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?

(2) Mass loading for magnetized planet with ionosphere

(3) Evidence of mass loading in the cusp and plasma mantle

(4) Is quantitatively important? YES!

(5) Further estimation (combining model and observations)

(6) Summary and Implications

(7) Extra importance for strong CMEs and Earth's evolution

(8) Future direction : simulation and Mars/comet application

(1) Mass-load = Inelastic mixing

(1) **Momentum conservation**:

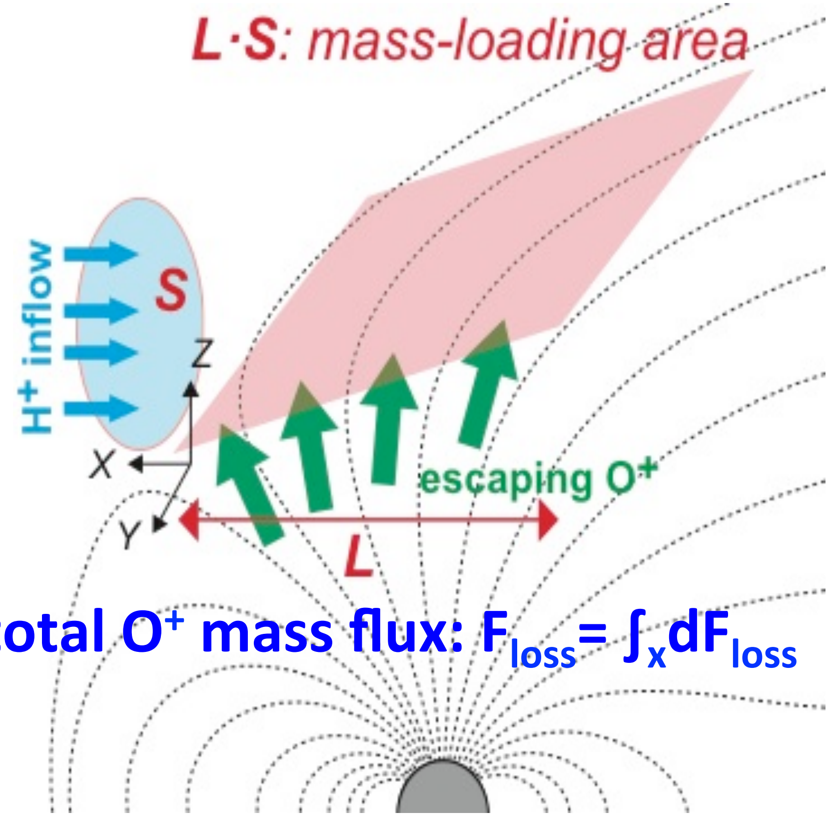
momentum flux in the -x direction = $\rho u^2 S|_{before} = (\rho+\Delta\rho)(u+\Delta u)^2 S\ |_{after}$

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

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

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

Simplify the mixing configuration



total O$^+$ mass flux: $F_{loss} = \int_x dF_{loss}$

(2) Role of the ionosphere

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(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

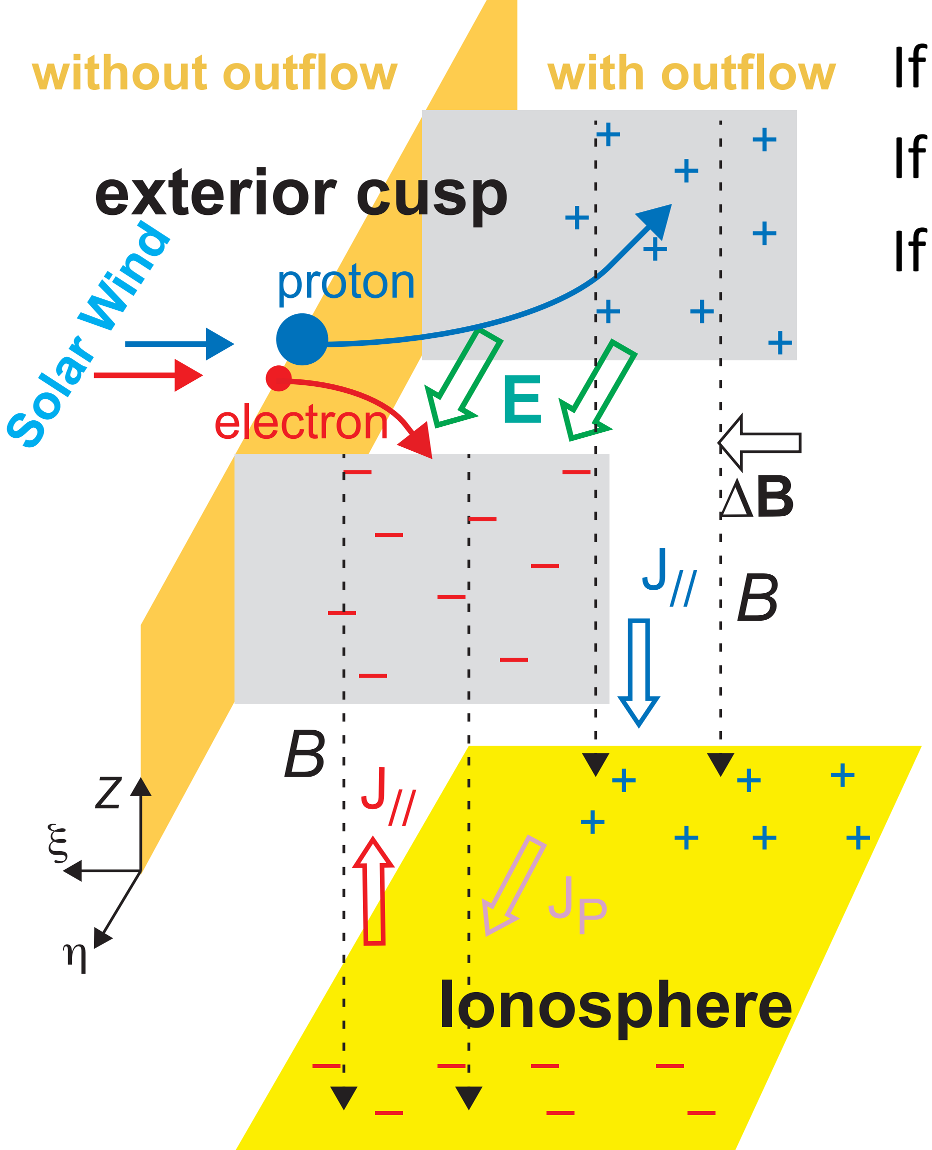
(3b) magnetized planet: mass-loading region is geomagnetically to the ionosphere, a conducting surface

⇒ separated charges can leave toward the ionosphere

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

(2) Role of the ionosphere

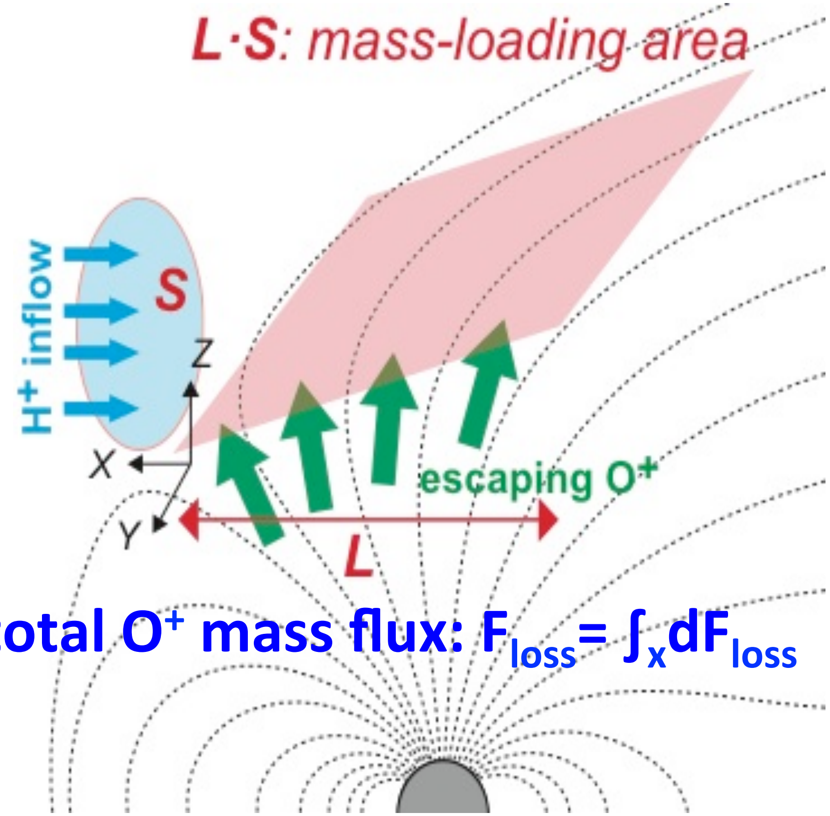
MHD dynamo during deceleration



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

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

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



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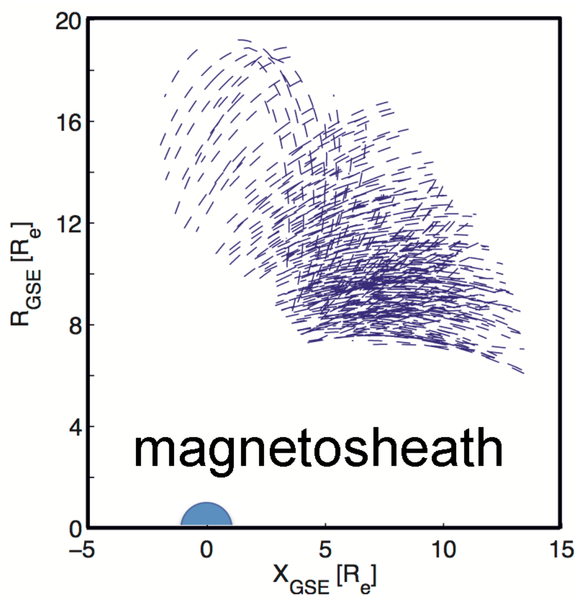
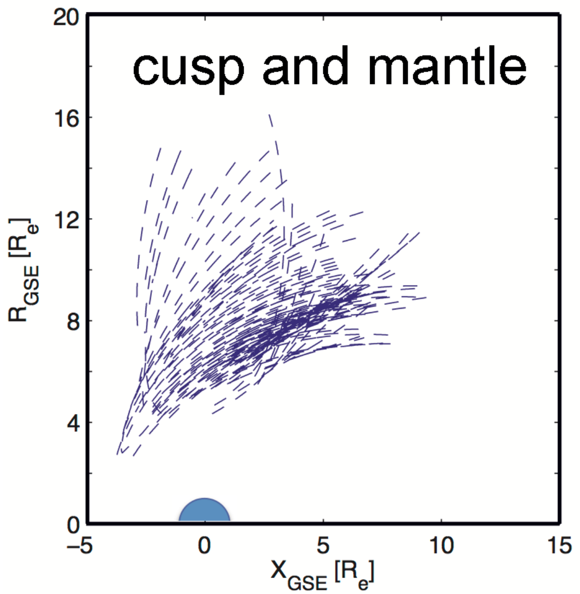
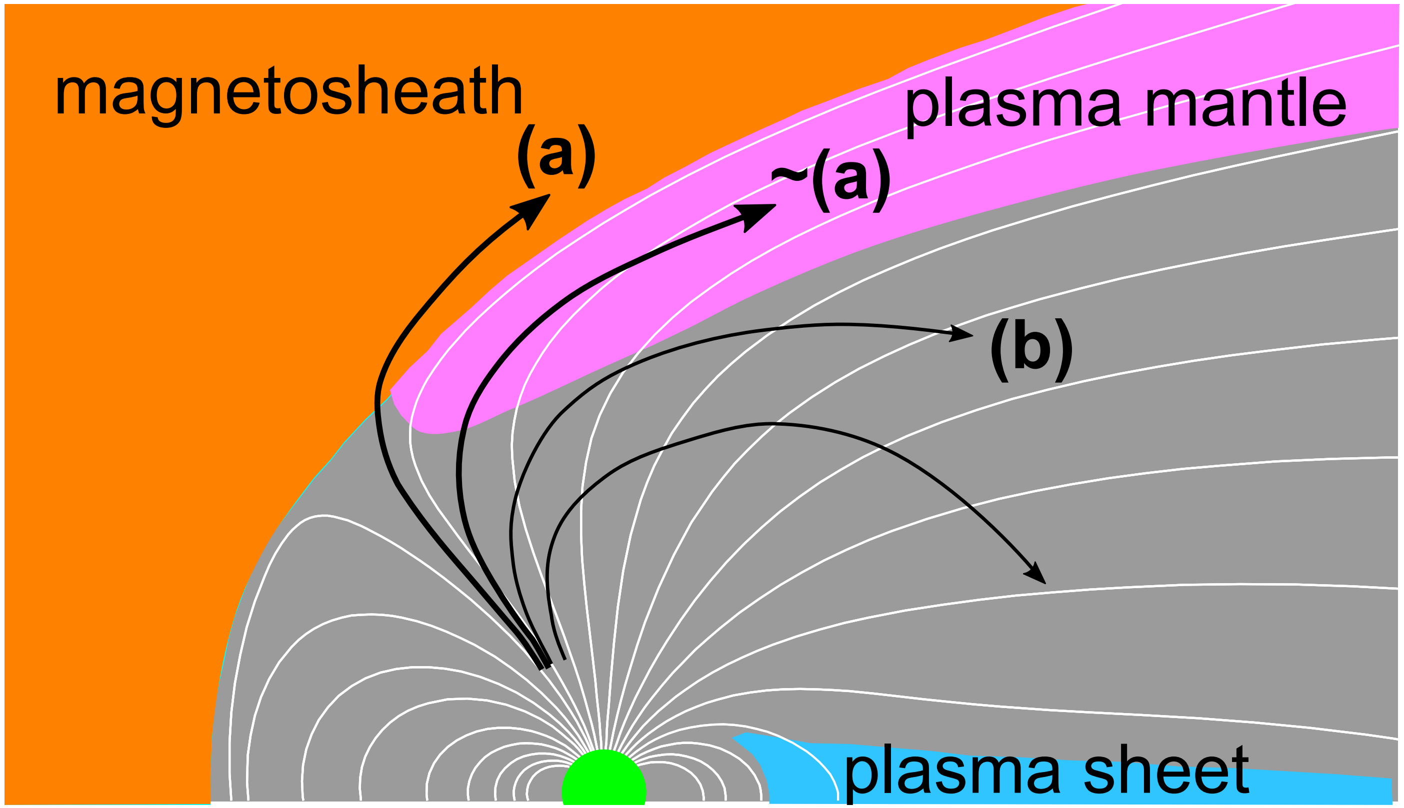
(3) O^+ observation by Cluster/CIS





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



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(3) O^+ observation by Cluster/CIS

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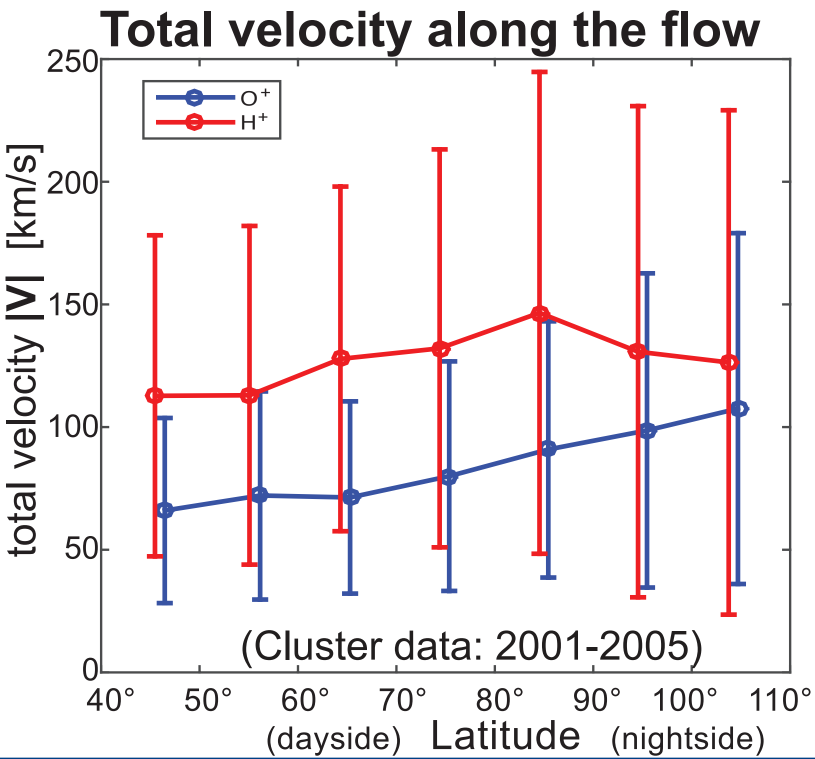

V_{O+} increases while V_{H+} decreases

⇒ Mixing is indeed inelastic toward the common velocity

⇒ $\Delta K/K = \Delta u/u$

Note: change is gradual in the –x direction

⇒ use integral form of dx distance

⇒ $\Delta K = \int dK$, where $dK/K = du/u \approx -d\rho/2\rho$

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(4) Estimation

* Using $d\rho$ = "added mass over dx / volume in dx"

$$= dF_{loss}/uS$$

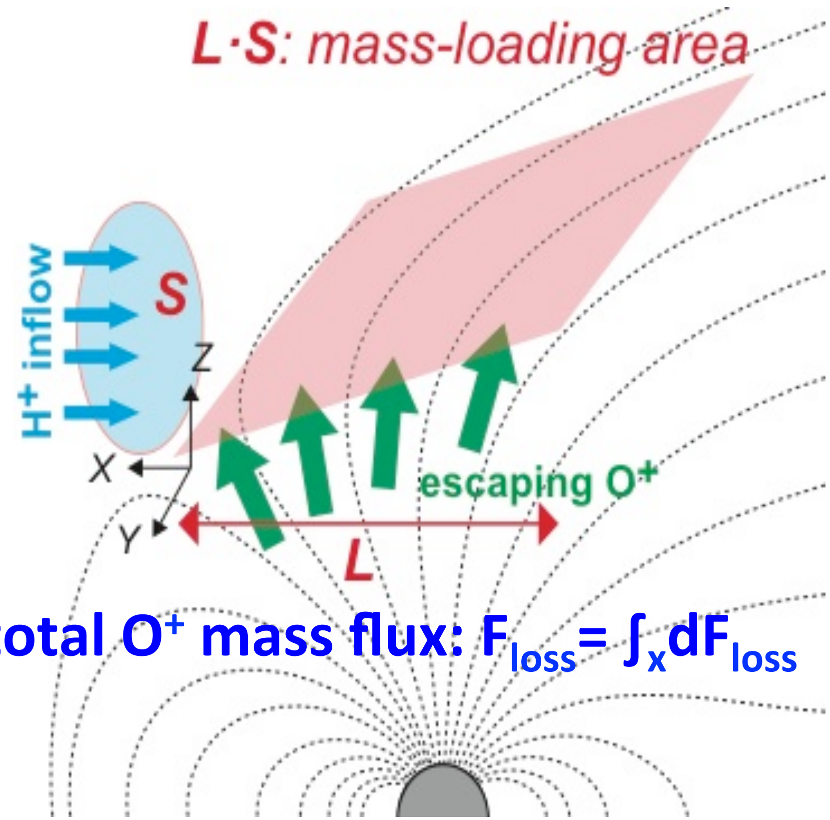
$$\Delta K/K_{in} = (-1/2)\cdot\int^{L} d\rho(x)/\rho(x)$$

$$= (-1/2)\cdot\int^{L} dF_{loss}(x)u^2(x)/(\rho(x)u^3(x)S(x))$$

$$= (-1/4K_{in})\cdot\int^{L} dF_{loss}(x)u^2(x)$$

$$\Rightarrow \Delta K \approx (-1/4)\cdot u^2_{SW}\cdot F_{load}$$

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.



total O^+ mass flux: $F_{loss} = \int_x dF_{loss}$

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(4) Estimation of amount

* Using dρ = "added mass over dx / volume in dx" $= dF_{loss}/uS$

$$\Delta K/K_{in} = (-1/2)\cdot\int^{L} d\rho(x)/\rho(x)$$
$$= (-1/2)\cdot\int^{L} dF_{loss}(x)u^2(x)/(\rho(x)u^3(x)S(x))$$
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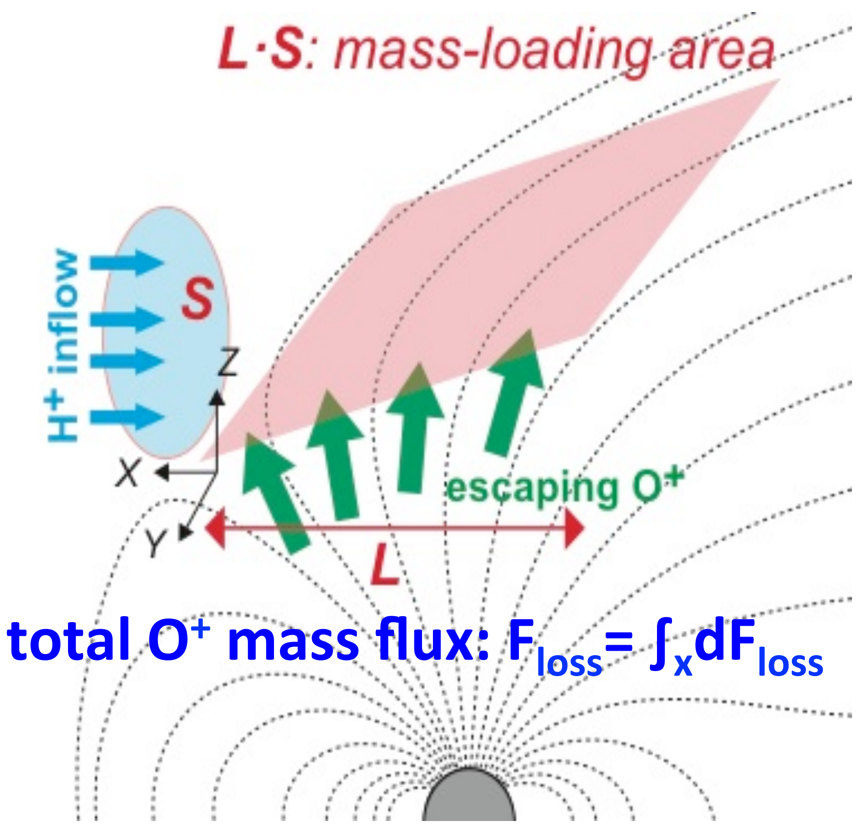
where K_{in} is the solar wind kinetic energy flux into the mass-loading area, F_{load} is total mass flux of escaping ions into the mass-loading area.

*** Amount is substantial:**

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

$\Rightarrow$ extract 7% of kinetic energy E

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



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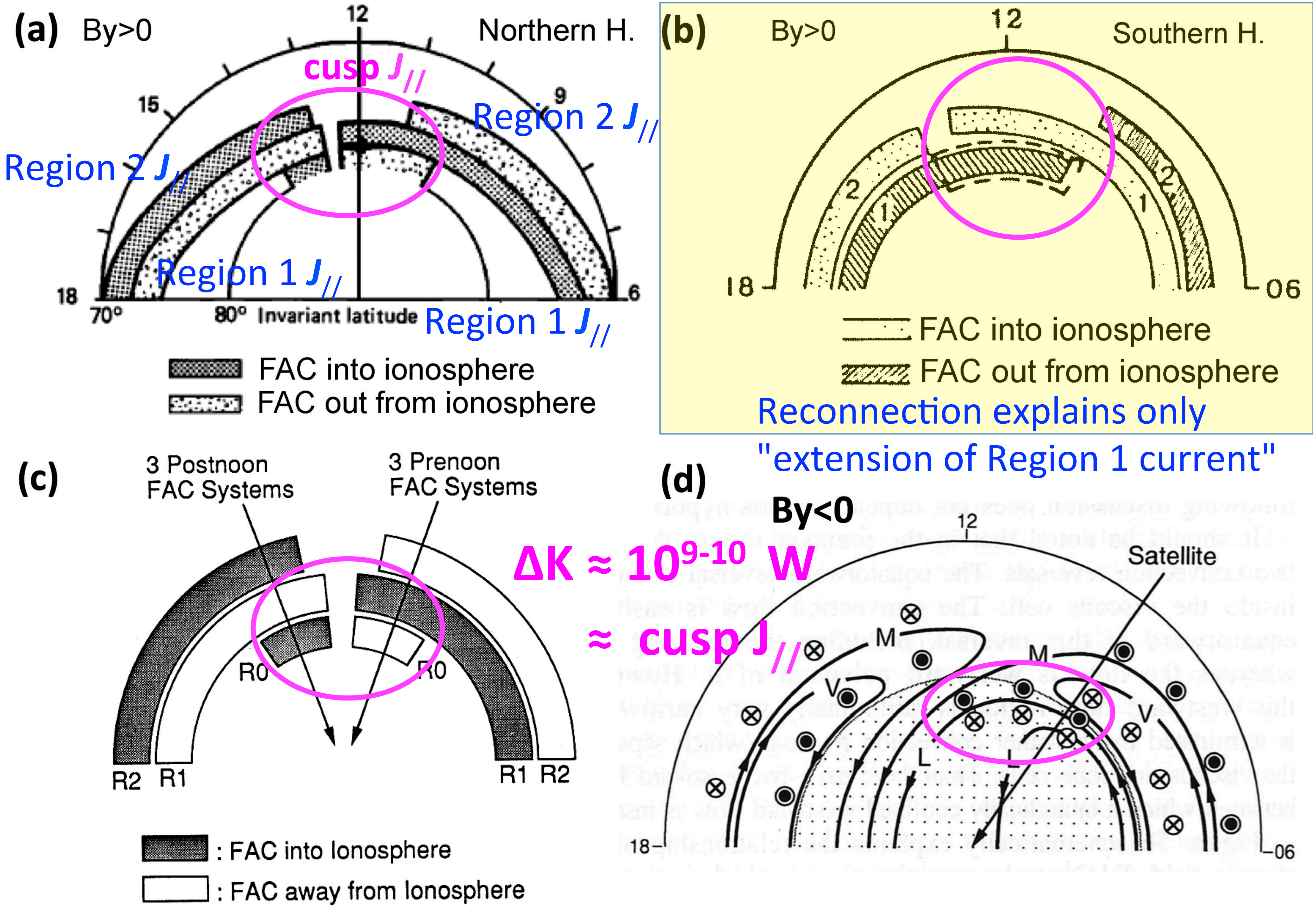
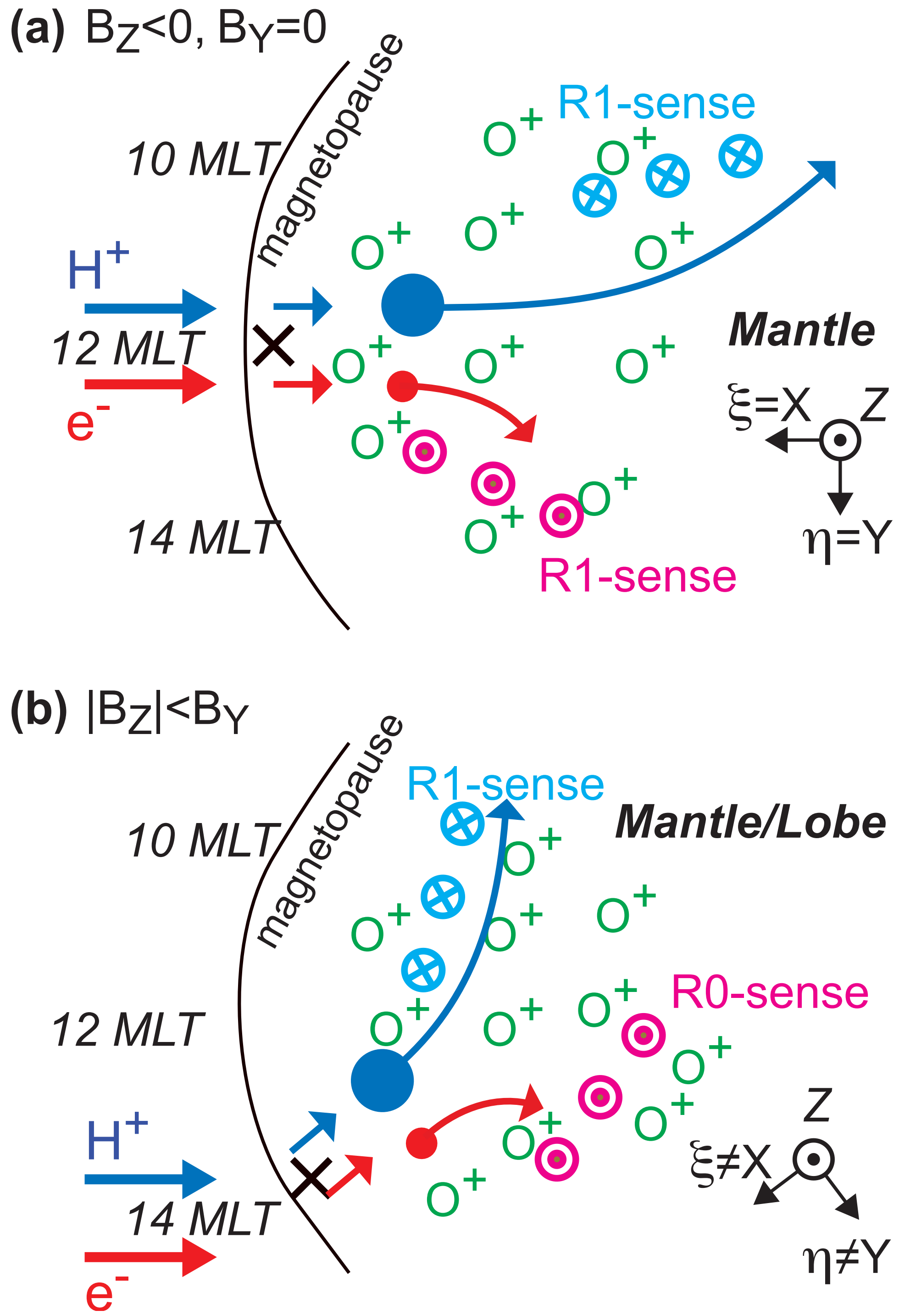

(a) By>0
Northern H.
12
cusp J//
15
9
Region 2 J//
Region 2 J//
Region 1 J//
18
6
70°
80° Invariant latitude
Region 1 J//
FAC into ionosphere
FAC out from ionosphere
(b) By>0
12
Southern H.
2
1
1
2
18
06
FAC into ionosphere
FAC out from ionosphere
Reconnection explains only
"extension of Region 1 current"
(c)
3 Postnoon FAC Systems
3 Prenoon FAC Systems
R0
R0
R2 R1
R1 R2
: FAC into Ionosphere
: FAC away from Ionosphere
(d)
By<0
12
Satellite
ΔK ≈ 10^9-10 W
≈ cusp J//
M
M
V
V
L
L
18
06

IMF B_Y effect can also be explained



(5) Combine with feedback to ion escape

Escape flux is a function of energy input:

$F_{loss} = F_{loss}(\Delta K)$

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

$\Rightarrow$ **Positive feedback !**

Add two empirical relations

(1) Ion Loss Rate (Cluster):

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

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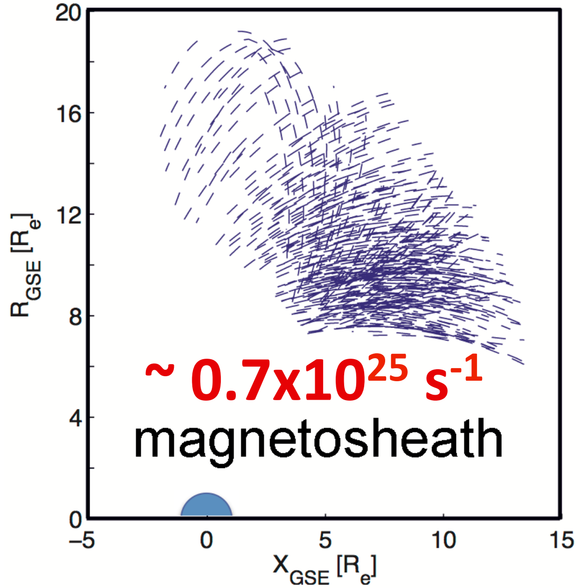
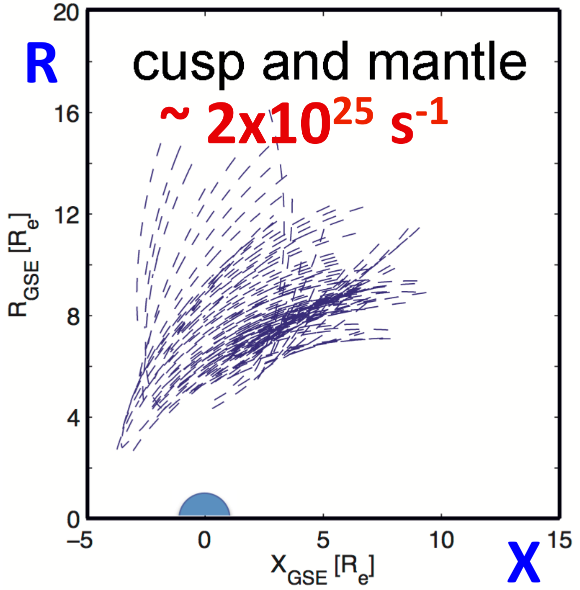
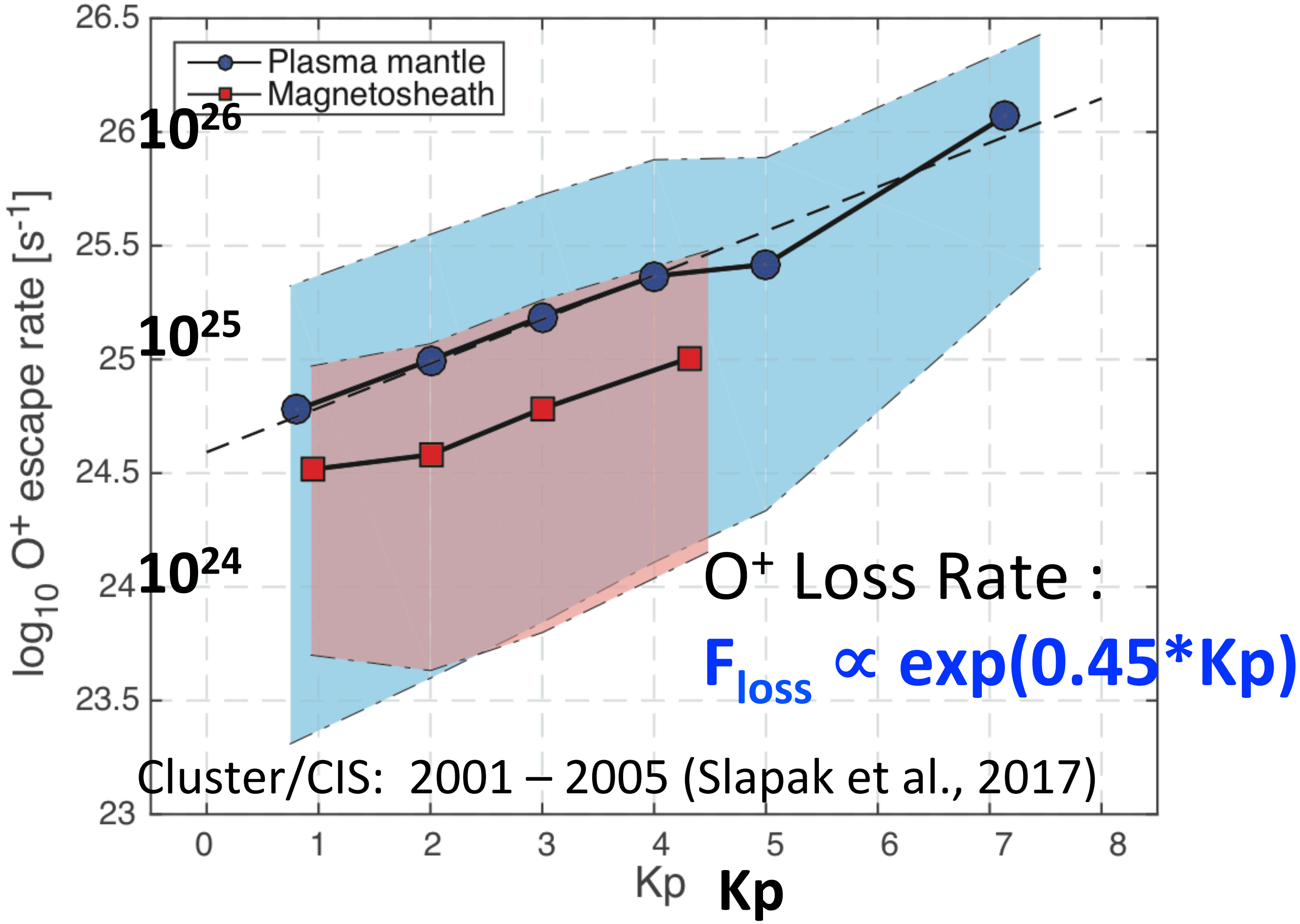
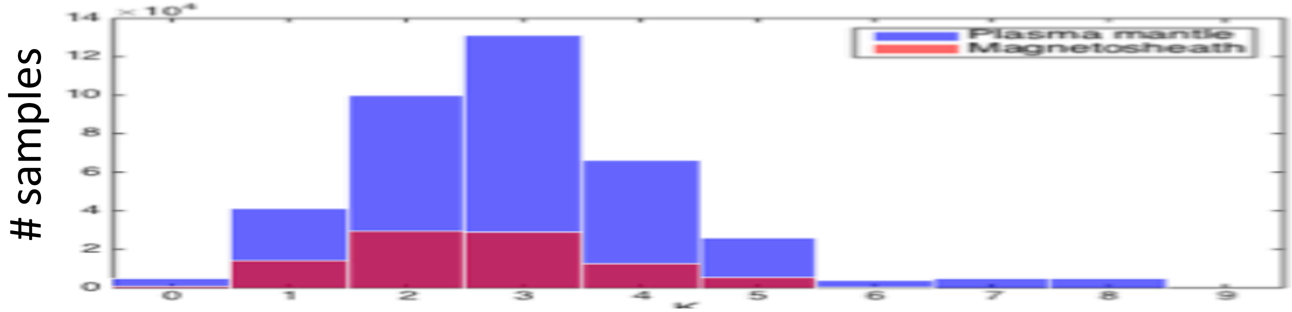
(5) Combine with feedback to ion escape

from Slapak et al., (2017)









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⇒ **Positive feedback !**

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(1) Ion Loss Rate (Cluster):

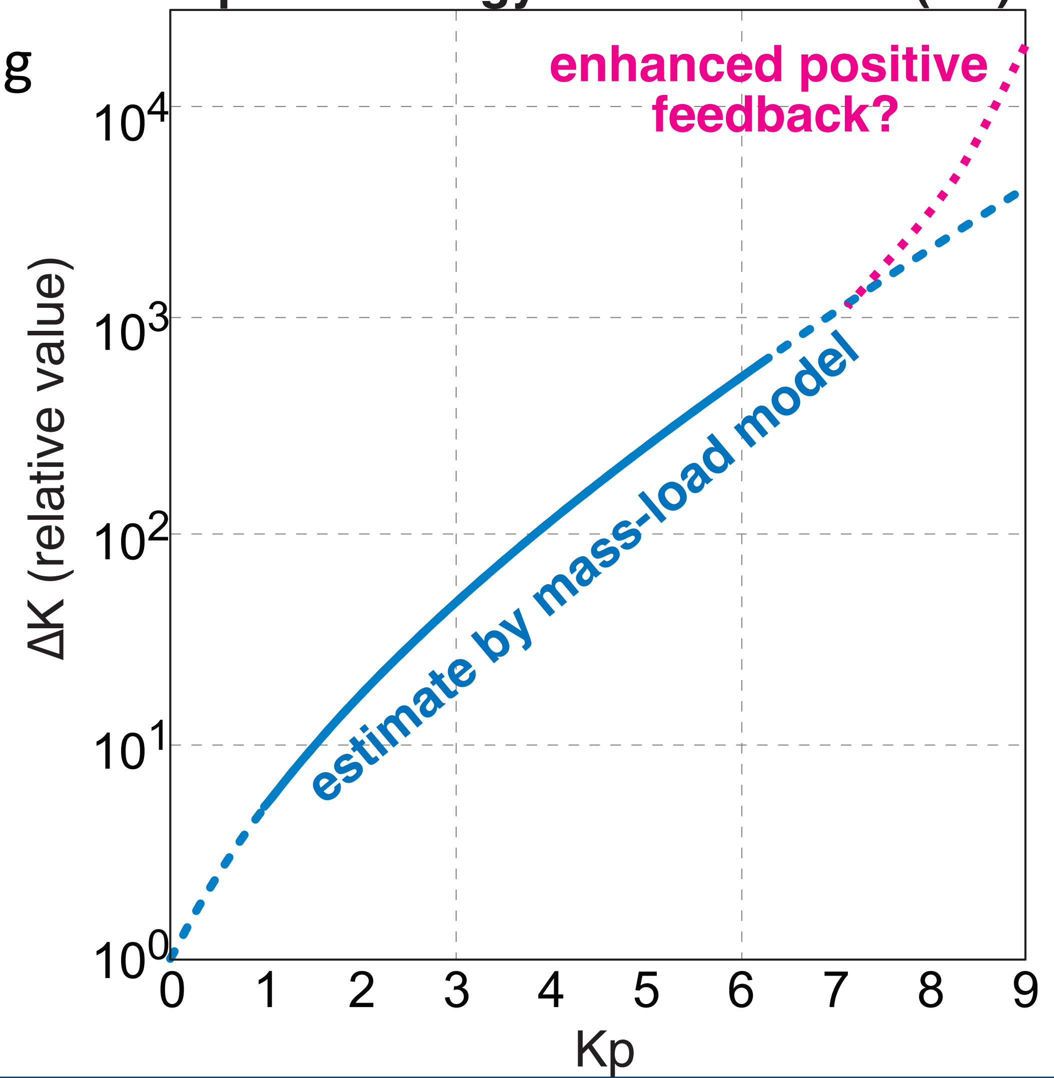
$F_{loss} \propto \exp(0.45*Kp)$

(2) Kp and V_{SW} :

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

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

Kp vs. energy extraction rate (ΔK)



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Key Point of the model

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

$\Delta K \propto (m_O/m_H)\cdot(n_O/n_H)$ ~ substantial

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

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

(c) Using empirical non-linear relation of F_{loss} and Kp (where Kp is a good proxy of ΔK), ΔK-Kp 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 Kp because

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

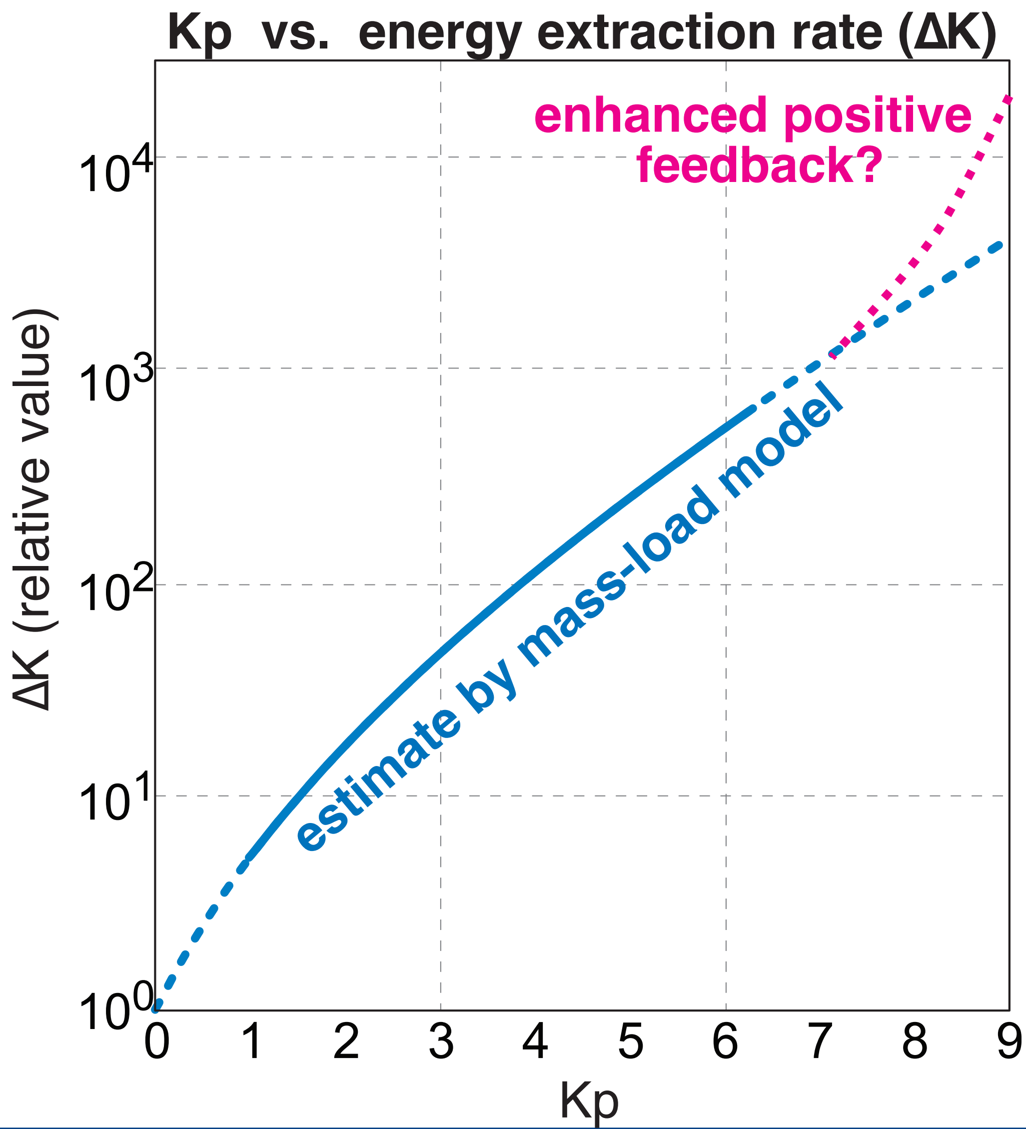
Mass-loading efficiency $\propto \exp(0.45*Kp)$: non-linear

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

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

(2) Considering Kp ∝ ε (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)



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

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

$F_{loss} \propto \exp(0.45*Kp) \Rightarrow F_{loss} \approx 10^{27}$/s @ancient (Kp equivalent to ≥ 10)

$\Rightarrow \int F_{loss} \approx 10^{18}$ kg ≈ atmospheric O_2

(3b) Combine with *Schillings et al*. (2017) for Kp ≥ 7+ (cf. ancient time)

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

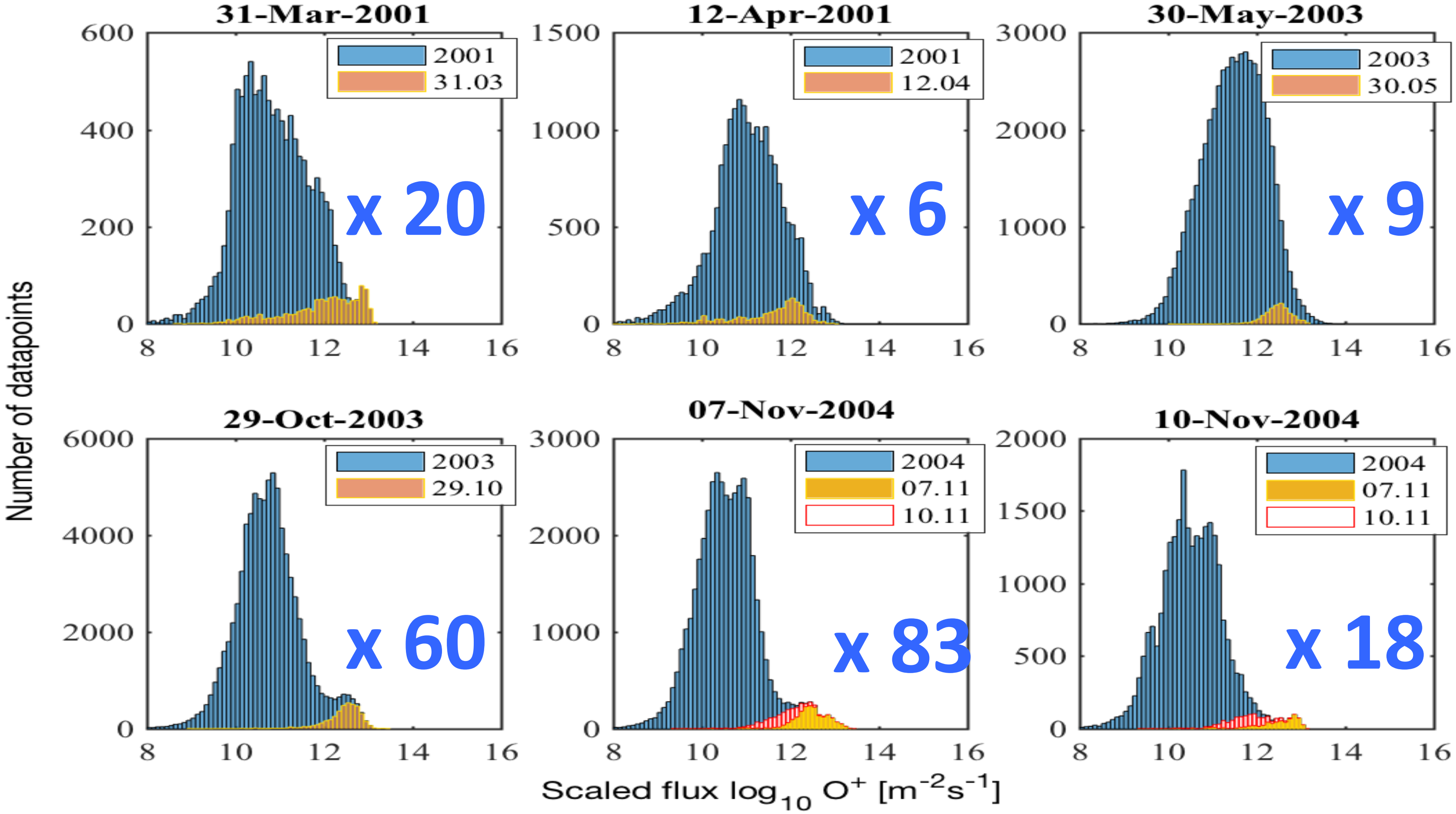
(7) Further non-linearity for Kp>7

from Schillings et al., (2017)

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-

(7) Further non-linearity for Kp>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

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

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

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(3b) Combine with *Schillings et al*. (2017) for Kp ≥ 7+ (cf. ancient time)

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

$\Rightarrow \int F \geq 5 \times 10^{18}$ kg (total atmospheric mass at present)

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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.

(8) Future direction

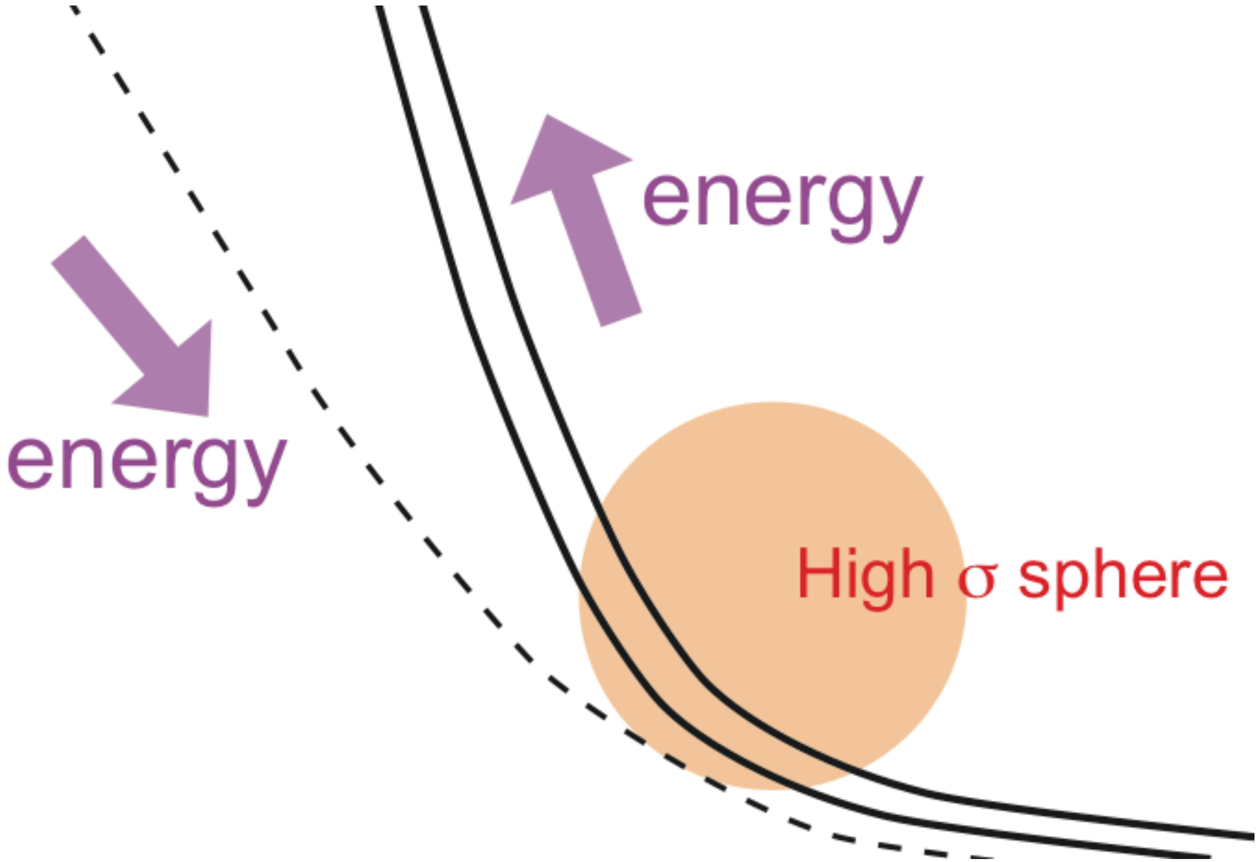
(A) Numerical simulation: fluid model allowing finite mass flux (in) and energy flux (out) should do the job.

(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 ?**



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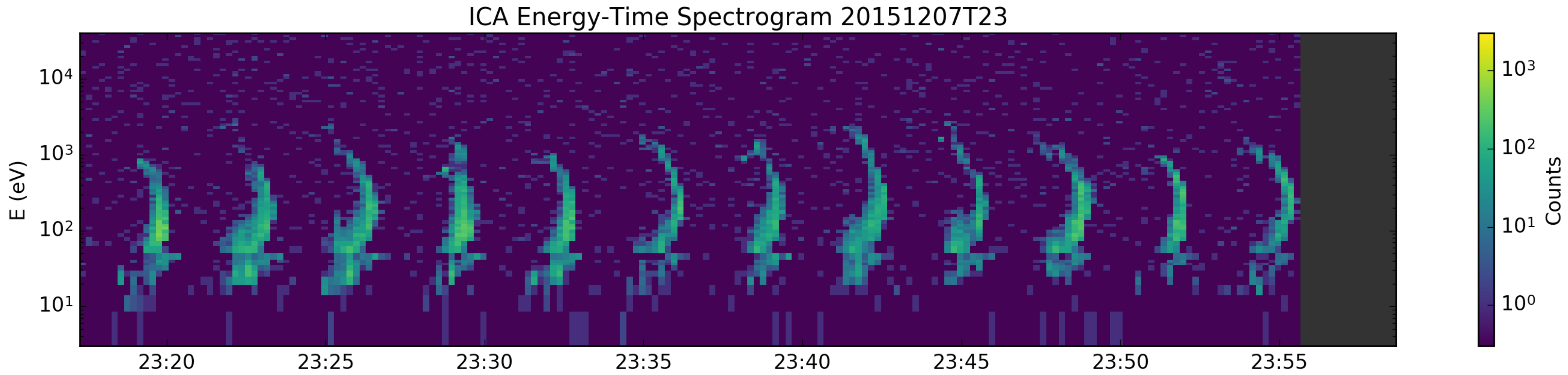
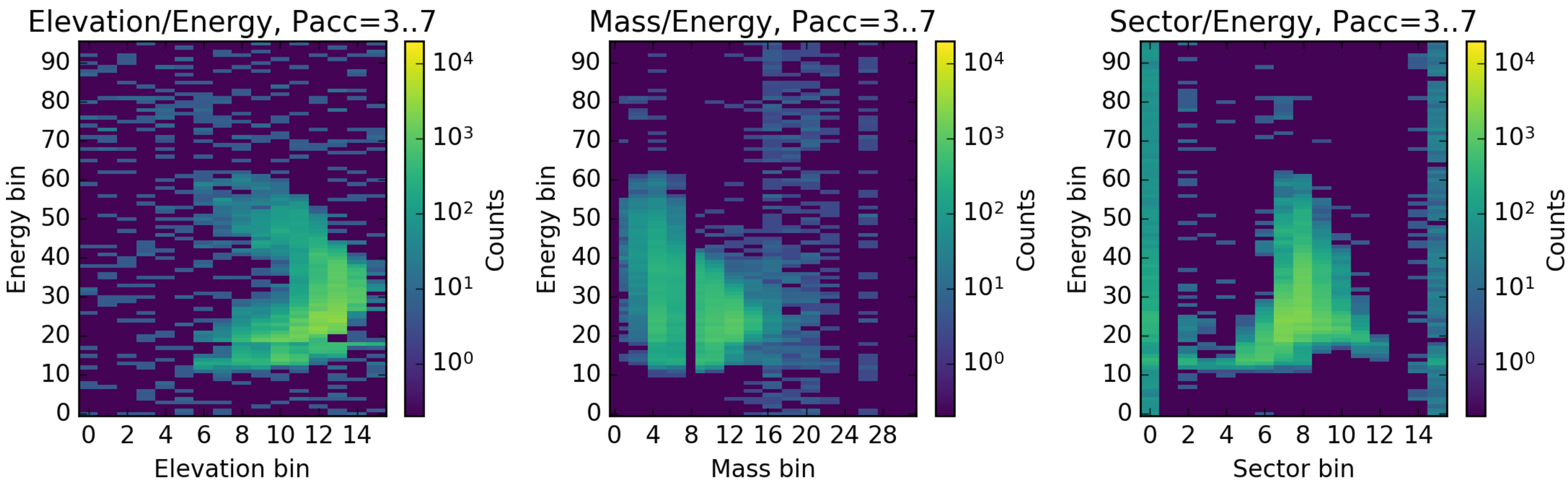
H_2O+ acceleration to > 1 keV with "nose" dispersion



2015-12-7, 23 UT



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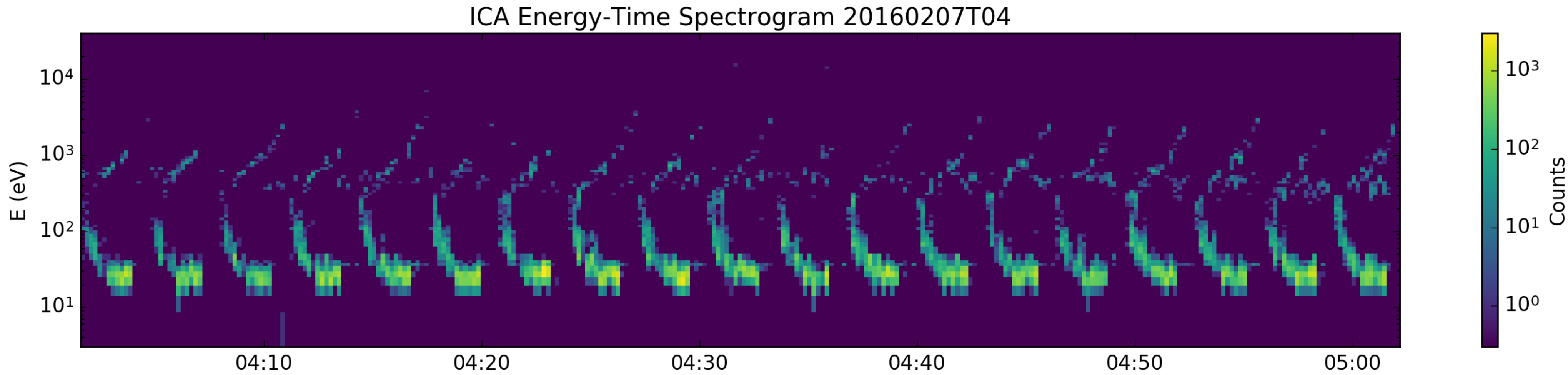
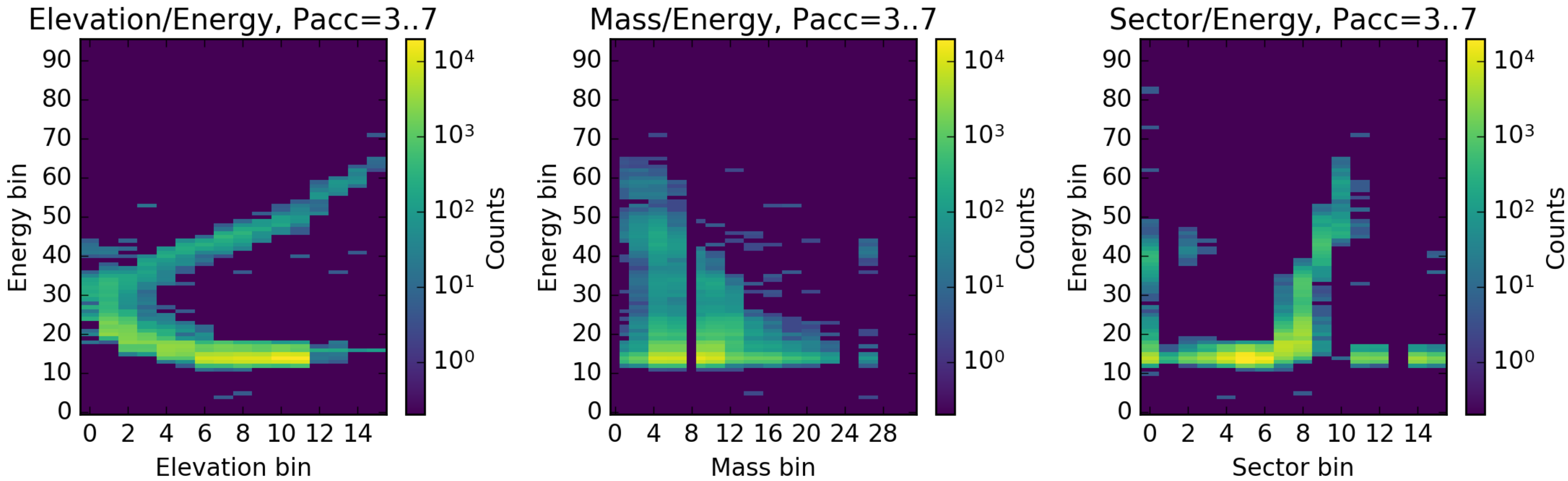


2016-2-7, 23 UT



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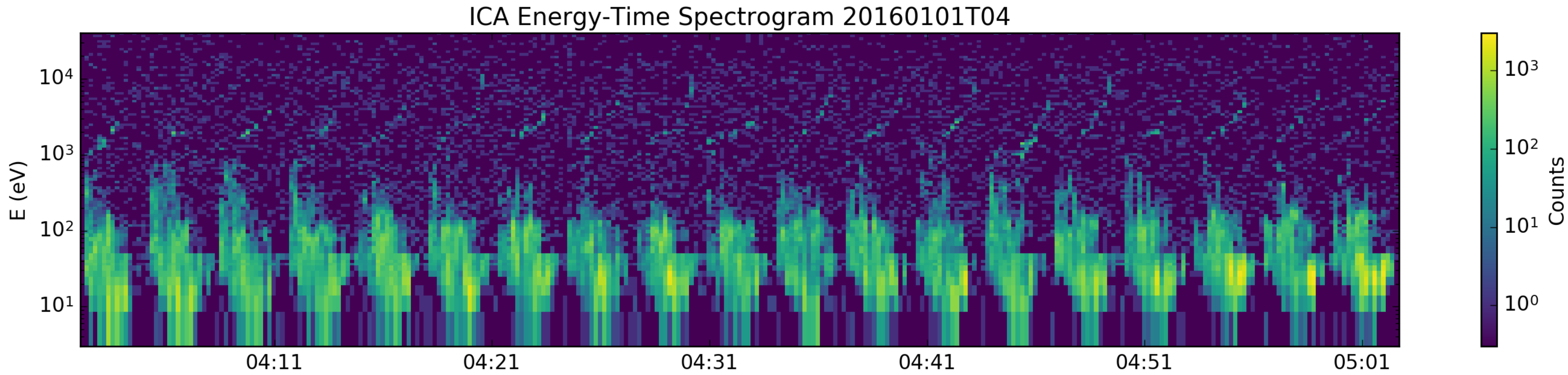
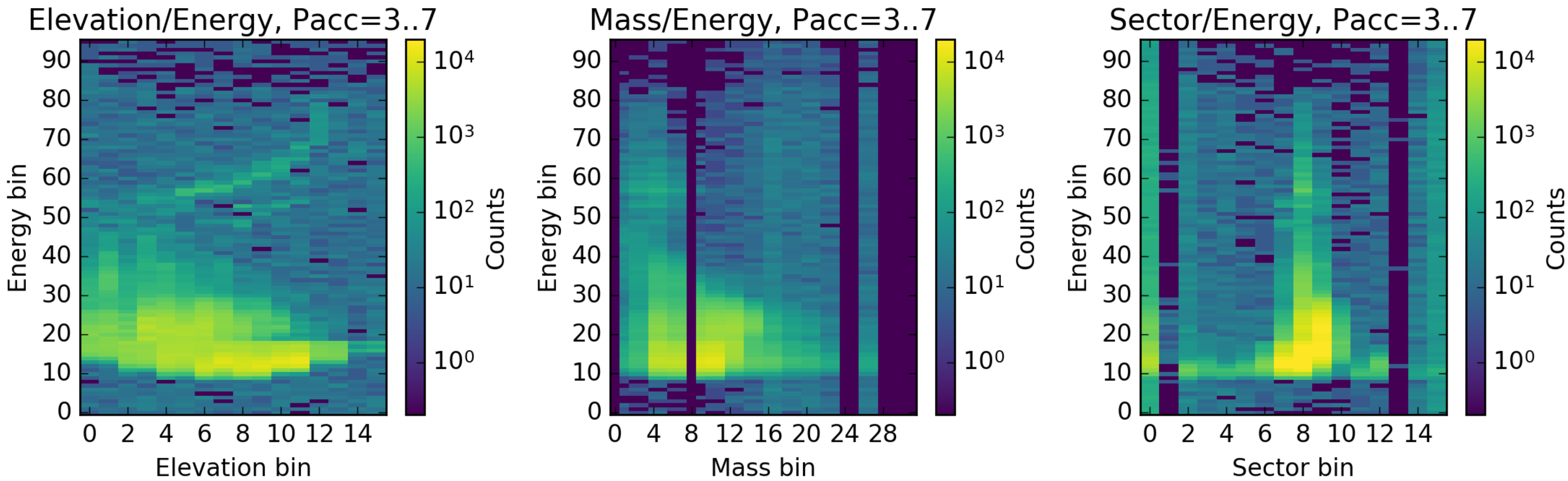


2016-1-4, 23 UT



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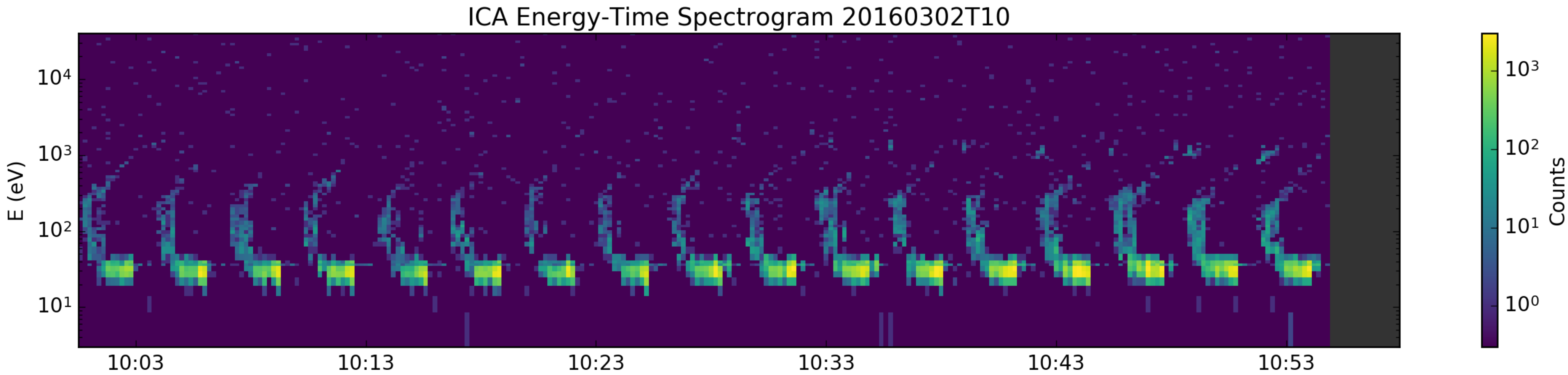
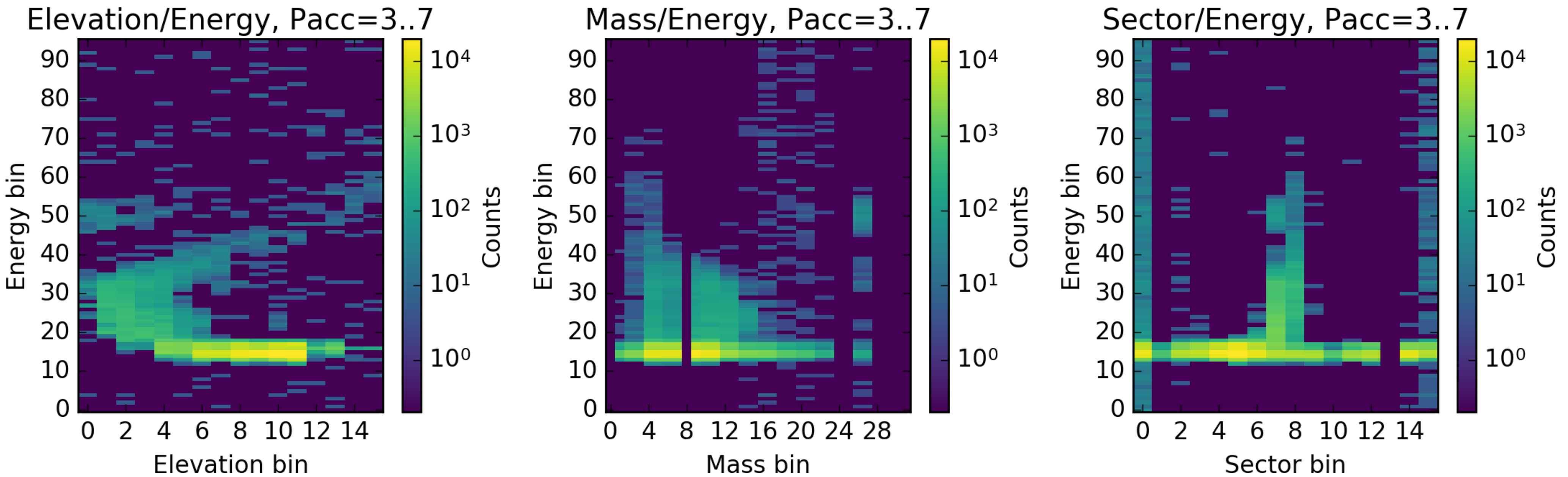


2016-3-2, 23 UT



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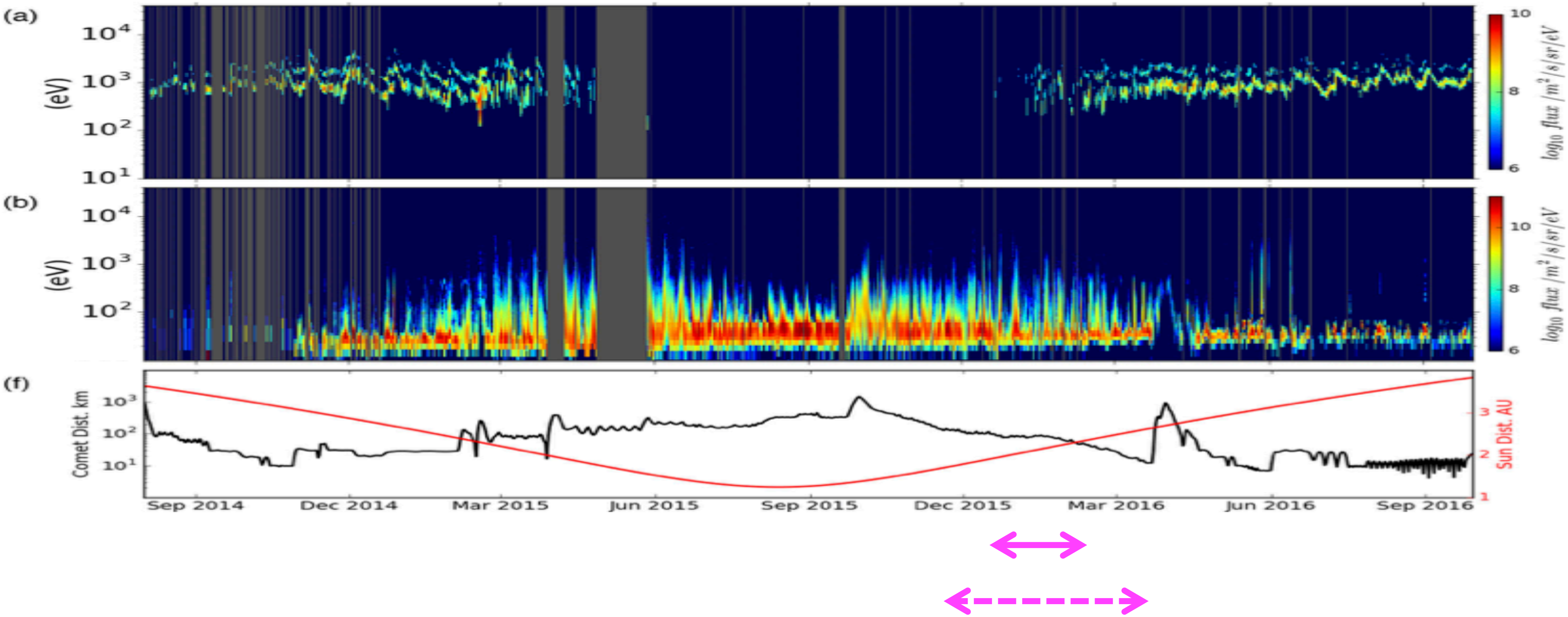

- **Heavy ion with higher energy than SW energy near x=0**
- **Nose dispersion (opposite dispersion for high/low energy)**
- **Surveyed after perigee: > 1keV only Dec-Feb (2 months)**

work continues……

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