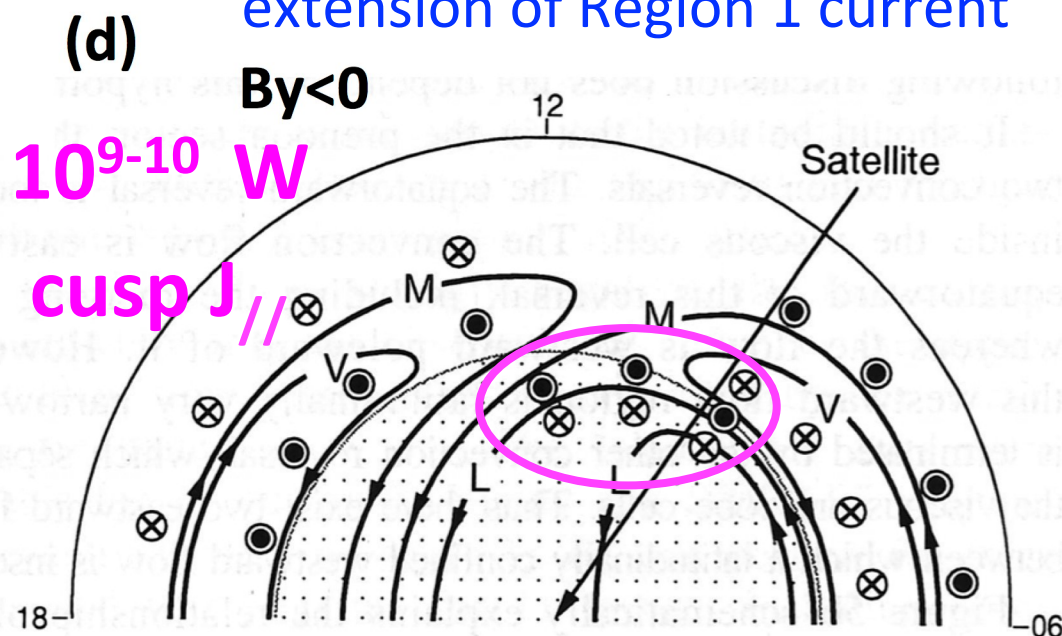
Reconnection explains only

"extension of Region 1 current"



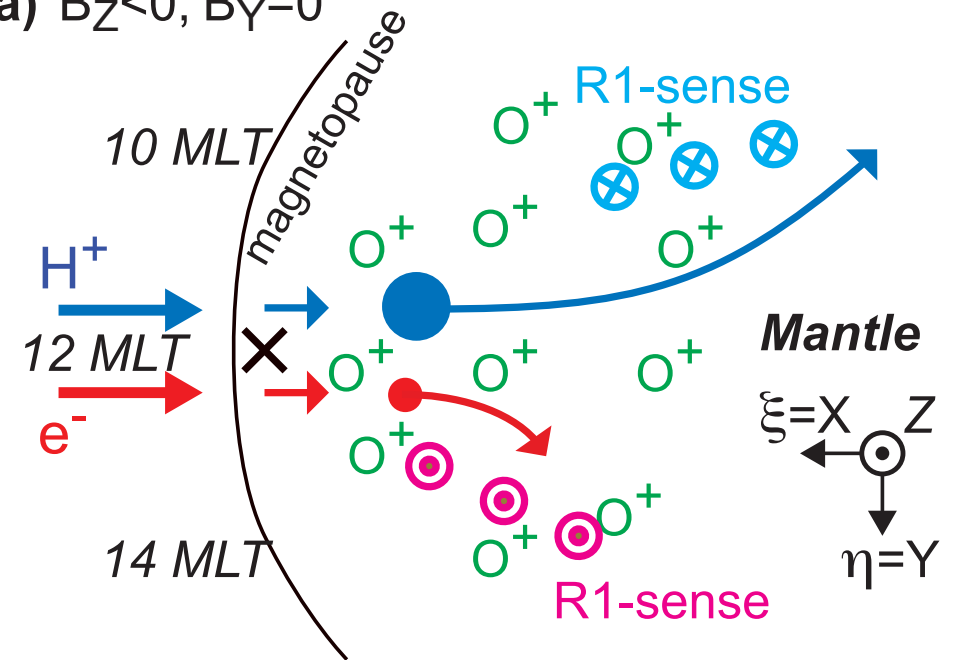
$$\Delta K \approx 10^9 - 10^{10} \text{ W}$$

$$\approx \text{cusp } J_{//}$$

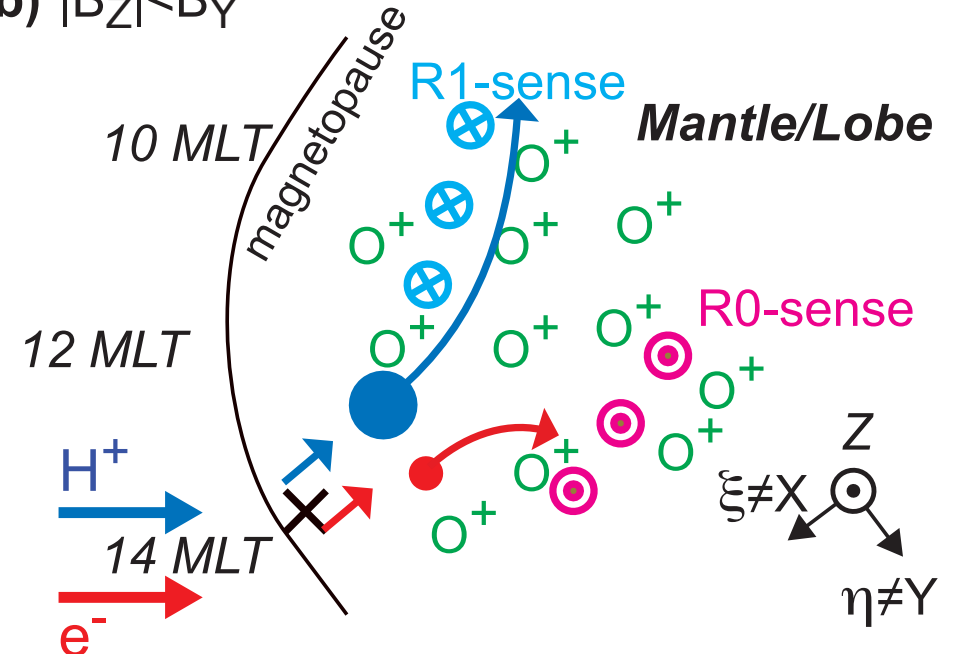


IMF B_Y effect can also be explained

(a) $B_Z < 0, B_Y = 0$



(b) $|B_Z| < B_Y$



(3) Combine with feedback to ion escape

Escape flux is a function of energy input:

$$F_{\text{load}} = F_{\text{load}}(\Delta K)$$

where $\Delta K \propto F_{\text{load}} \cdot v_{\text{SW}}^2$ by mass-loading

⇒ Positive feedback !

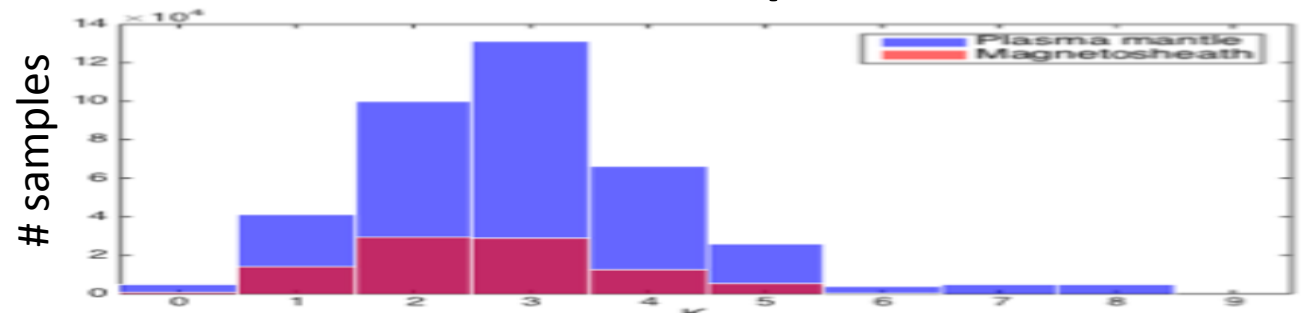
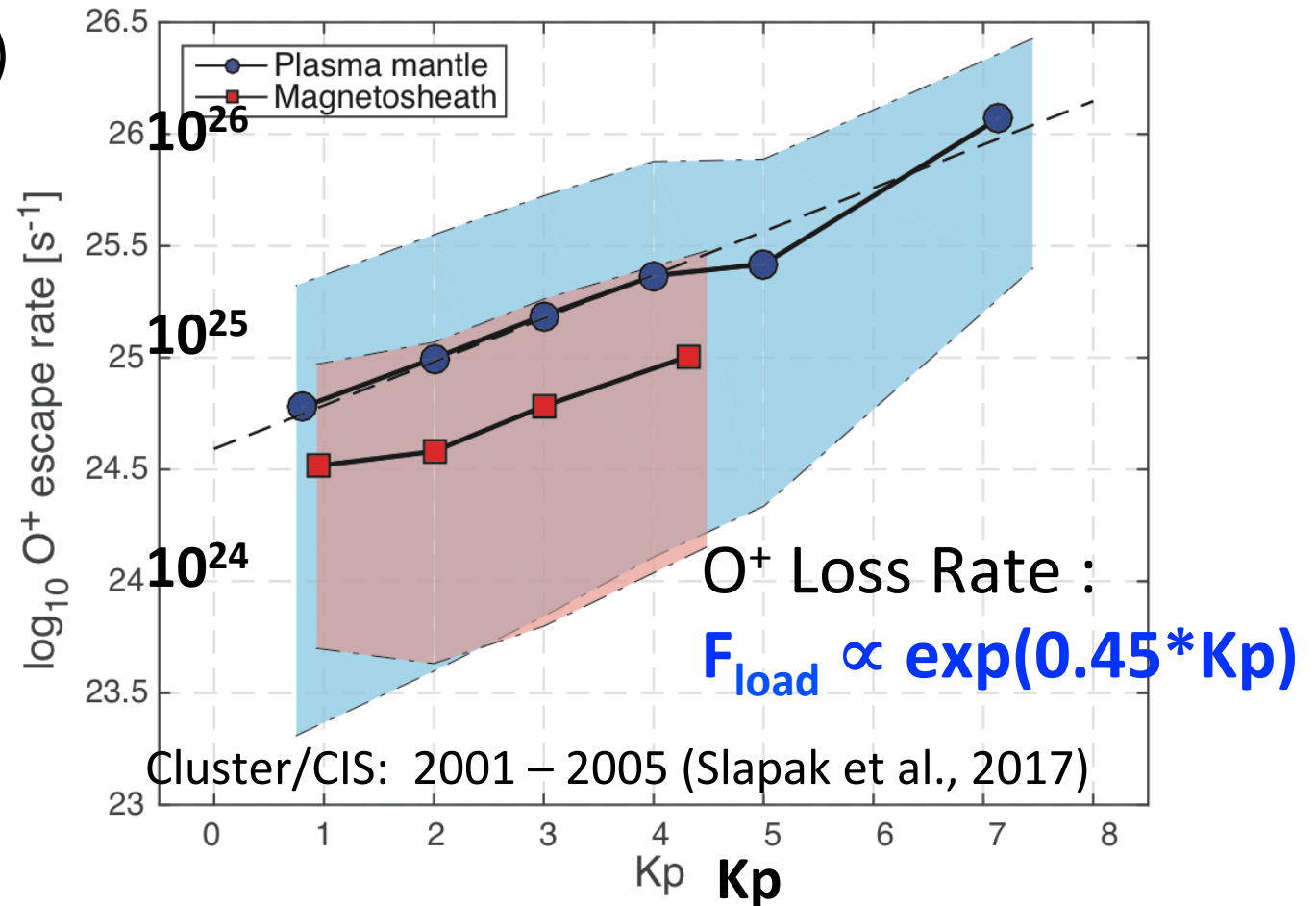
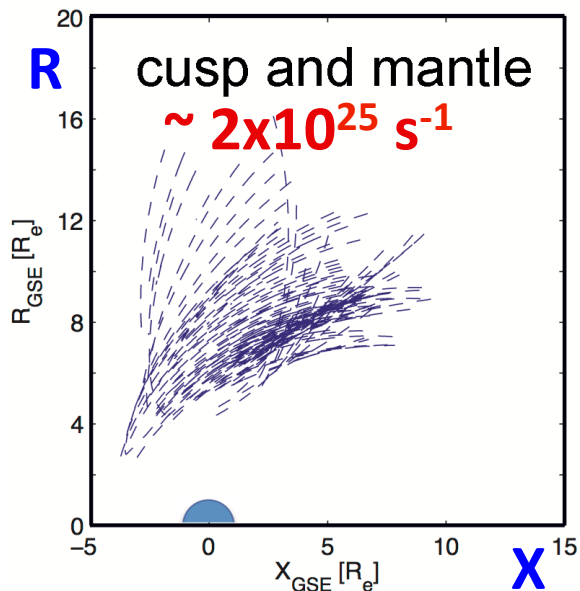
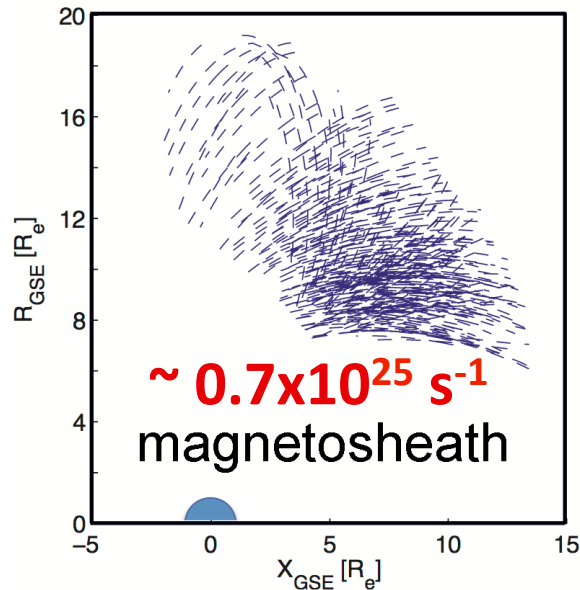
Add two empirical relations

(1) Ion Loss Rate (Cluster):

$$F_{\text{load}} \propto \exp(0.45 \cdot K_p)$$

(3) Combine with feedback to ion escape

from Slapak et al., (2017)



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Add two empirical relations

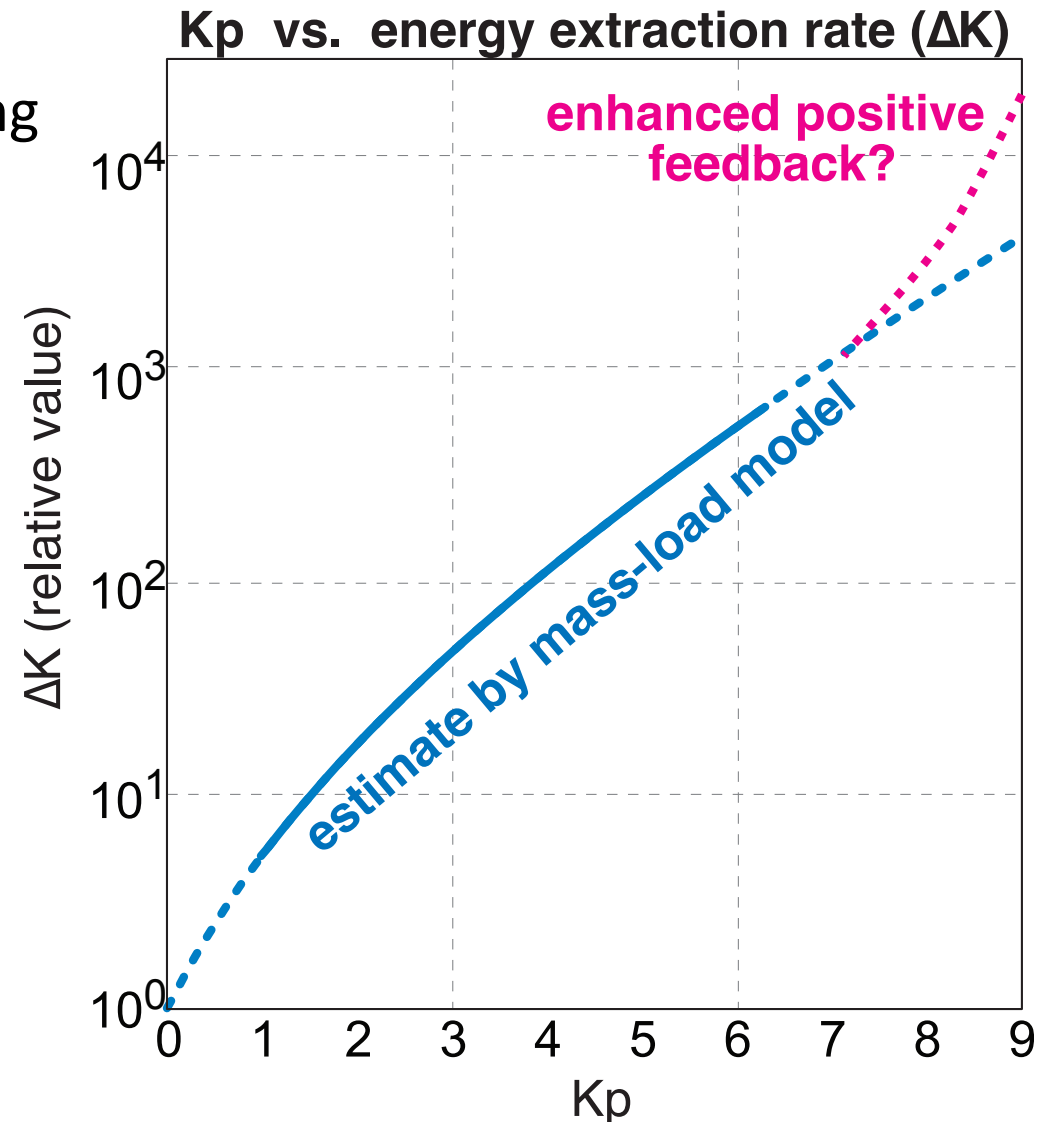
(1) Ion Loss Rate (Cluster):

$$F_{\text{load}} \propto \exp(0.45 \cdot Kp)$$

(2) Kp and v_{SW} :

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

$$\Rightarrow \Delta K \propto Kp^2 \cdot \exp(0.45 \cdot Kp)$$



Key Point of the model

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

$$\Delta K \propto (m_O/m_H) \cdot (n_O/n_H) \sim \text{substantial}$$

$$\propto F_{\text{load}} \cdot v_{\text{SW}}^2 \text{ where } F_{\text{load}} \text{ is the total } O^+ \text{ flux into the solar wind.}$$

(b) Positive feedback between ΔK into the ionosphere and O^+ energization by ΔK (i.e., $\Delta K \propto v_{\text{SW}}^2 \times \text{function of } \Delta K$)

(c) Using empirical non-linear relation of F_{load} and K_p (where K_p is a good proxy of ΔK), ΔK - K_p relation is also non-linear

(d) This energy extraction is independent from reconnection

Reconnection $\Rightarrow$ global, determined by magnetic field

Mass-loading $\Rightarrow$ local polar cap, determined by ionospheric O^+

(e) Significant during high K_p because

Reconnection efficiency $\propto \varepsilon$ (coupling function): linear

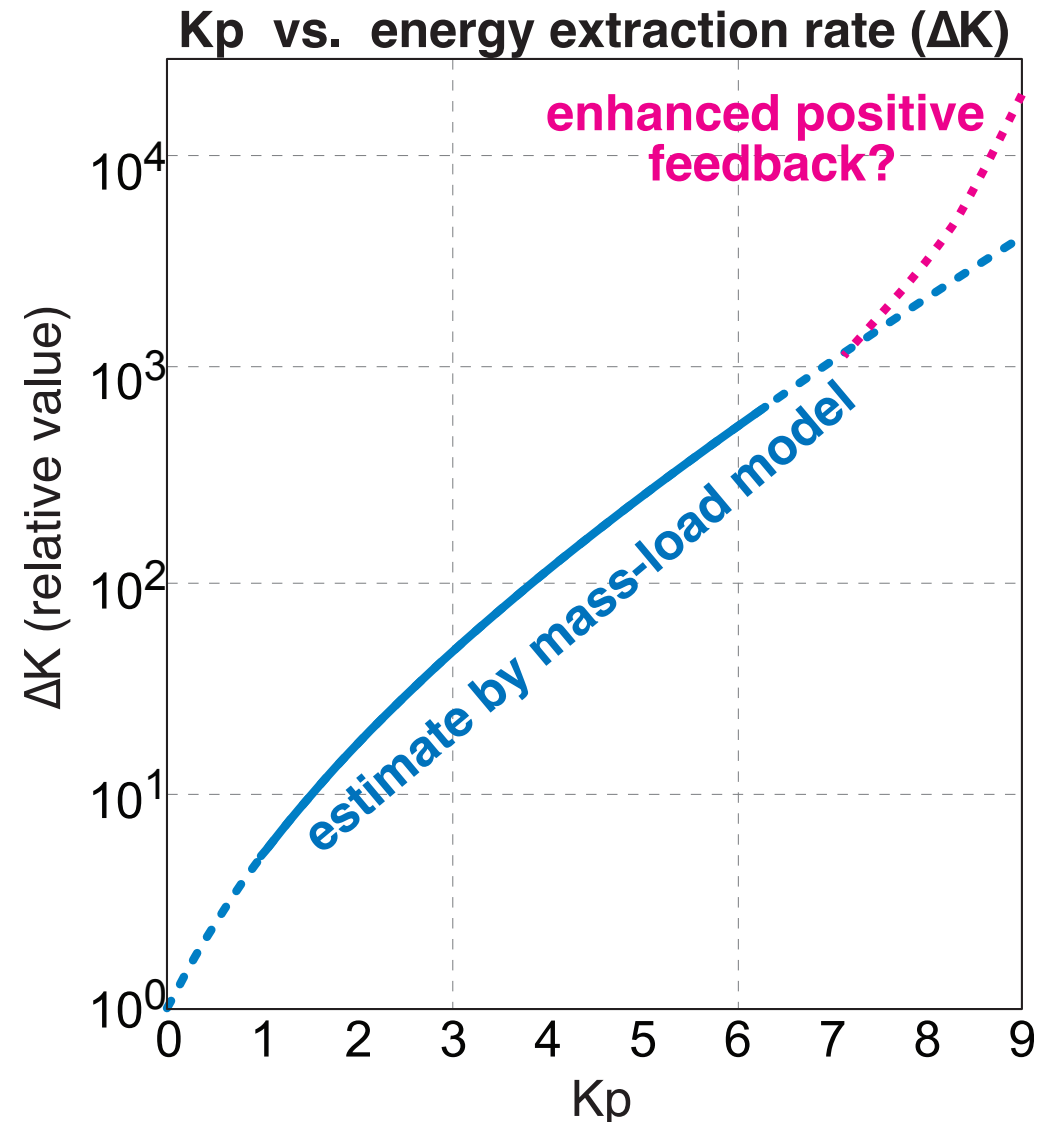
Mass-loading efficiency $\propto \exp(0.45 \cdot K_p)$: non-linear

(4) Implications of $\Delta K \approx -u_{sw}^2 \cdot F_{load}/4$

(1) $\Delta K \approx 10^{9-10}$ W into the ionosphere
≈ the cusp current (explains
independency from Region 1
current)

(2) Considering $Kp \propto \varepsilon$ (coupling
function), relative importance of
mass loading compared to
reconnection is getting more
important during severe space
weather events

⇒ Need to further study ion
escape for $Kp > 7$ (when statistics
is poor)



(4) Implications of $\Delta K \approx -u_{\text{SW}}^2 \cdot F_{\text{load}}/4$

(3a) Combine with *Slapak et al.* (2017) for $K_p < 7$:

$$F_{\text{load}} \propto \exp(0.45 \cdot K_p) \Rightarrow F_{\text{load}} \approx 10^{27}/\text{s} \text{ @ancient (} K_p \text{ equivalent to } \geq 10)$$
$$\Rightarrow \int F_{\text{load}} \approx 10^{18} \text{ kg} \approx \text{atmospheric O}_2$$

(3b) Combine with *Schillings et al.* (2017) for $K_p \geq 7+$ (cf. ancient time)

$$F_{\text{load}} \text{ (and } \Delta E) \gg \text{ prediction by } \exp(0.45 \cdot K_p)$$

(5) Further non-linearity for $K_p > 7$

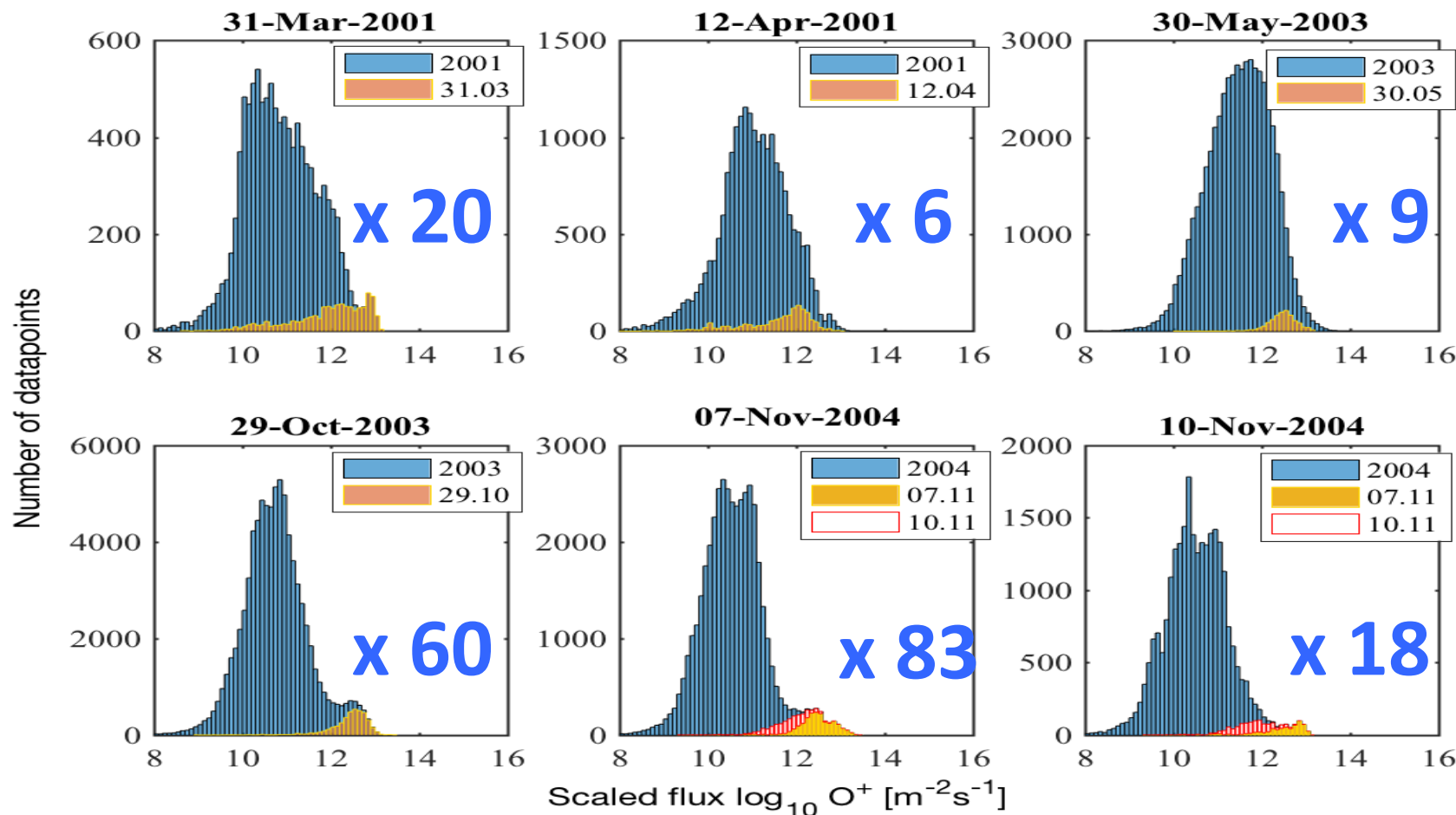
from Schillings et al., (2017)

Dates	V_{sw} (km/s)	N_{sw} (cm ⁻³)	Dst [nT]	K_p
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-

(5) Further non-linearity for $K_p > 7$

Shift of median flux Northern hemisphere

from Schillings et al., (2017)



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

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$$F_{\text{load}} \text{ (and } \Delta E \text{)} \gg \text{ prediction by } \exp(0.45 \cdot K_p)$$
$$\Rightarrow \int F \geq 5 \times 10^{18} \text{ kg (total atmospheric mass at present)}$$

Summary

- (1) Can explain "independency" of the cusp current from region 1 current**
- (2) For severe space weather conditions, mass-loading energy extraction may become more important than reconnection** (which is nearly "linear" to Akasofu ϵ or Newell's $d\Phi/dt$) because of non-linear response of the ionosphere.
- (3) Ionosphere plays active role in amplifying the space weather hazard.**
- (4) O^+ escape can no longer be ignored in the evolution of the atmosphere.**

Future direction

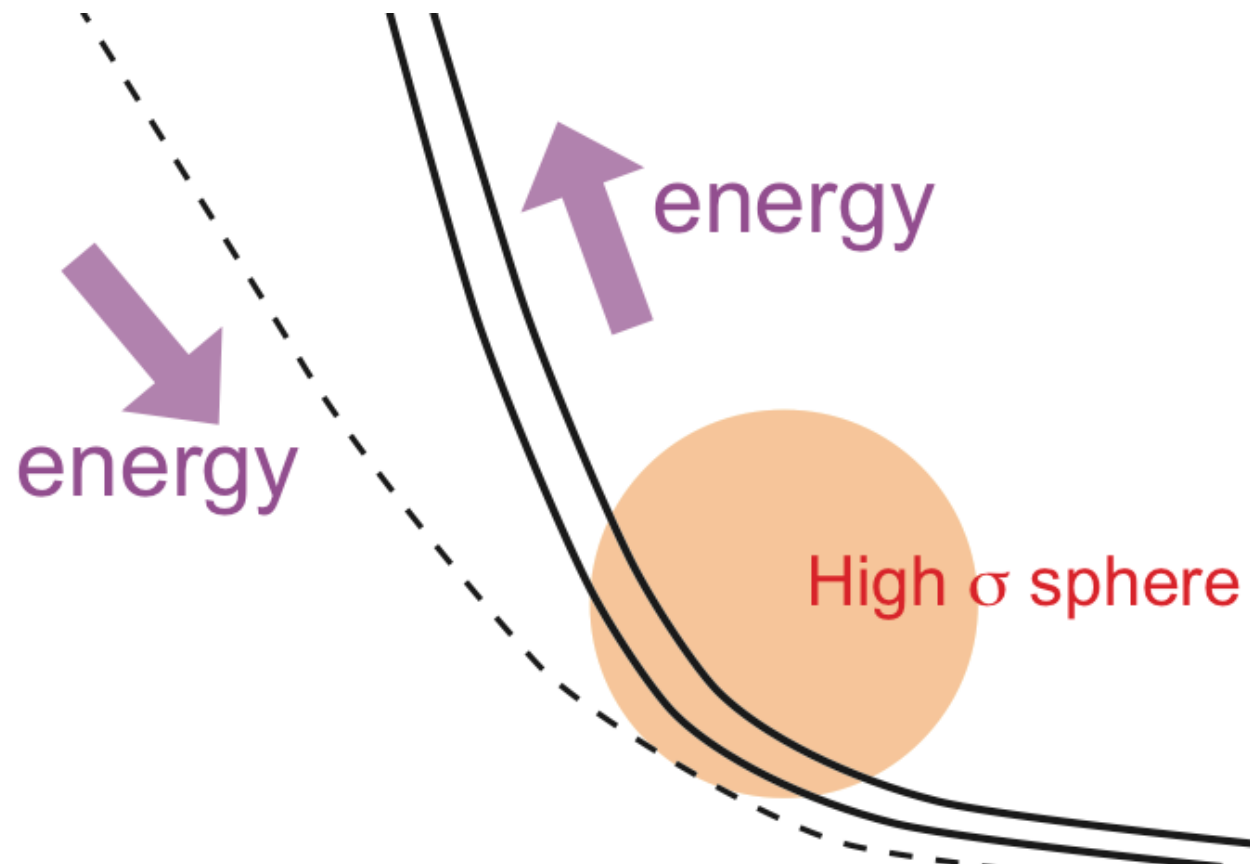
(A) Numerical simulation: **fluid model** allowing finite mass flux (in) and energy flux (out) should do the job.

(B) Apply to **Mars/Comet** where solar wind and "conducting environment" are magnetically connected.

- localized open magnetic field (Mars)
- localized draping IRF to ionopause (comet)

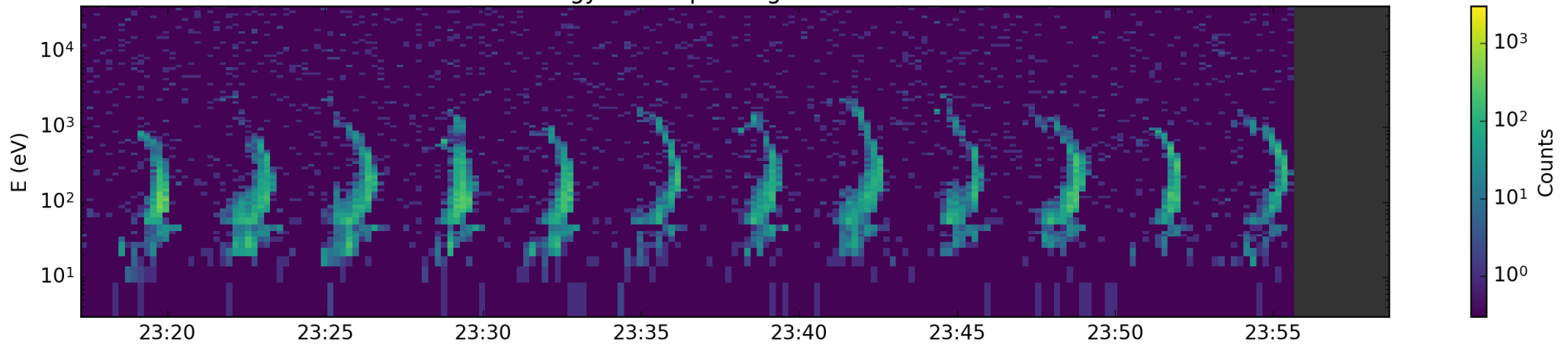
Comet case

- localized draping IRF to ionopause
⇒ **extra deceleration or acceleration ?**

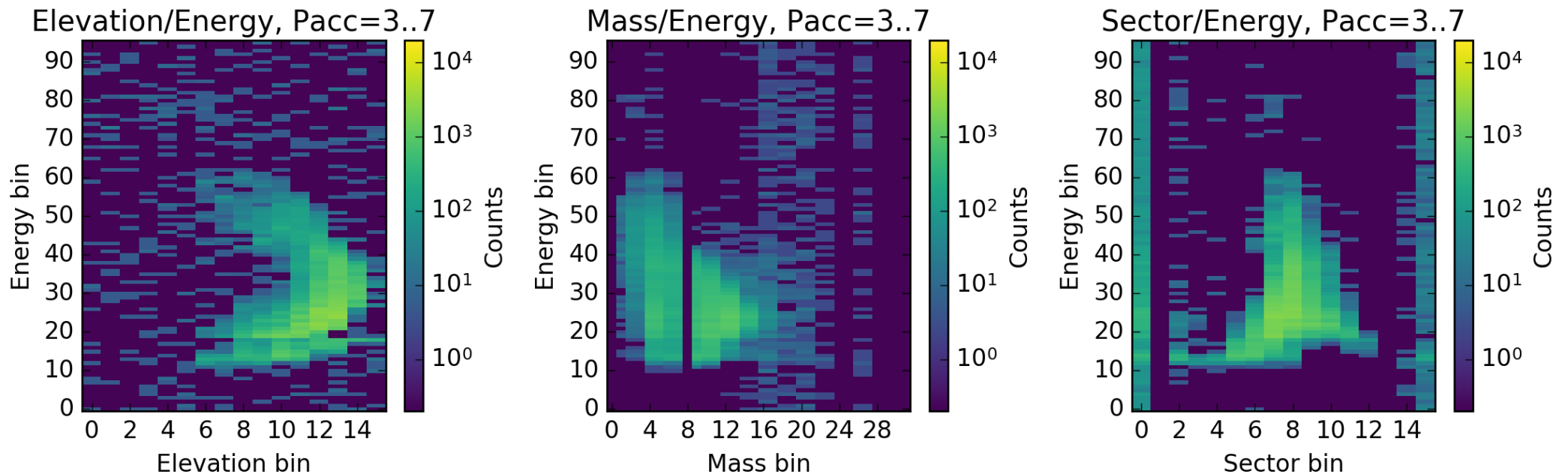


H₂O⁺ acceleration to > 1 keV with "nose" dispersion

ICA Energy-Time Spectrogram 20151207T23

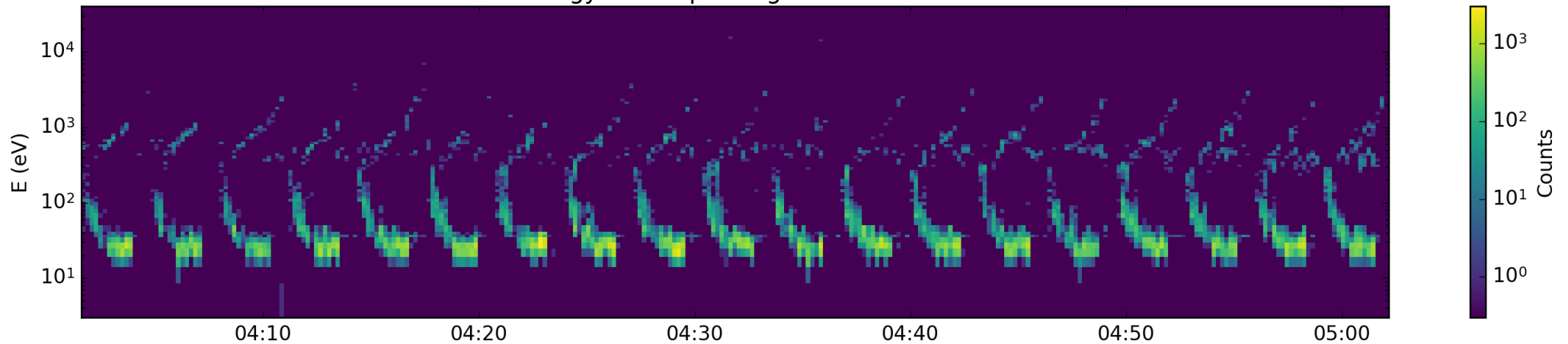


2015-12-7, 23 UT

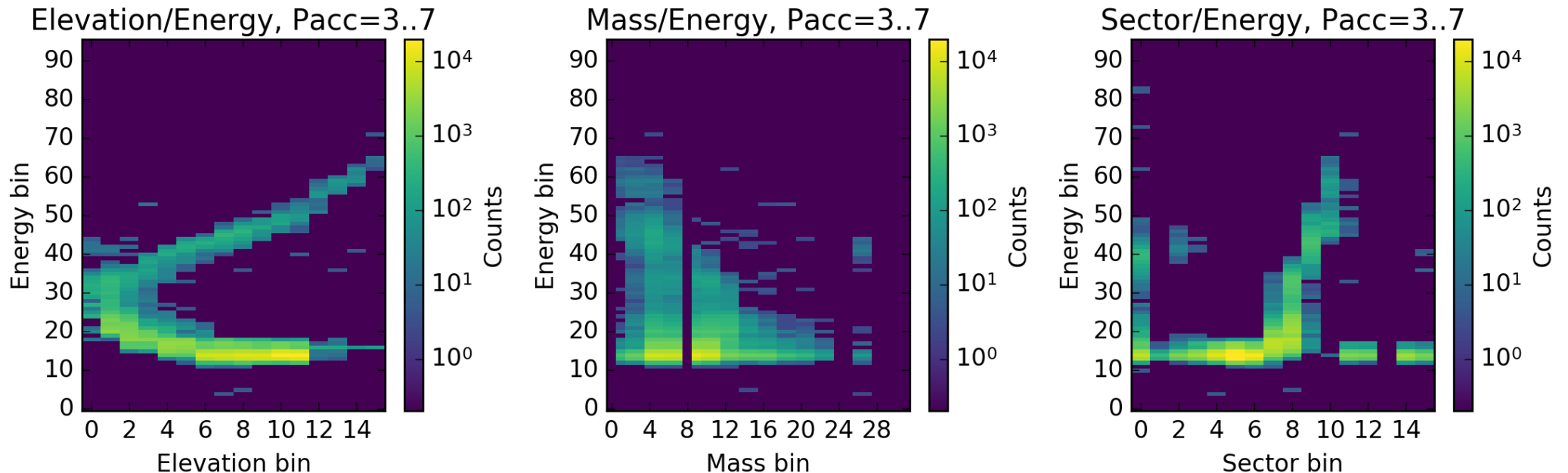


H₂O⁺ acceleration to > 1 keV with "nose" dispersion

ICA Energy-Time Spectrogram 20160207T04

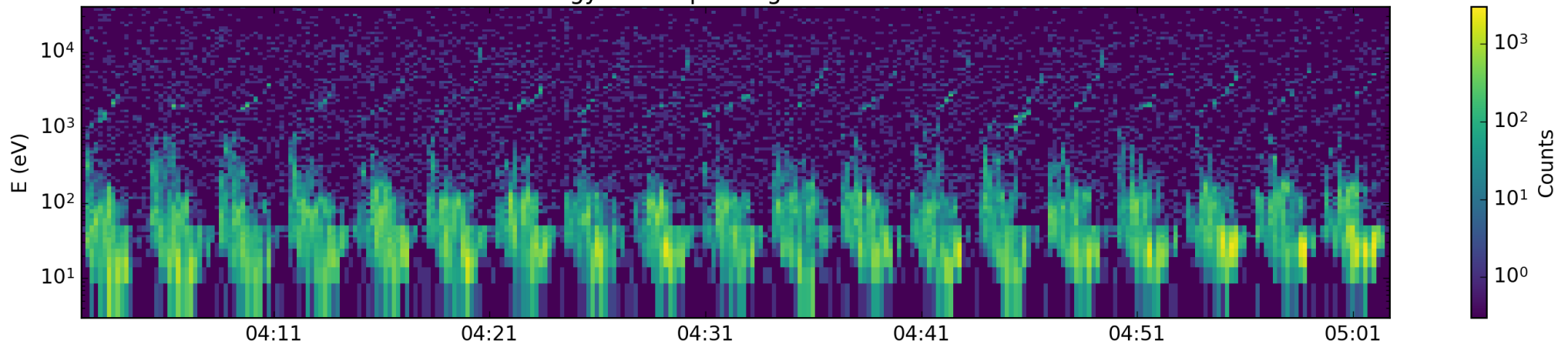


2016-2-7, 23 UT

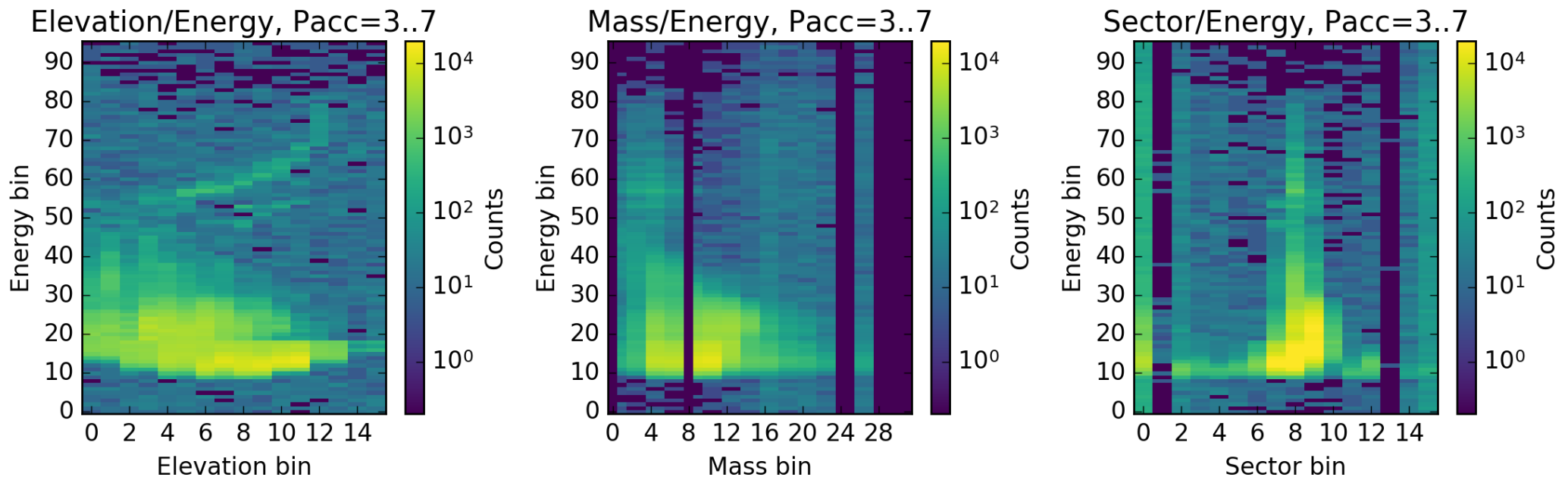


H₂O⁺ acceleration to > 1 keV with "nose" dispersion

ICA Energy-Time Spectrogram 20160101T04

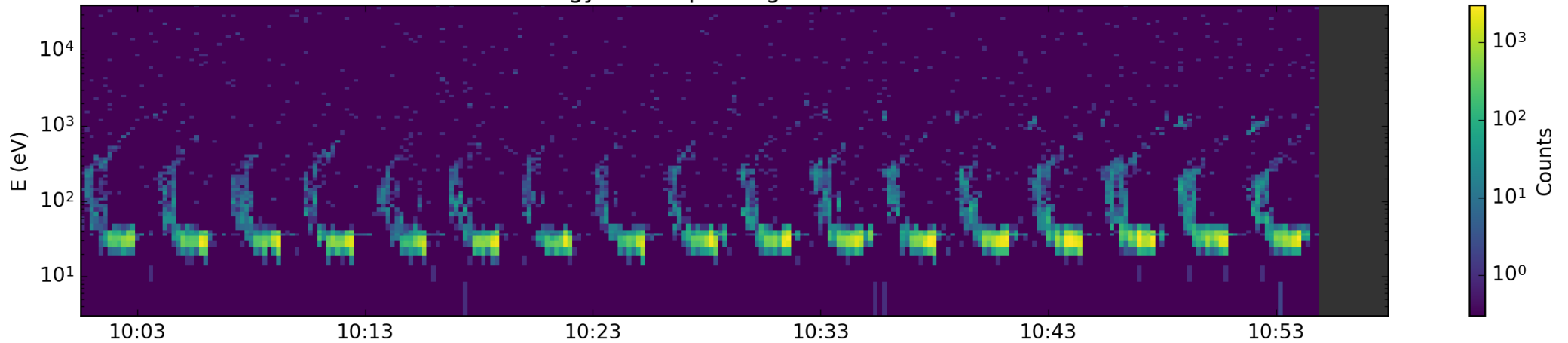


2016-1-4, 23 UT

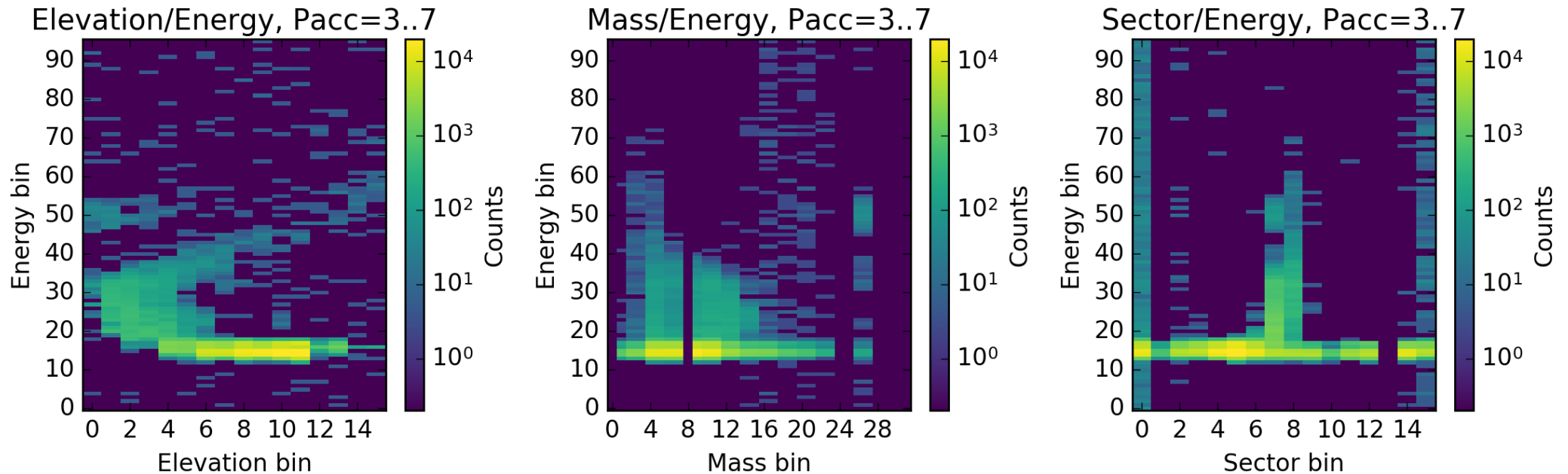


H₂O⁺ acceleration to > 1 keV with "nose" dispersion

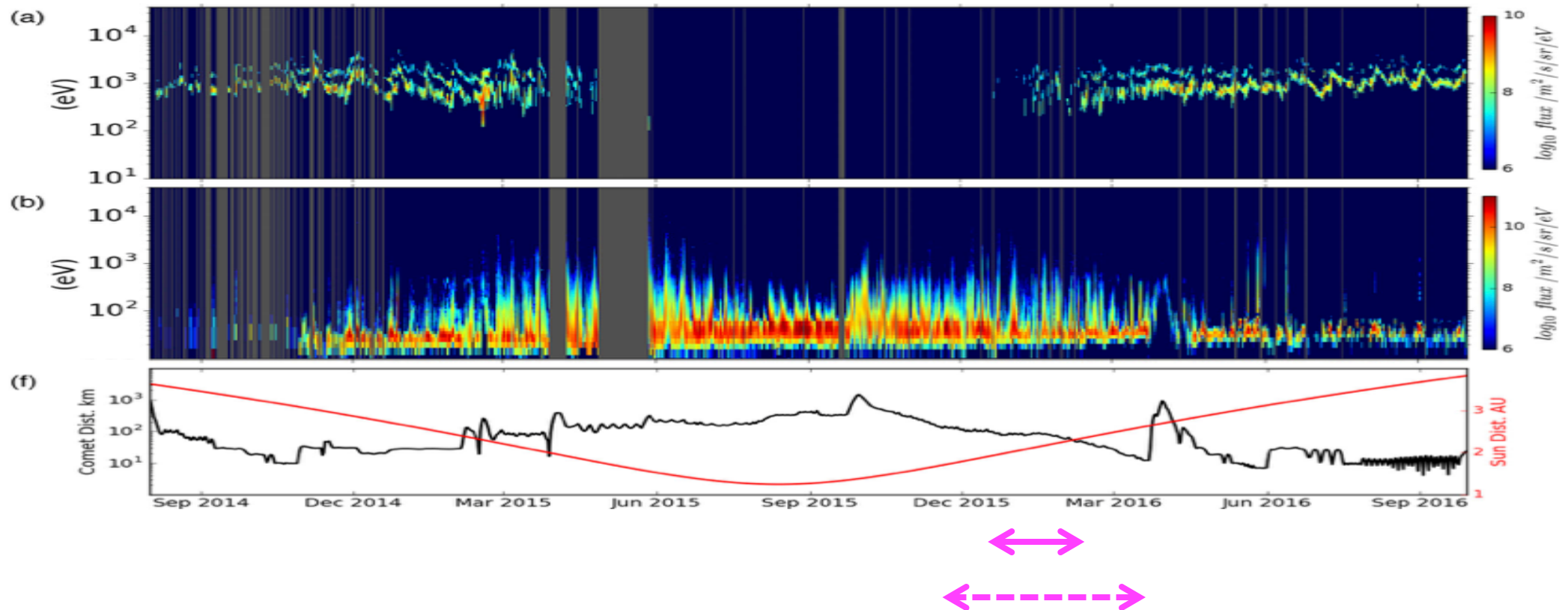
ICA Energy-Time Spectrogram 20160302T10



2016-3-2, 23 UT



H₂O⁺ acceleration to > 1 keV with "nose" dispersion



- Heavy ion with higher energy than SW energy near $x=0$
- Nose dispersion (opposite dispersion for high/low energy)
- Surveyed after perigee: > 1keV only Dec-Feb (2 months)

work continues.....