Ion escape from the terrestrial magnetosphere: **New findings by Cluster** and remaining questions

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Outline

(1) Escape routes through different destinations
Sorry, no time for acceleration/heating mechanisms

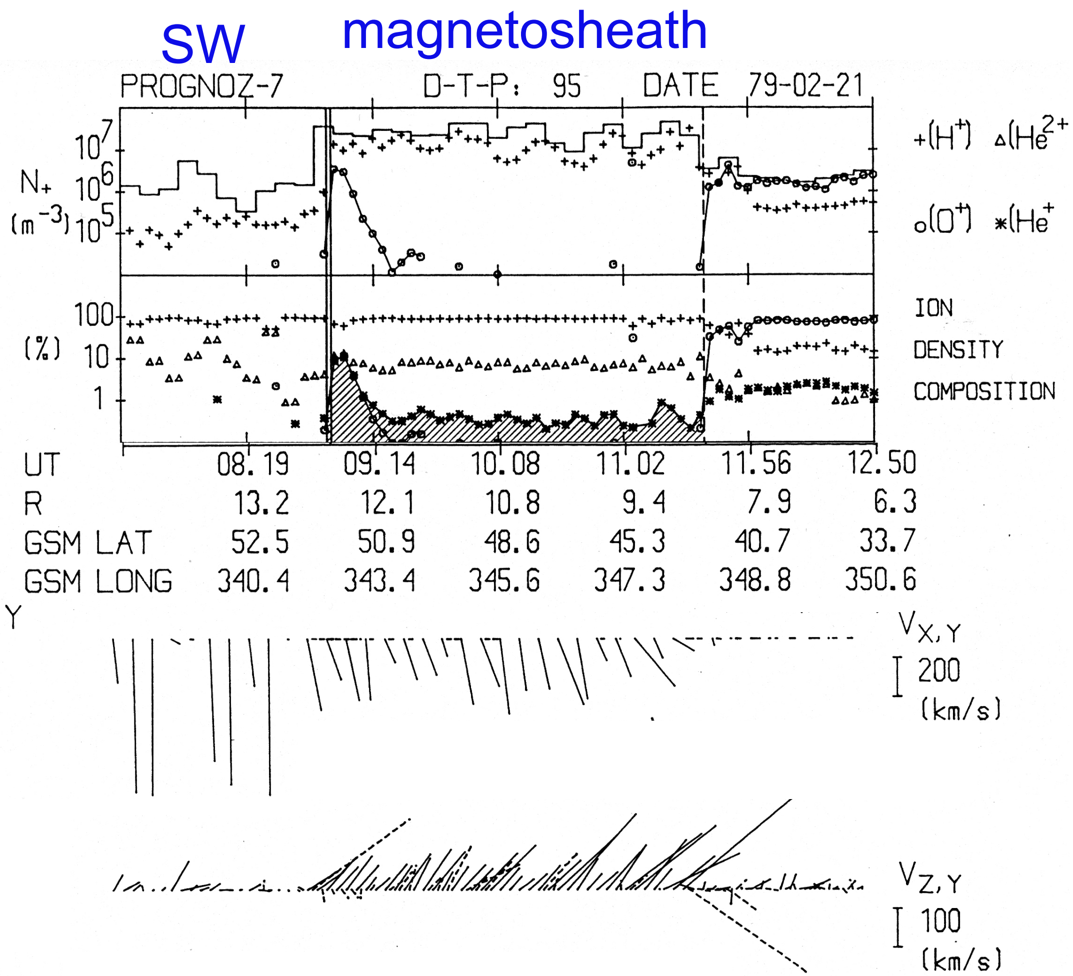
(2) Cluster Instruments that contributed

(3) Short-term effect on the Earth
Sorry, only for directly escaping ions, and no time for ions into the magnetosphere

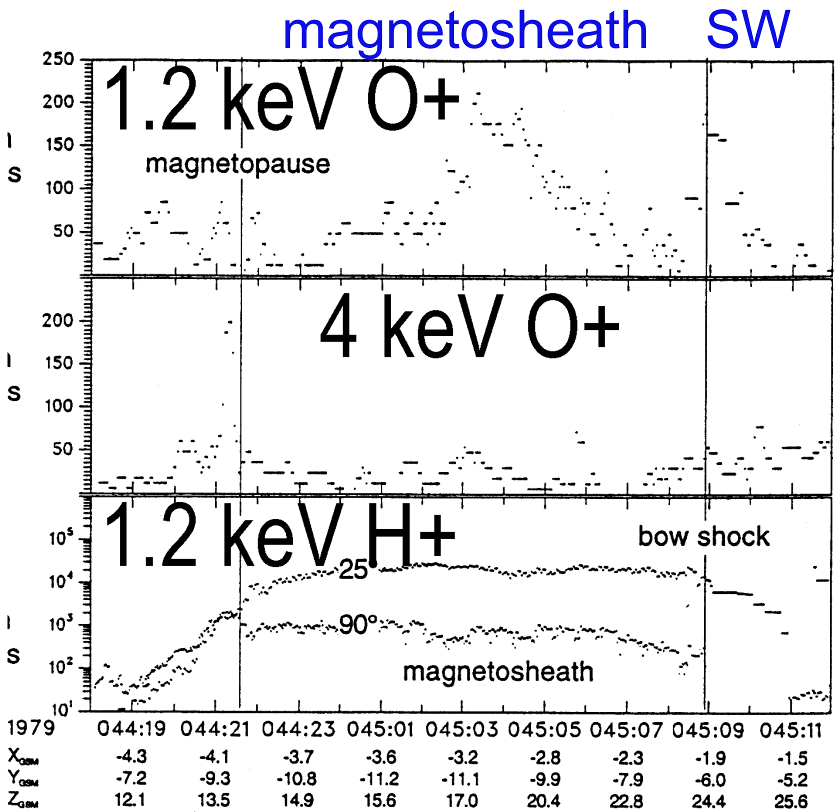
(4) Geological-scale effect on the Earth

cf. previous missions (magnetosheath O^+)

Prognoz 7 → too little energy channels



(Lundin et al., 1980)

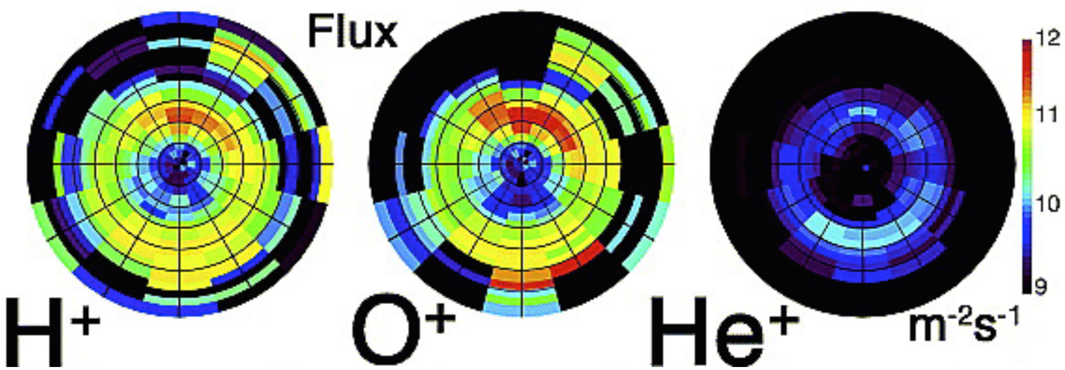


(Eklund et al.,1997)

cf. previous missions (polar outflow)

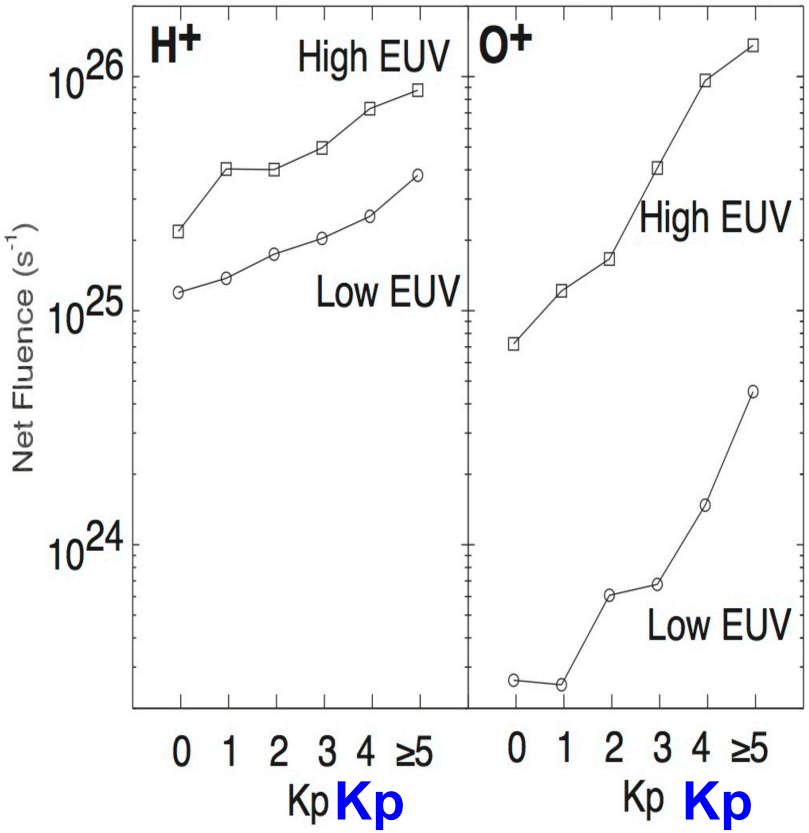
Polar view instead of **Magnetospheric view**
→ could not distinguish destination

Quiet time hot H^+ & O^+ ~ $0.3 \cdot 10^{25}$ s^{-1}



Polar perigee@8000km, 1996-1998
(Peterson et al., 2008)

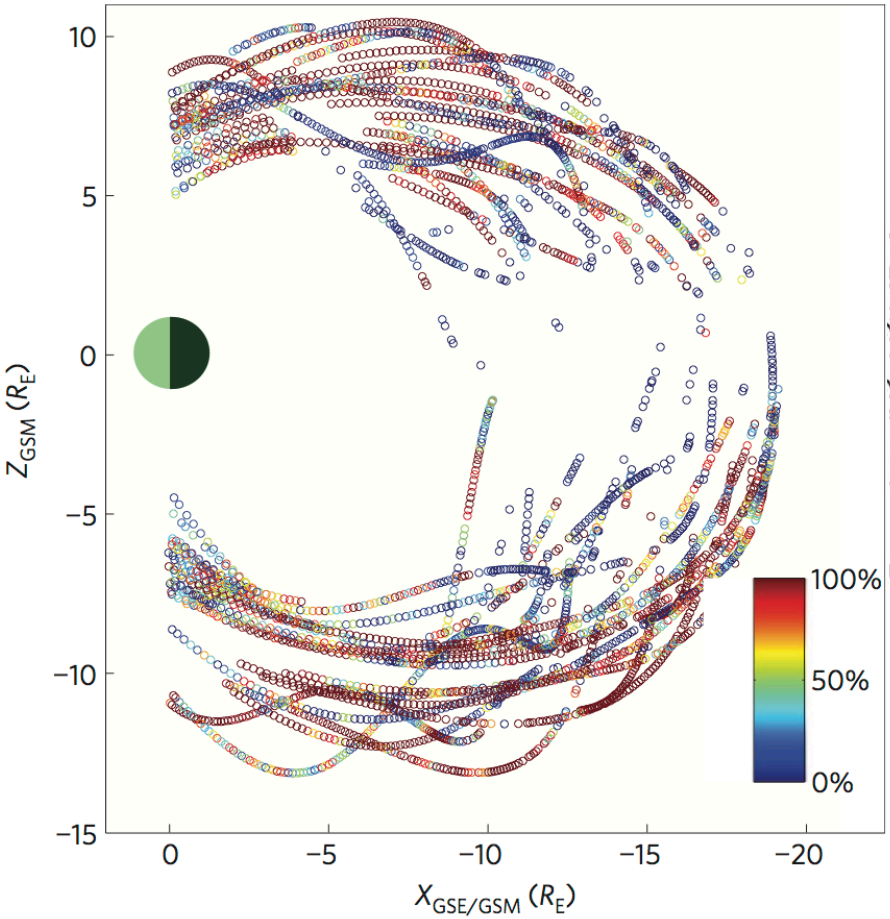
thermal H^+ & O^+ < 20 eV



Akebono@9000km, 1989-1998
(Cully et al., 2003)

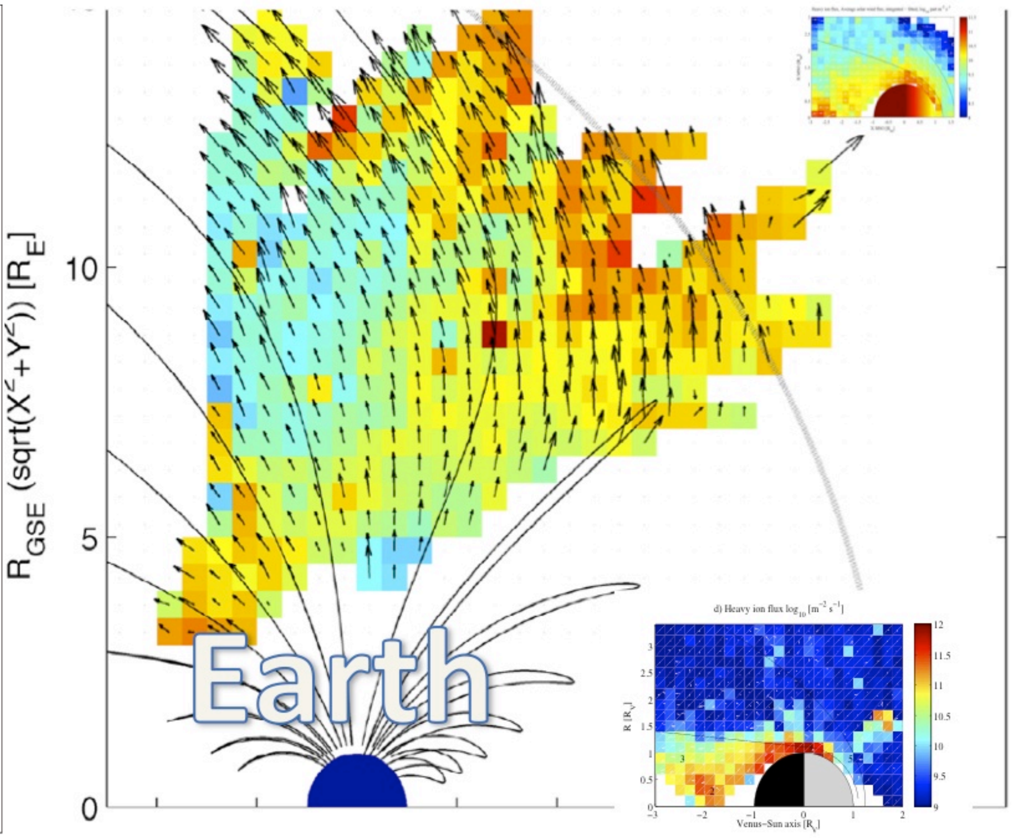
Cluster Examples (polar outflow)

Cold H^+ (EFW): tail ~ 10^{26} s^{-1}
supersonic ions ~ wave



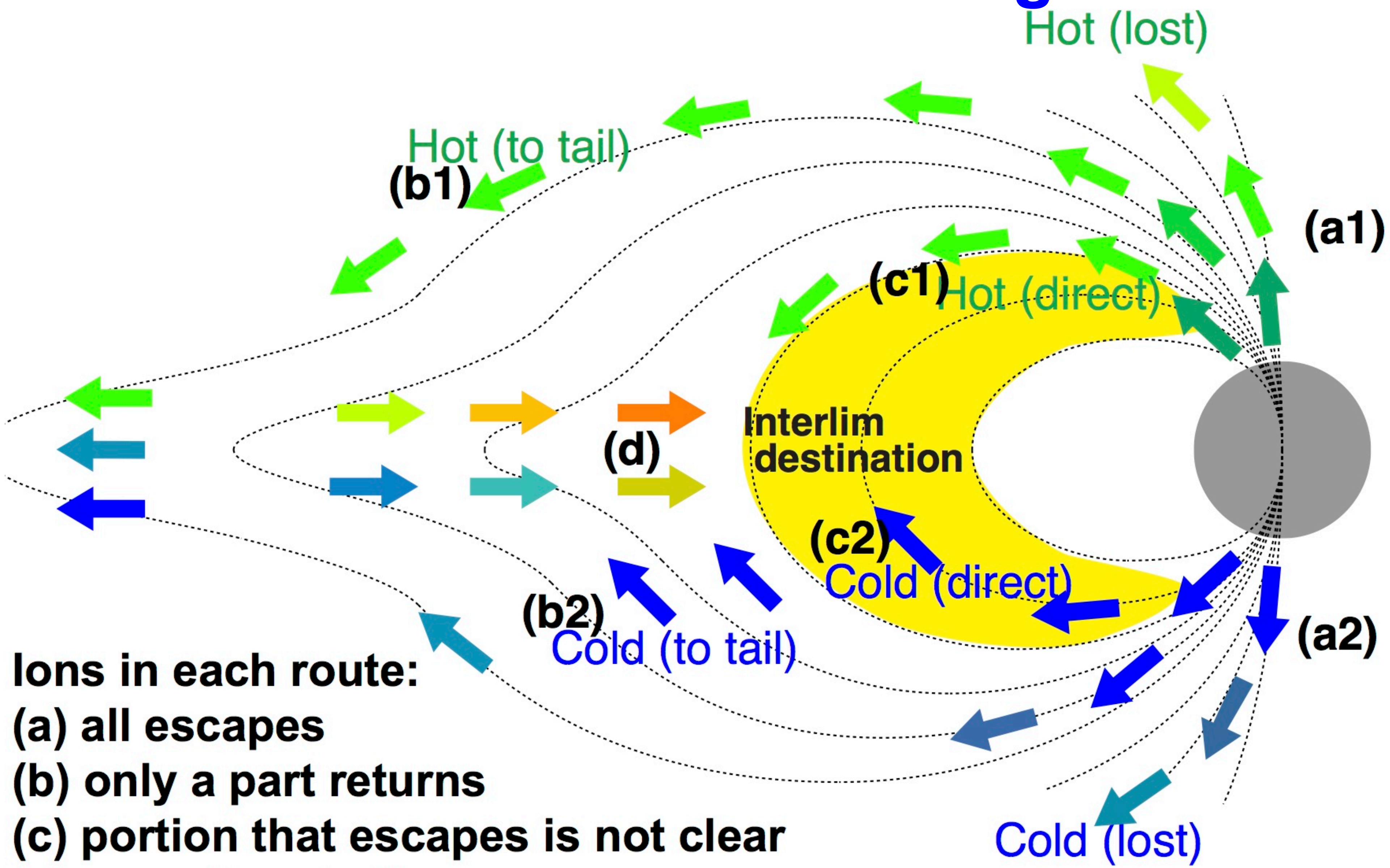
SC-3, 2002.07 - 2002.10
(Engwall et al., 2009)

Hot O^+(CIS) ~ escape 10^{25} s^{-1}
direct detection ~ 0.03 – 40 keV



2001 - 2005
(Nilsson et al., 2011, 2012)

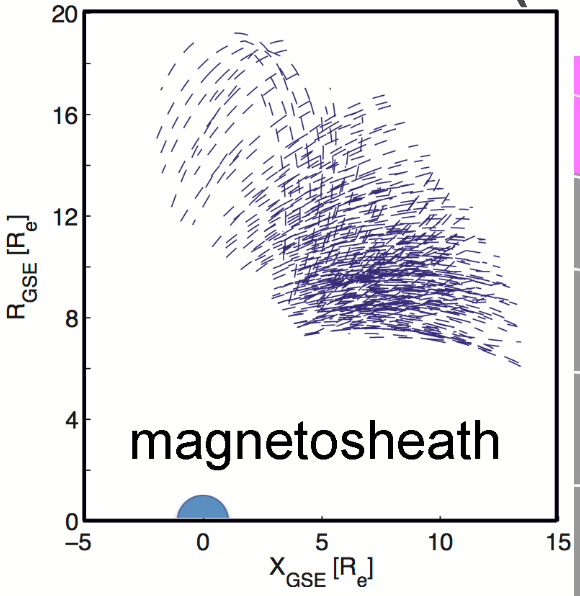
Destinations of outflowing ions

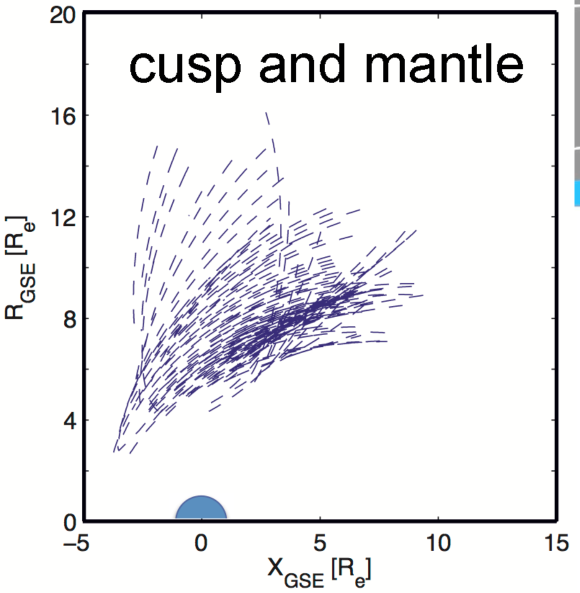


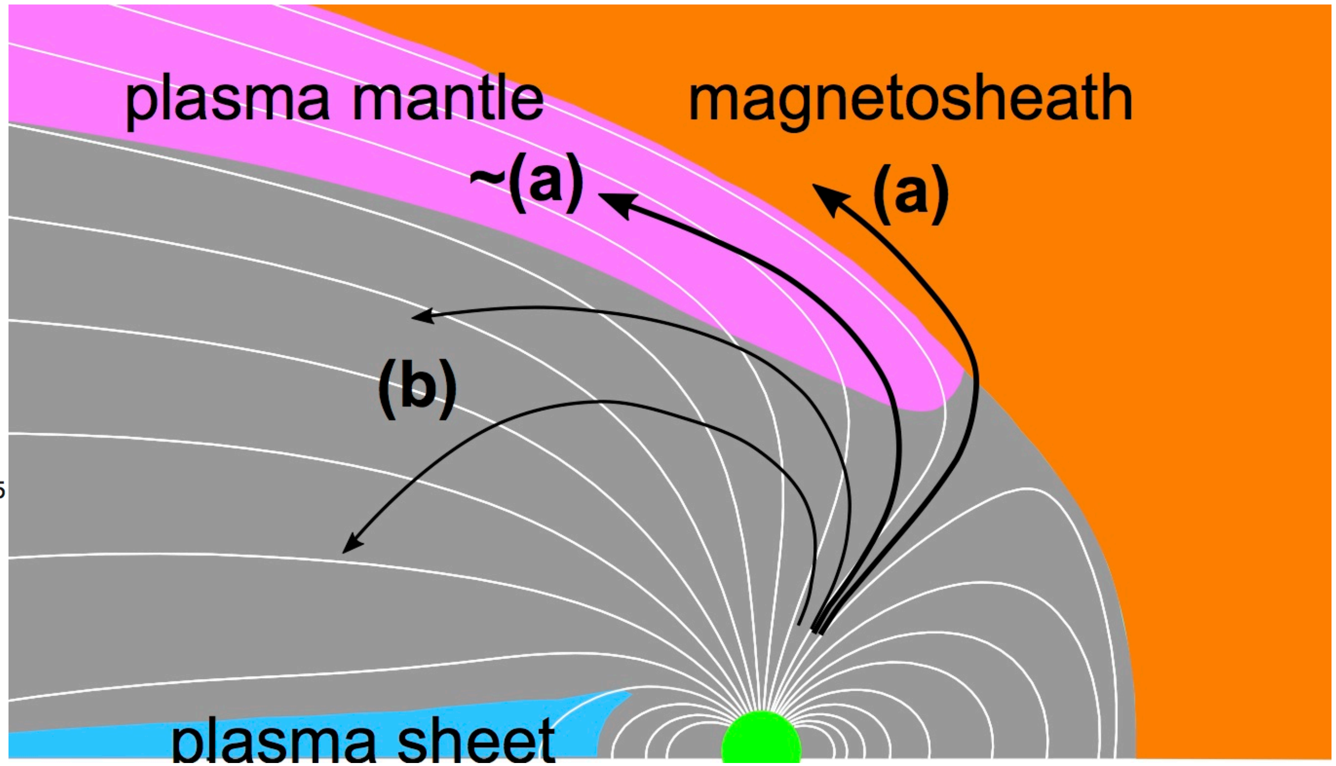
Ions in each route:
(a) all escapes
(b) only a part returns
(c) portion that escapes is not clear
(d) more than half escapes

Cluster could distinguish (a) and (b)

Cluster orbit (enough statistics)

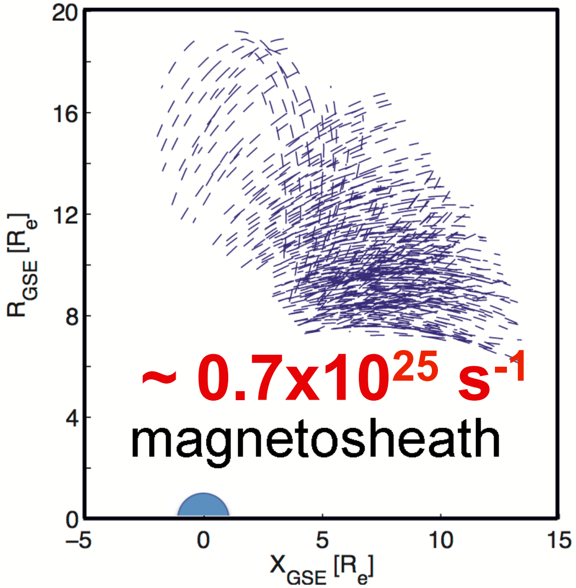


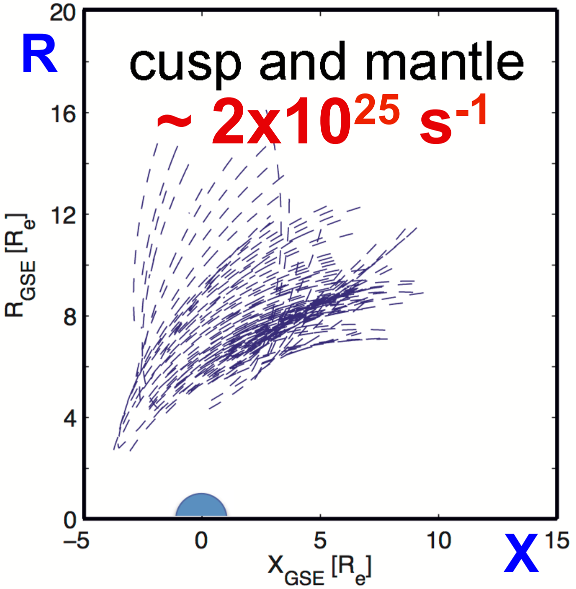


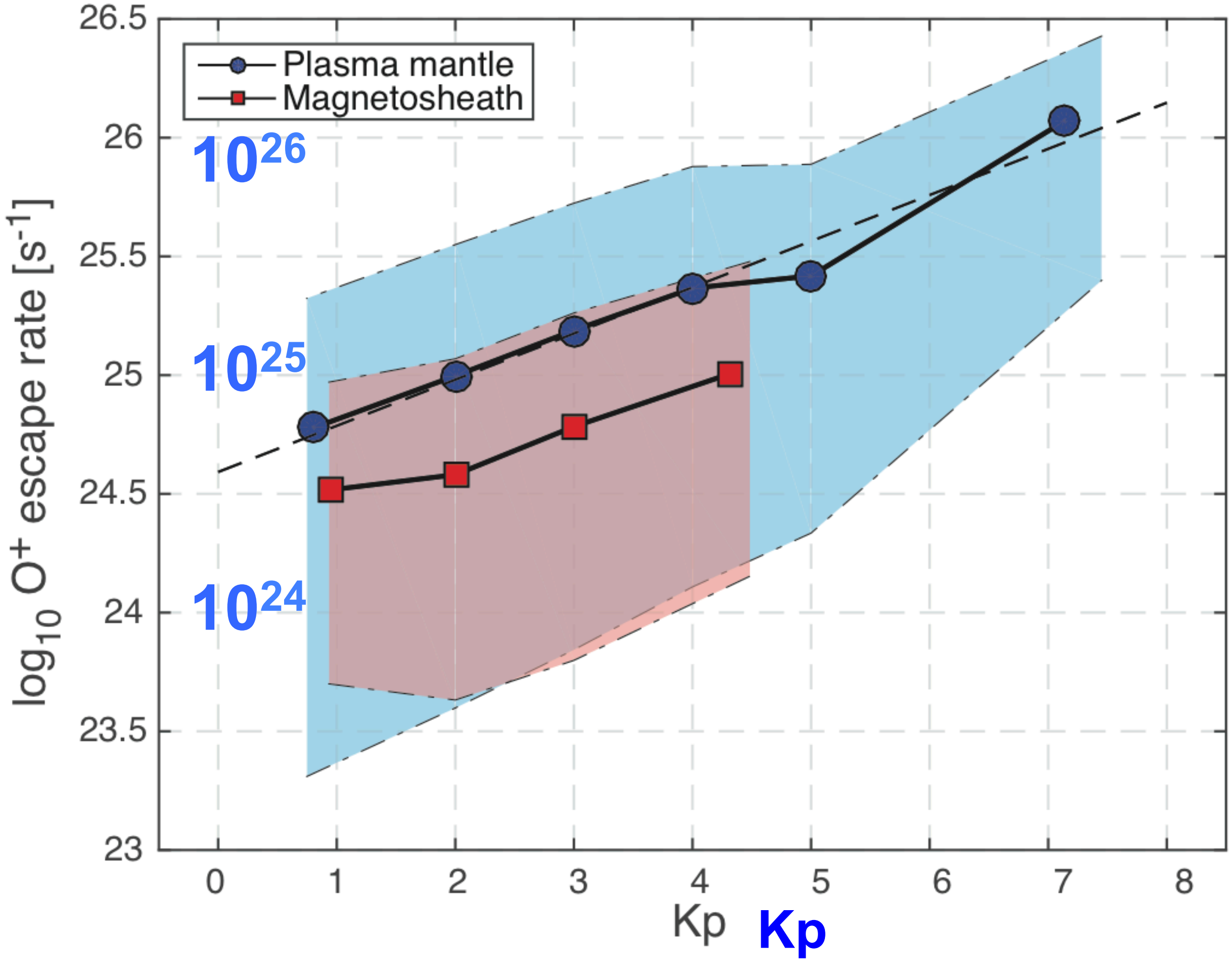


(a) Cluster/CIS obs. of direct escape

Hot O^+ observations



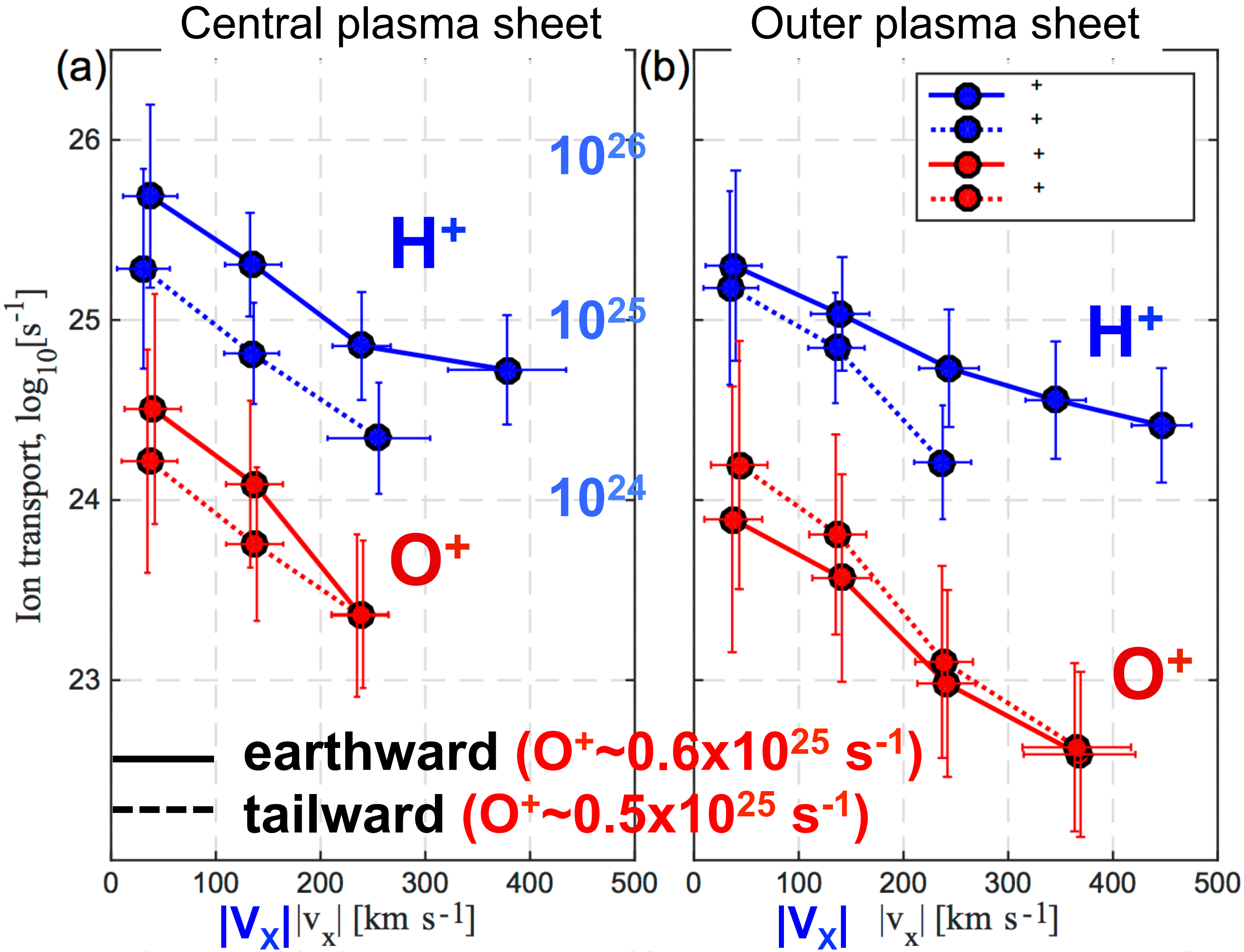




Cluster/CIS: 2001 - 2005
(Slapak et al., 2013, 2017a, Poster)

(b1) Cluster/CIS obs. of Magnetotail

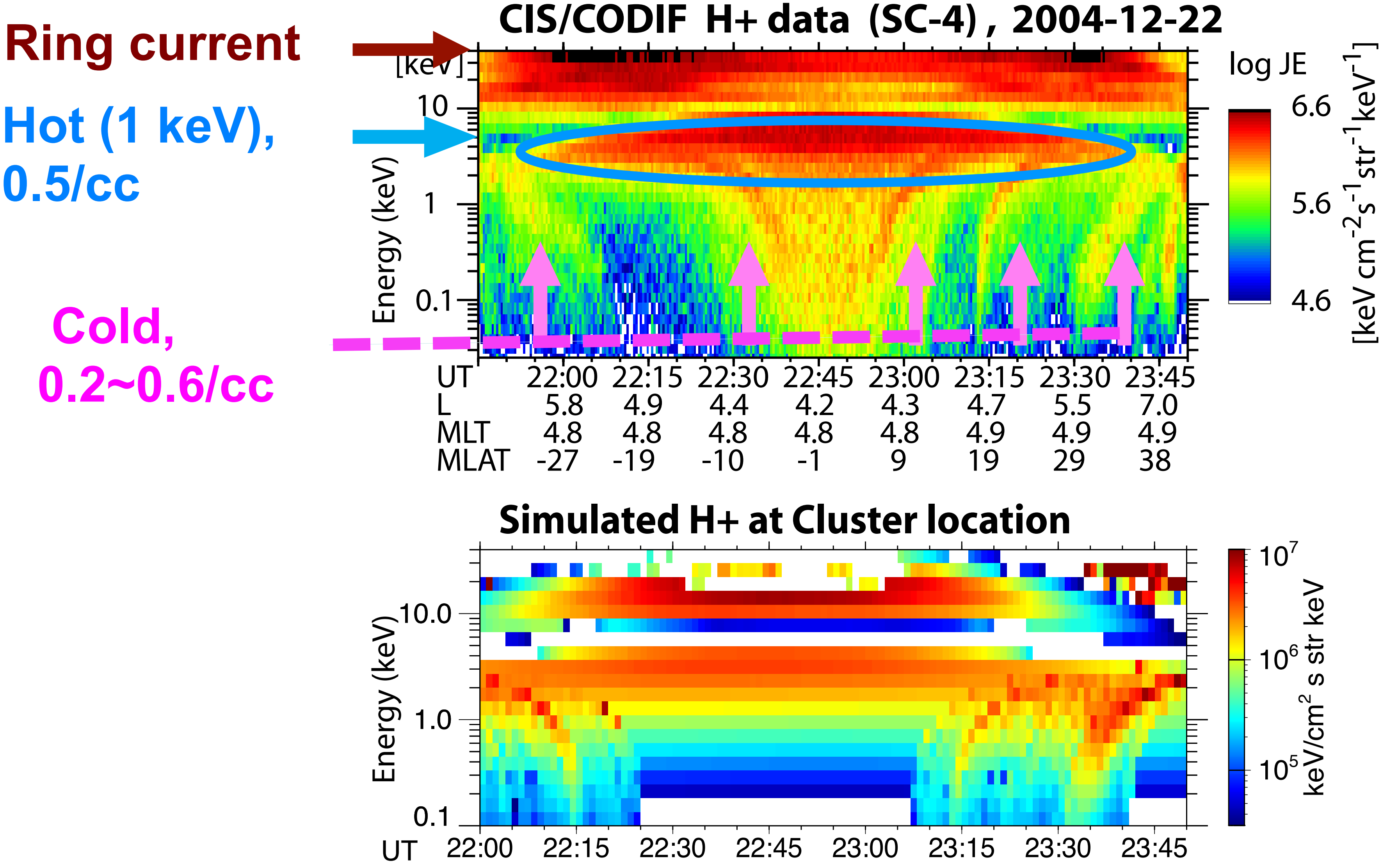
Net return (10^{24} s^{-1}) << polar region outflow



Cluster/CIS: 2001-2005 (Slapak et al., 2017b, Poster)

(b2) Fate of returning cold ions

They are accelerated before charge-exchange: CIS detected all



Cluster/CIS + simulation (Yamauchi et al.,2009)

(c1) Plasmaspheric Plume

Before Cluster/IMAGE:

Satellites: missing 40 tons during storm → burst up to 10^{27} s^{-1}

IMAGE revealed the motion

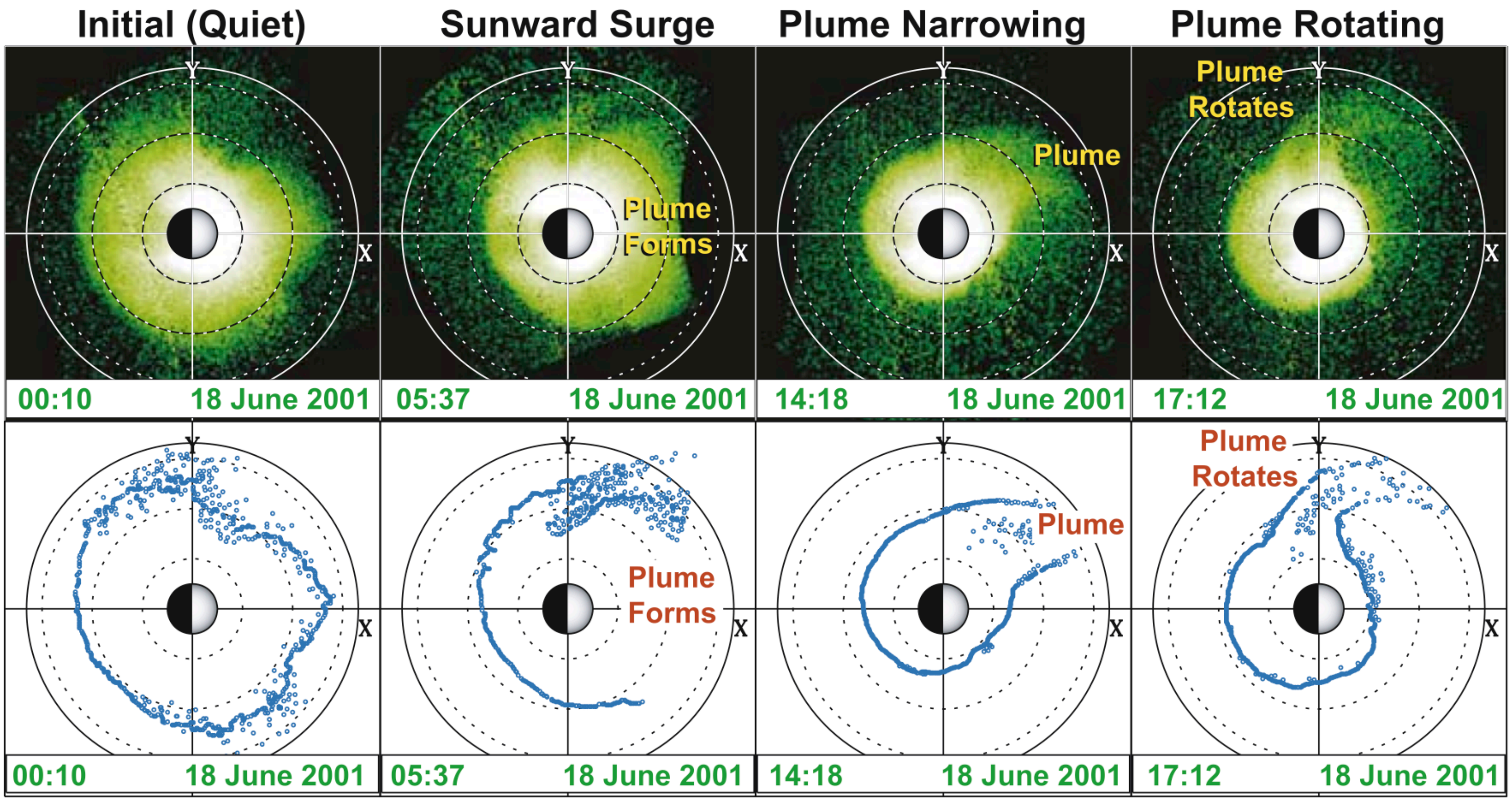
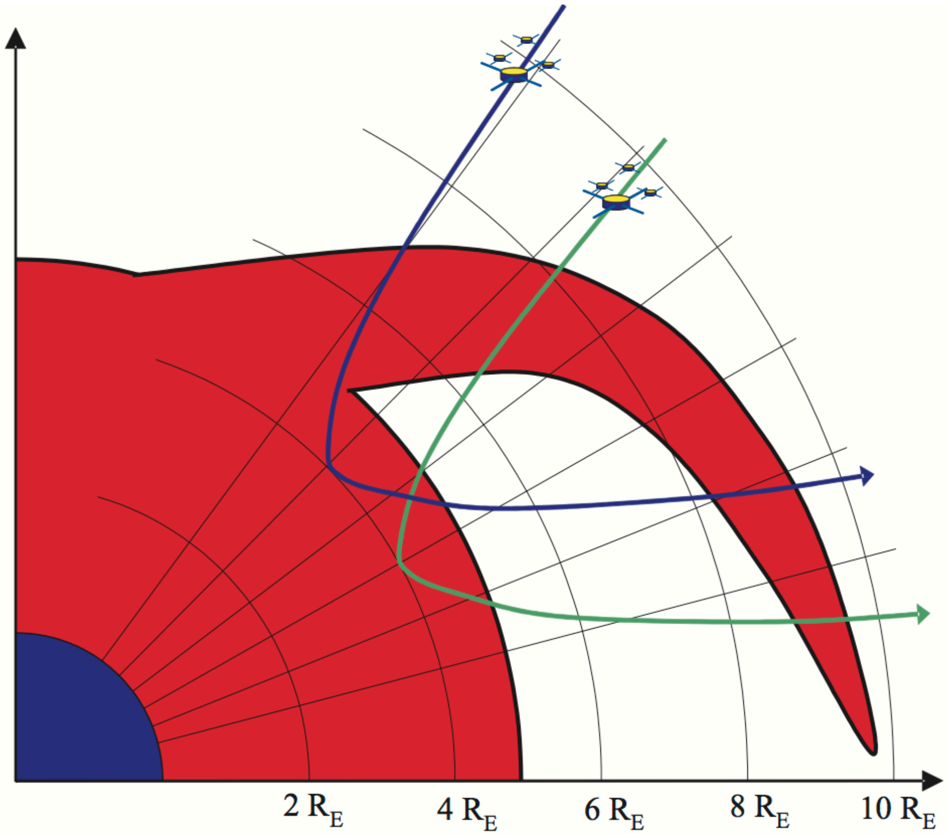


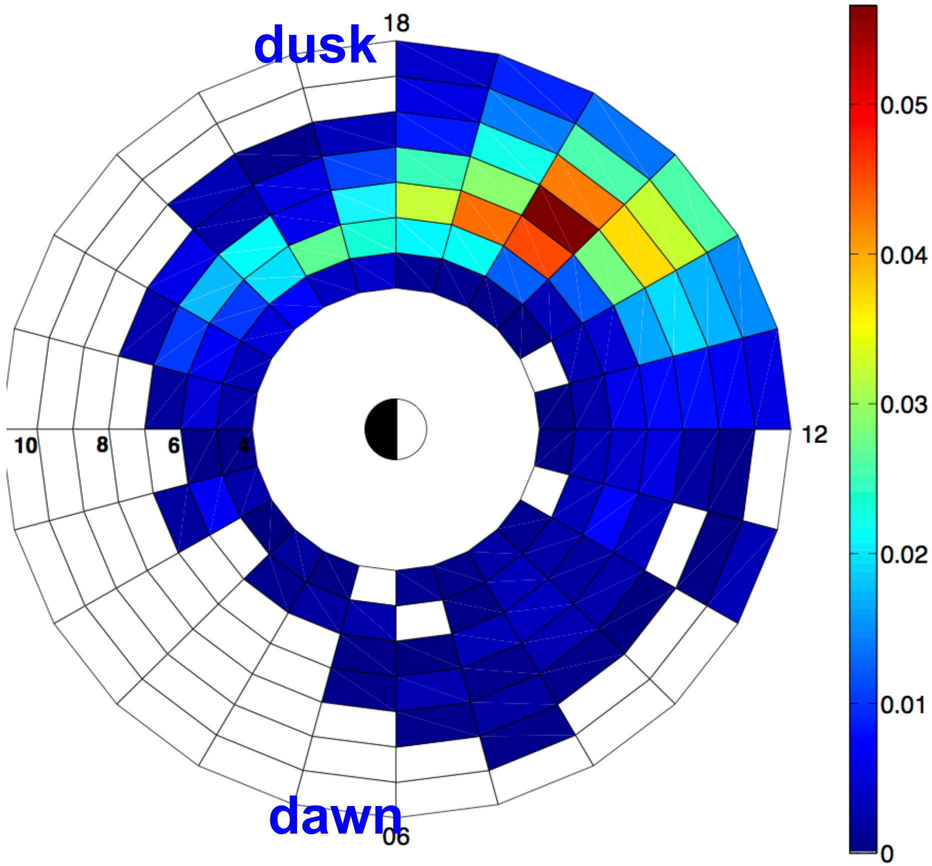
IMAGE FUV (Goldstein, 2006)

(c1) Cluster obs. of Plasmaspheric Plume

Cluster/WHISPER statistics: **confirmed dynamics/number**



(Darrouzet et al., 2008)

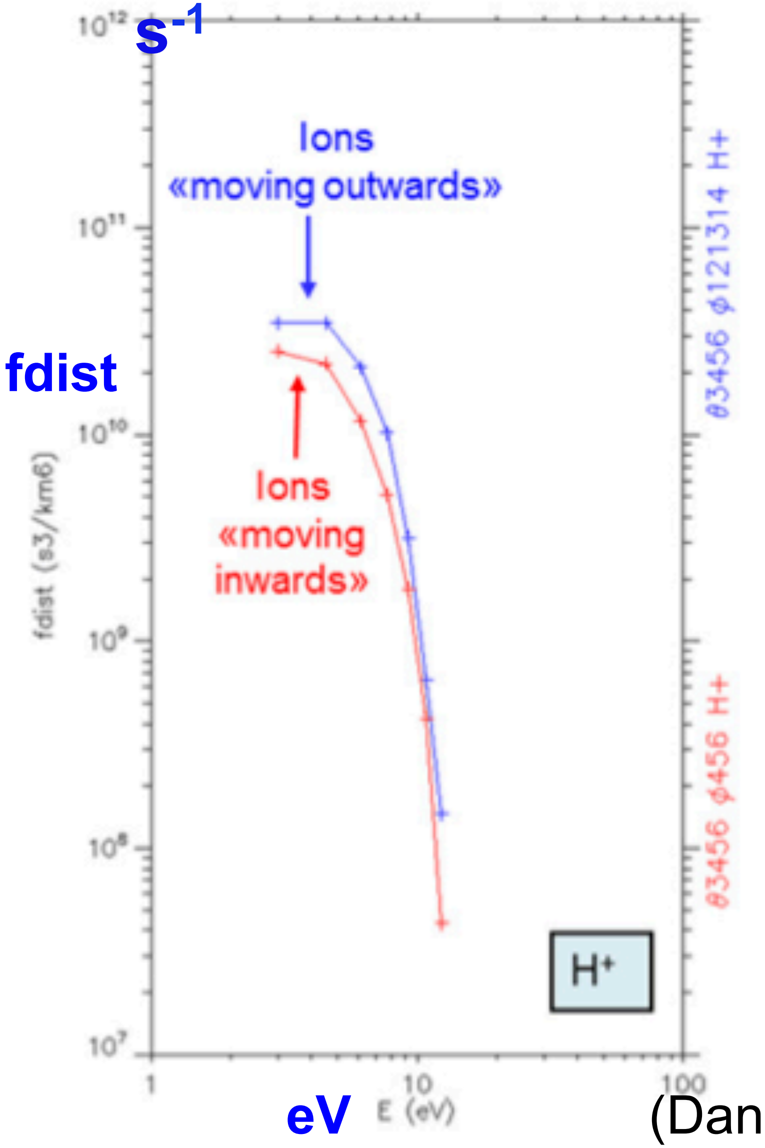


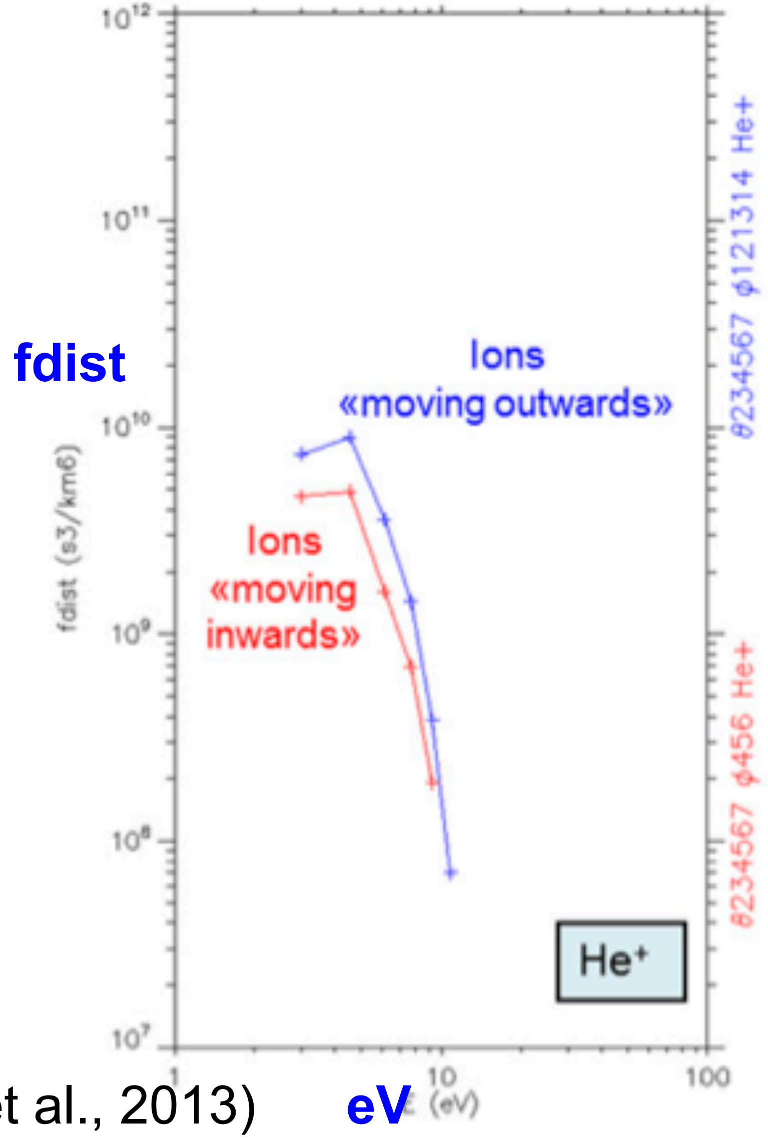
Up to 10^{27} s^{-1} for H^+, but short time

?? for O^+

(c2) Cluster finding of Plasmaspheric Wind

Cluster/CIS (cold mode: H^+ & He^+): **H^+ escape ~ 0.5x10^{27} s^{-1}**





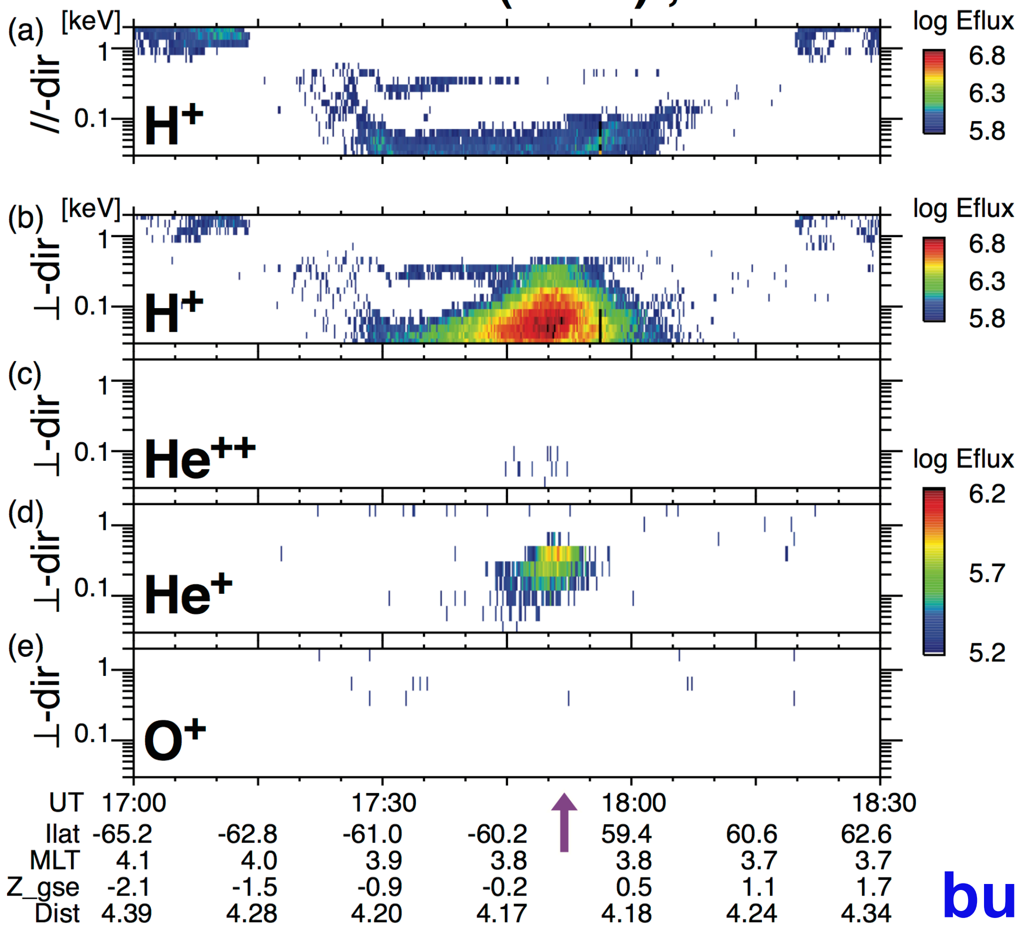
(Dandouras et al., 2013)

(c3) Cluster finding plasmaspheric heating

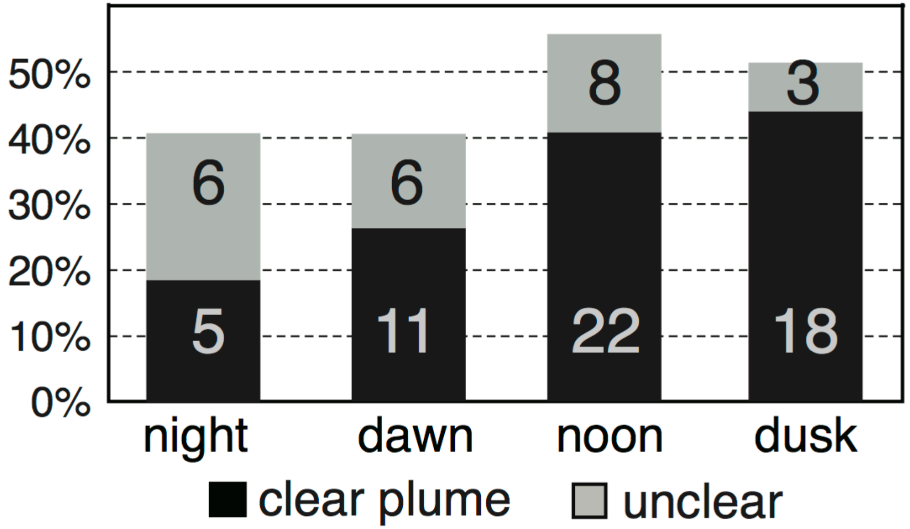
Hot ions are known to enter the inner magnetosphere

Cluster/CIS: they might contribute escape through ⊥ heating

CIS/CODIF data (SC-4) , 2002-1-3



Observation of Equatorial Warm Ion Plume
Cluster CIS/CODIF data (SC-4, 2001-2002)

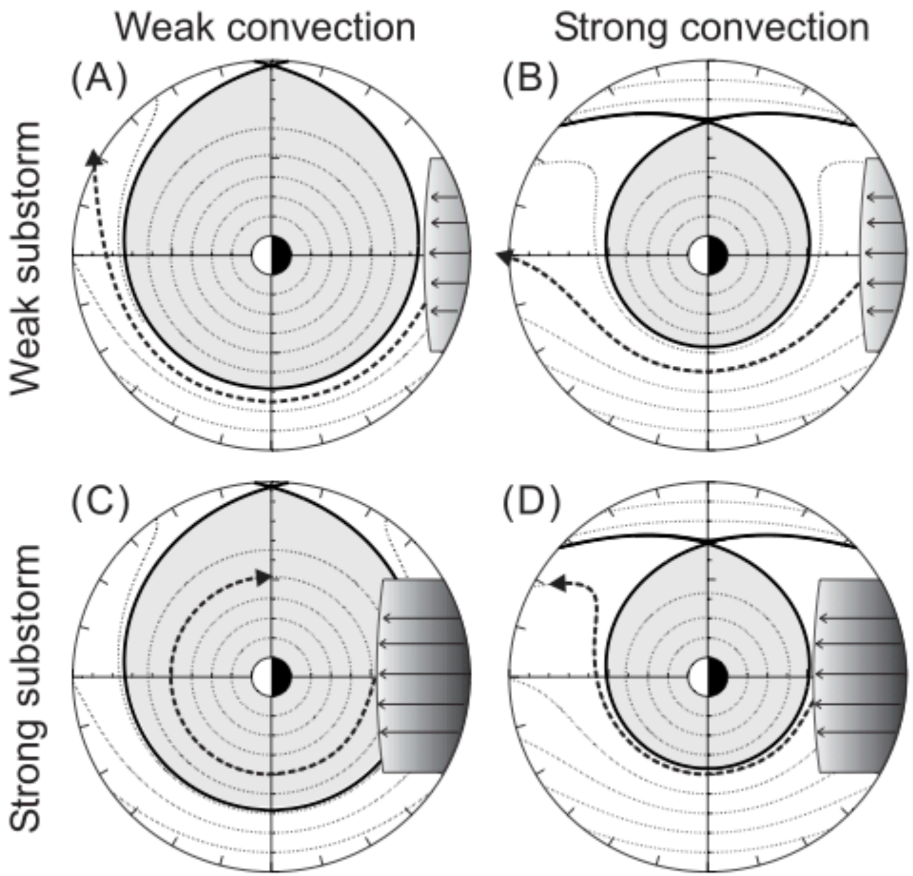


but maximum escape < 10^{23} s^{-1}

(Yamauchi et al., 2012)

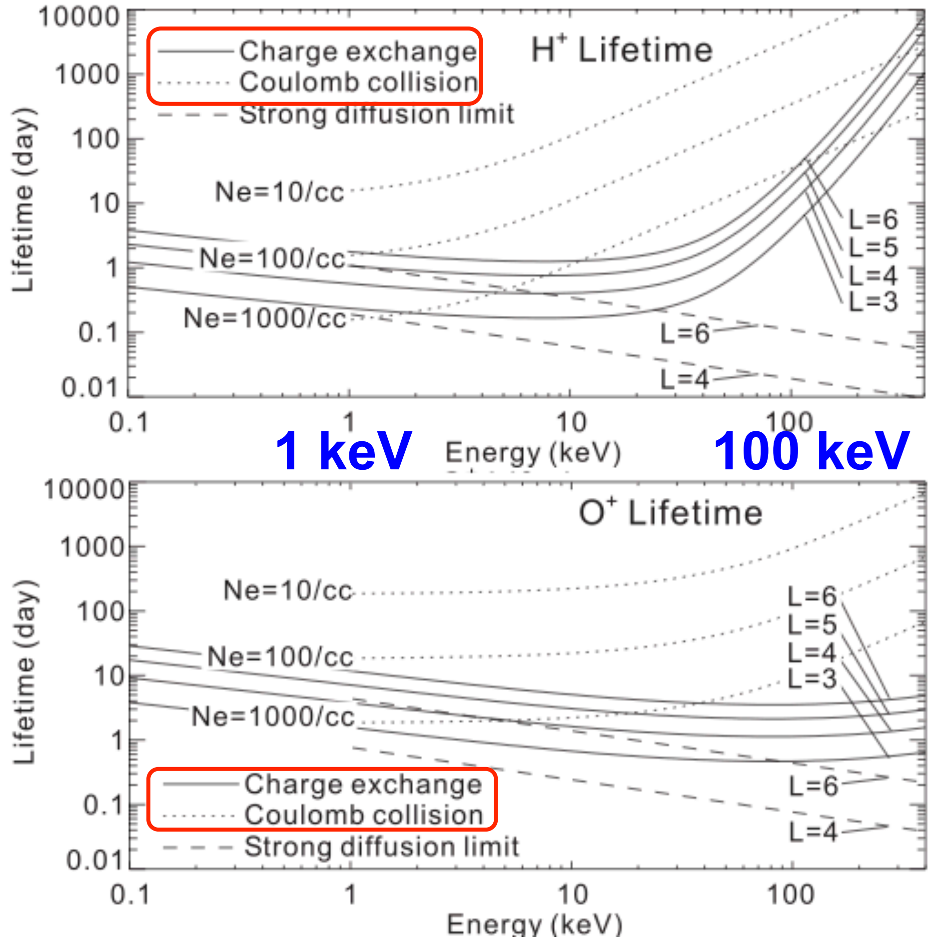
(d) Return/Ring Current (Model prediction)

(1) leak from magnetopause



(Ebihara & Ejiri, 2003)

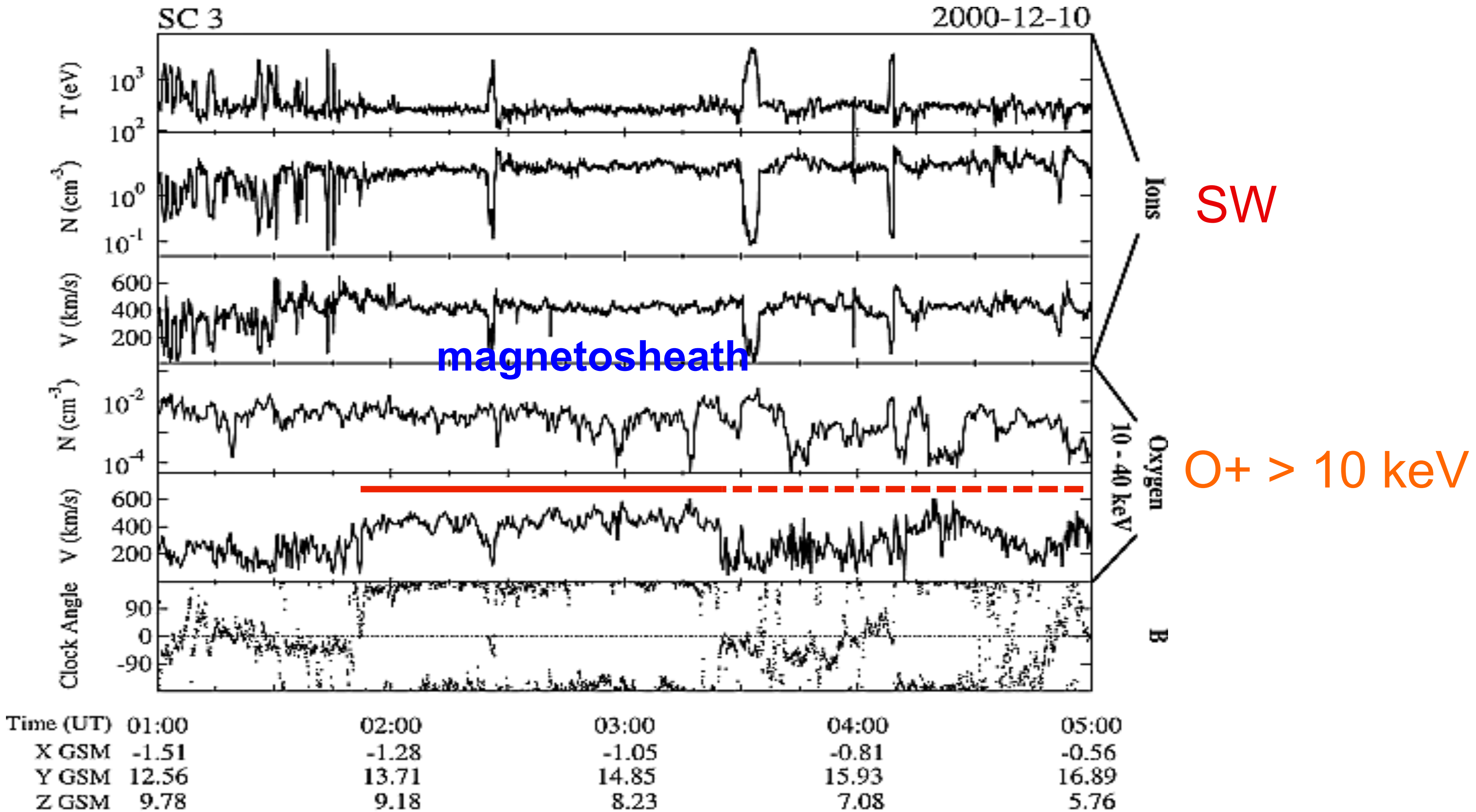
(2) charge exchange loss



For ring current, charge exchange dominates

(d1) MP shadowing (Magnetosheath obs.)

Cluster/CIS: confirmed ring-current O+ leak from dayside

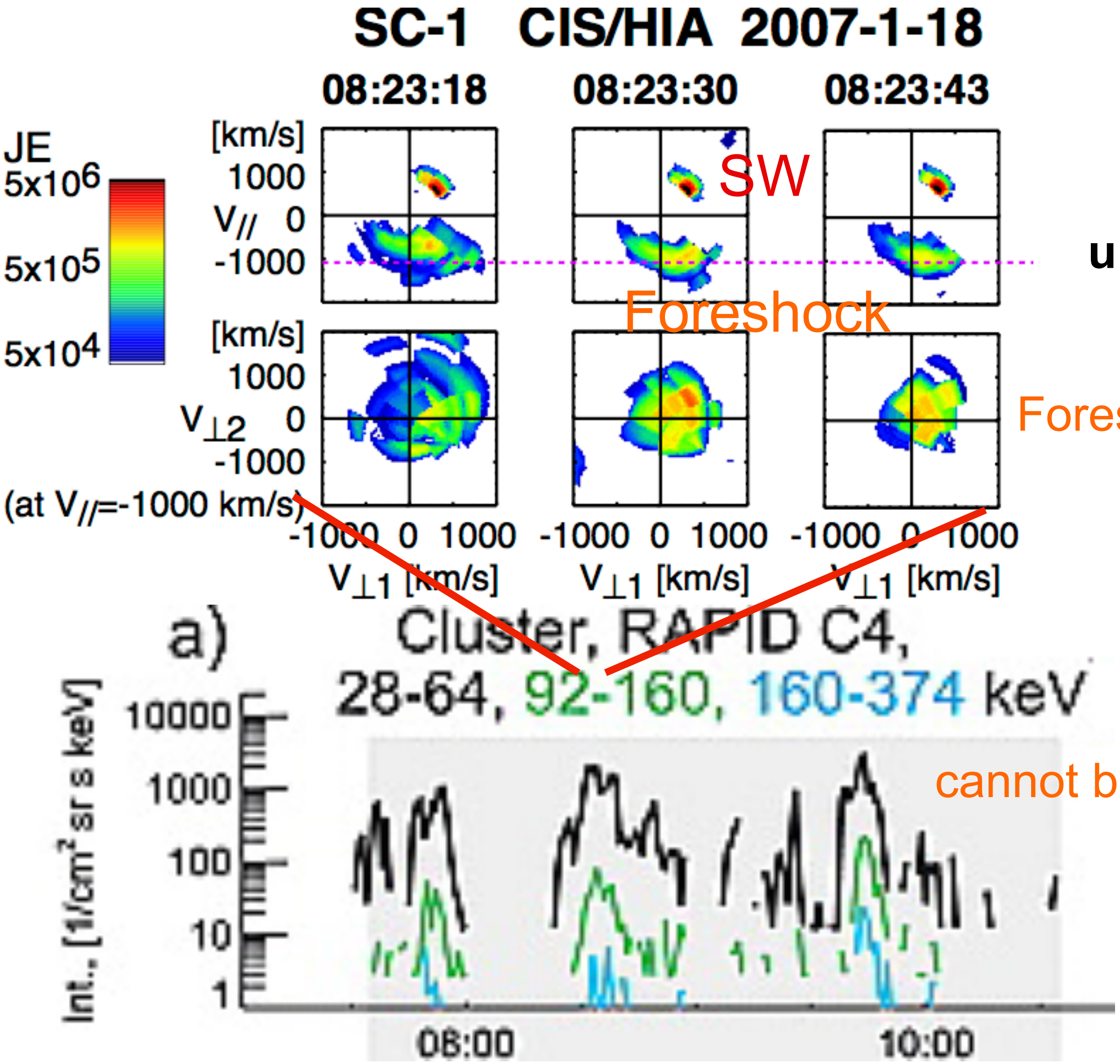


(Marcucci et al., 2004)

MP shadowing during storm ~ 1/3 of input O^+ (Zong et al., 2001)

(d1) MP shadowing (Upstream obs.)

Cluster/RAPID: leaked ring-current ions(?) move upstream



upstream the bow-shock (RAPID/CIS)

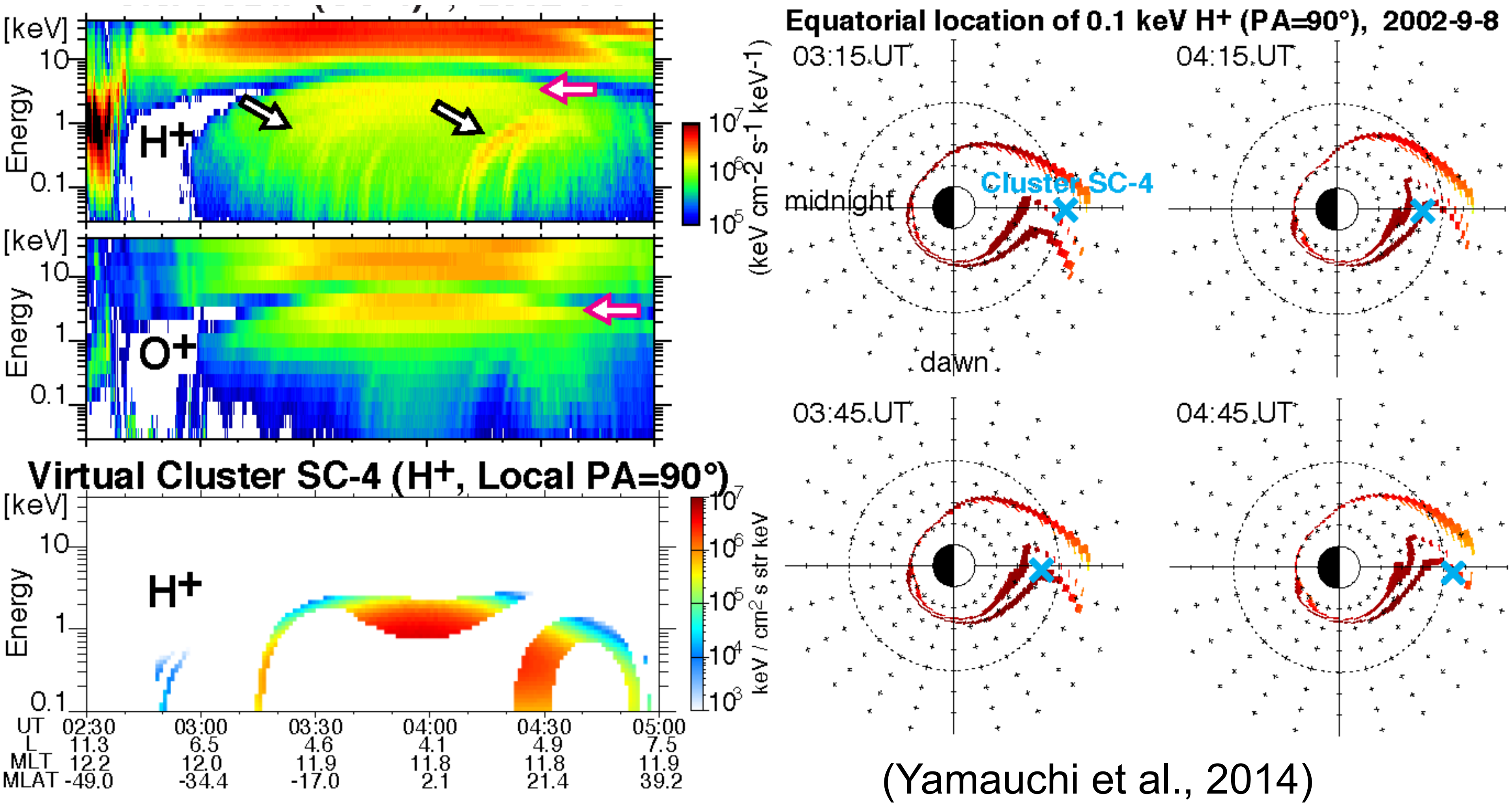
Foreshock = gyrotropic beam

cannot be Fermi-acceleration

(Kronberg et al., 2011)

(d2) Charge exchange (drift obs.)

Cluster/CIS + simulation: confirmed loss only charge-exchange (no diffusion) works
+ cold ions are counted by CIS due to adiabatic energization



(Yamauchi et al., 2014)

(1)&(2) Fate of ions in each route

(a) Polar outflow to **solar wind:** **all ions escape (O^+~$10^{25\text{-}26}$ s^{-1})**
cf. Prognoz-7, but not enough statistics (Hawkeye without composition) → Cluster answered, and x 10 from low-altitude values

(b) Polar outflow to **magnetotail:** **return is small (O^+~$10^{24\text{-}25}$ s^{-1})**
cf. Geotail, but too many assumptions → Cluster corrected.
(earthward ~$0.6 \cdot 10^{25}$ / tailward ~$0.5 \cdot 10^{25}$ / net return ~$0.1 \cdot 10^{25}$)

(c) Auroral/subauroral outflow to **inner magnetosphere & plasmasphere**: portion that escapes is **not clear for O^+**
cf. Geosynchronous, DE-1, etc., but not sufficient knowledge
→ Cluster found **H^+~10^{27} s^{-1}** **(O^+~10^{25} s^{-1}?)** in average.

(d) Return from magnetotail: **>50% escapes (O^+~10^{24} s^{-1})**
cf. simulations + many past missions → Cluster confirmed.

Summary of amount

(a) polar outflow

Satellite	R (Re)	Energy Range keV	Outflow Rate (10^{25} s^{-1})		References
			H^+	O^+	
Cluster (CIS)	> 8	0.028-40		escape ~ 2	Nilsson et al. 2012 Slapak et al. 2017
Cluster (EFW)	> 10	supersonic	tail ~ 10		Engwall et al. 2009
Polar (Apogee)	8.5	0.015–33	1	1.5	Lennartsson et al. 2004
DE–1	4	0.010–17	1	0.7	Yau et al. 1986 Collin et al. 1988
Polar (Perigee)	2-2.3	0.015–33	0.3	0.3	Peterson et al. 2001
Akebono	2.3	< 0.07	2	0.2	Cully et al. 2003a
FAST	1.4	0.003–12	-	0.2	Andersson et al. 2005

(b) magnetotail (x10^{25} s^{-1}): earthward O^+~0.6 / tailward ~0.5 / net return ~0.1

(c) inner magnetosphere / Cluster (only H^+ and He^+, with O/H ratio ~ 10^{-2})

Instrument	phenomenon	method	escape rate (10^{25} s^{-1})	References
WHISPER	Plume	ω_{ce}	peak H^+ > 100	Darrouzet et al. 2009
CIS (cold)	Wind	direct	H^+ ~ 50	Dandouras et al. 2013
CIS (hot)	Heating	direct	H^+ < 0.01	Yamauchi et al. 2012

(d) returned flow: about half are lost < 0.1·10^{25} s^{-1}

Escape Mechanisms & Cluster detection

Type / detection	Mechanism	Explanation
thermal, neutral	(Jeans escape)	Thermal tail exceeds the escape velocity
thermal, neutral/ion **EFW**	**Hydrodynamic blow off (H^+ only)**	kT > escape energy, like solar wind formation (O^+ for extreme EUV radiation during early Sun)
non-thermal/ thermal, neutral	**charge exchange (and momentum exchange)**	Heavy (trapped) ions or light (polar wind) neutrals collide with heavy molecules
thermo-chemical, neutral/ion	**(Photochemical heating)**	Release of e.g. recombination energy of the excited state that accelerates the atom
combined, ion	**(Ion pickup)**	Newly-born ion are removed by solar wind ExB
non-thermal, neutral/ion	**(Atmospheric sputtering)**	Energetic particles interact with atmosphere
non-thermal, ion **CIS/RAPID**	**Large-scale momentum transfer & instabilities**	The solar wind dynamic pressure and EM forces push the planetary plasma anti-sunward
non-thermal, ion **CIS**	**Ion energization by EM waves and $E_{//}$**	EM disturbances and/or static E-fields energise ions, by e.g. the ion cyclotron resonance
non-thermal, ion **WHISPER/CIS**	**Plasmaspheric wind, plasmaspheric plumes**	Plasma instabilities near the plasmapause
non-thermal, ion **CIS/RAPID**	**Magnetopause shadowing**	Drifting ions overshoot the magnetopause

(3) Feedback from escaping ions

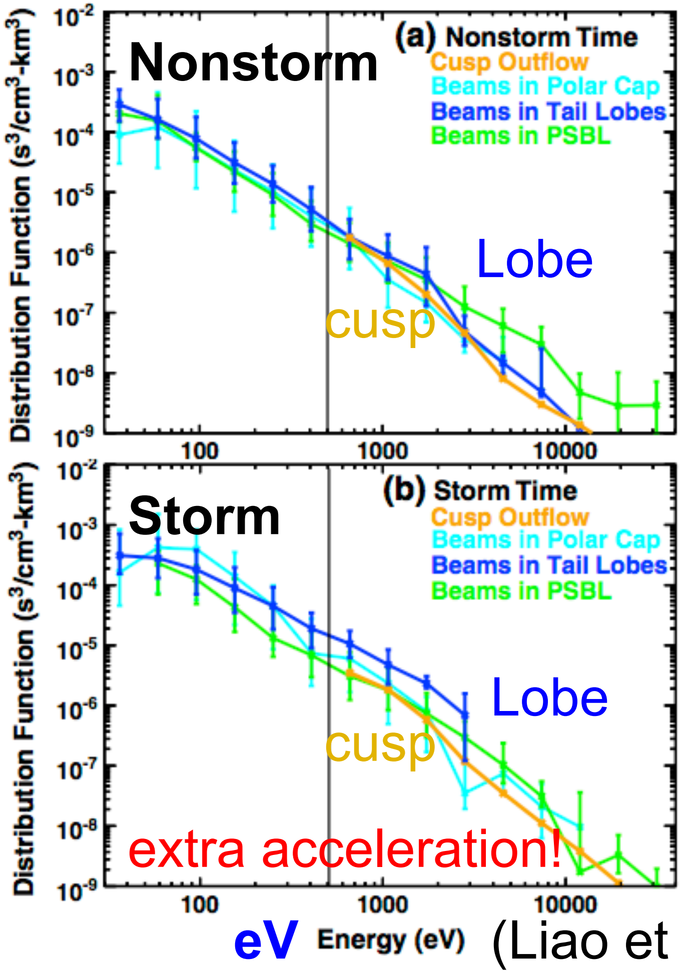
O^+ in magnetosphere plays important roles. How about **escaping ions**?

→ **Mass Loading**? (extremely effective@ROSETTA)

Momentum conservation → kinetic energy extraction

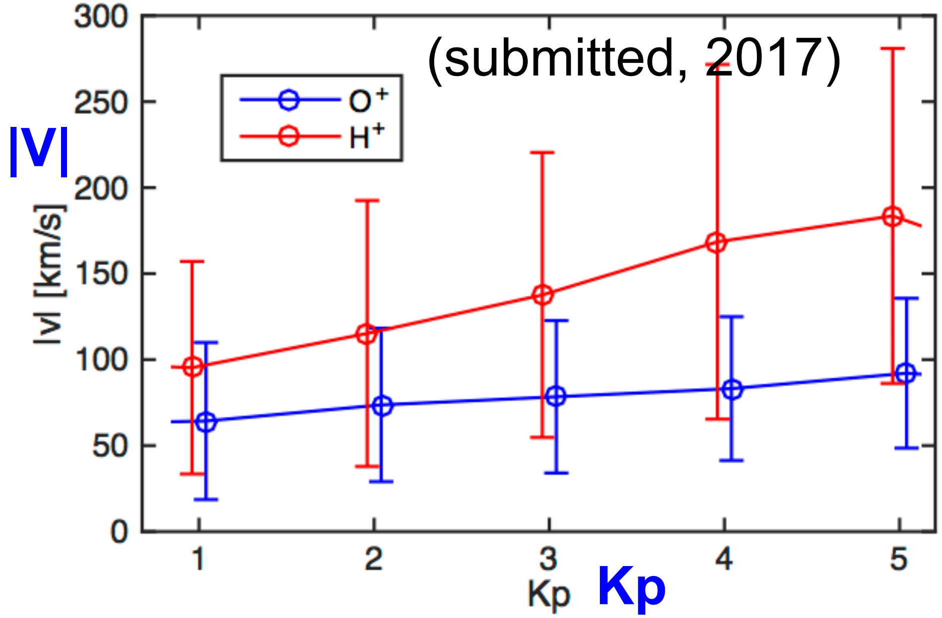
e.g., n_{O+}/n_{SW}~0.01 → ρ_{O+}/ρ_{SW}~0.16 → 7% of kinetic energy ($10^{9\text{-}10}$ W) to $J_{//}$ etc.

large Kp/EUV → high ρ_{O+}/ρ_{SW} → high V_O/V_H?



(Liao et al., 2015)

Cluster/CIS



How much does mass-loading increase the escape rate???

(4) Geological-scale evolution

(f) Can we guess the past escape?

cf. Sun-in-Time project (e.g., Wood 2006)
→ higher EUV, faster SW, stronger IMF, stronger CME,
→ scaling to **Kp=10** (Slapak et al., 2017a, **poster**)
or use **extreme events** as proxy (Krauss et al., 2012;
Schillings et al., **Thursday 9:00 am**), 2003-10-29 event ≈ 2.3 billion y.a.

(g) Any effect on atmospheric composition, e.g., O/N ratio?

cf. O^+/H^+ ratio increases with EUV/Kp (e.g., Maes et al., 2015), and
N^+/O^+ ratio also increases with EUV/Kp (Yau et al., 1993).
→ Billions years ago, N^+/O^+ ratio might have been ≥ 1.
→ total loss of hot N^+ and hot O^+ could be $0.5 \cdot 10^{18}$ kg over4 billions y.a.
→ Atmospheric O/N ratio was different by ~8%
→ Escape (only hot component) could have affected the biosphere !

(h) What is missing / Future measurements: include changes in the source

cf. Exosphere-Ionosphere-Magnetosphere/Plasmasphere coupling
→ ESCAPE proposal for M5 (poster)

Past N/O ratio fluctuated a lot

fluctuation more than biology model explains

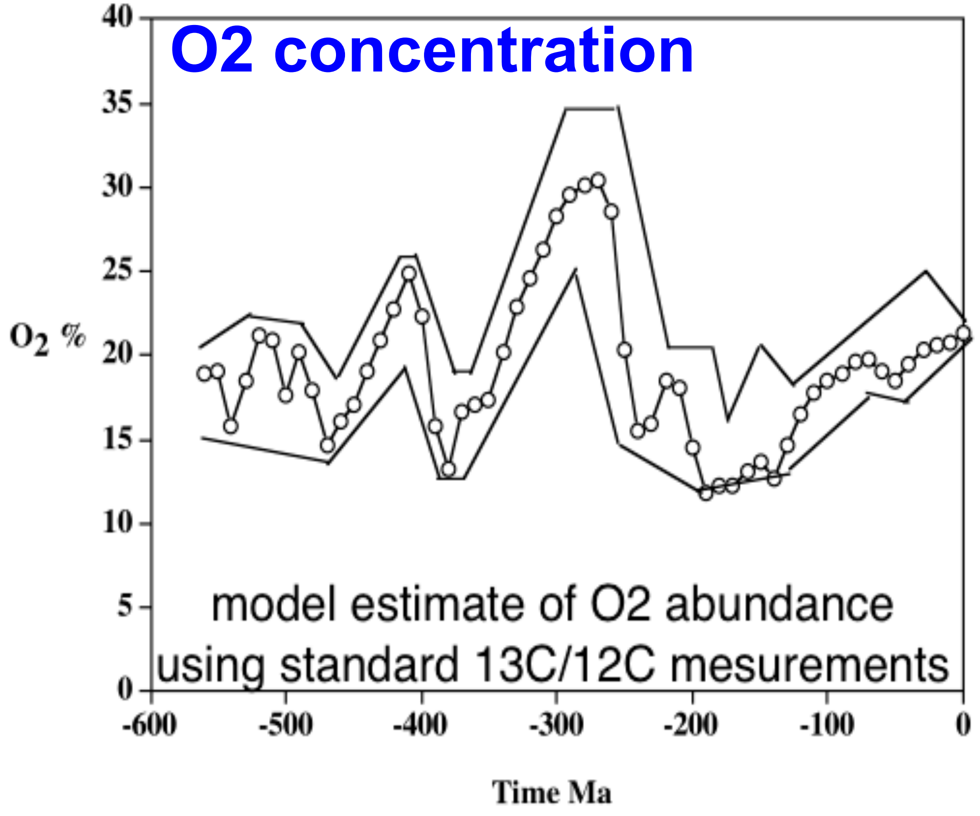
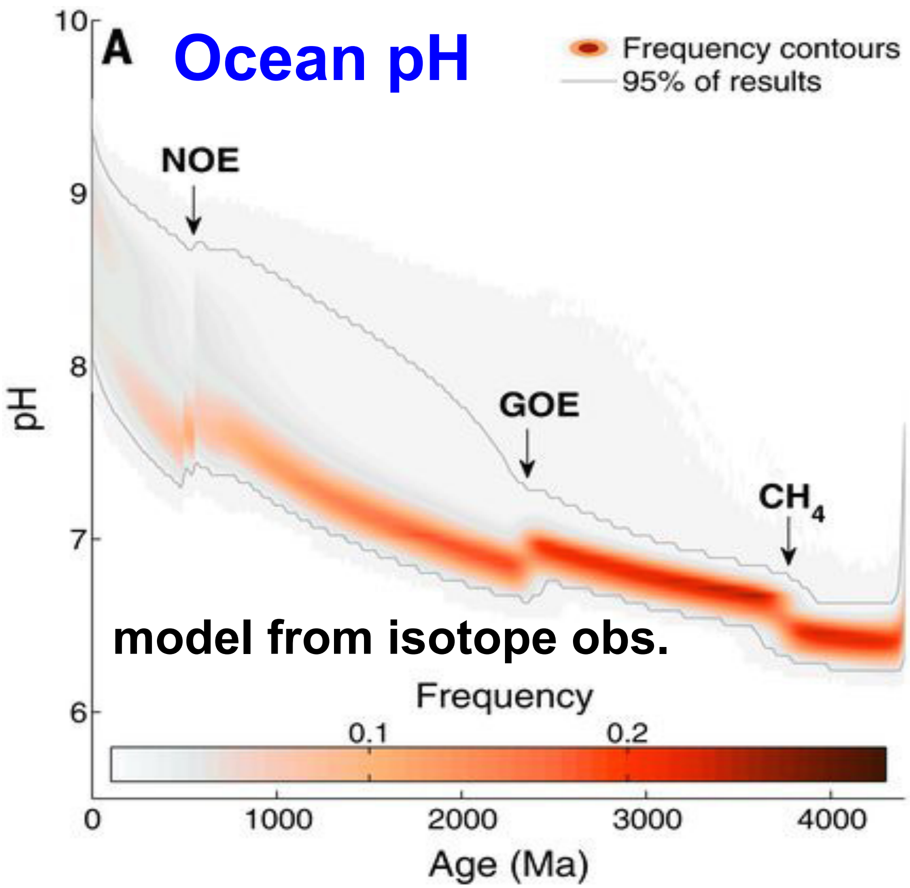


Fig. 20. Plot of O_2 vs time for the standard GEOCARBSULF model with



(Berner, 2006)

(Halevy, 2017)

O^+ escape Mechanisms (what should be measured?)

Type	Mechanism	Where?	Δv for same T
thermal	**Jeans escape**	exobase (M>E≥V)	exp()
non-thermal neutrals	Charge exchange	above mirror altitude (E)	m^0
thermal	Momentum exchange	above exobase (M>V)	m^0
thermal	**Hydrodynamic blow off**	near exobase (ancient, all)	$m^{-0.5}$ to m^0
chemical	**Photochemical heating**	exosphere (M>V~E)	$m^{-0.5}$
combined	Ion pickup	outer exosphere (M, V)	m^0
non-thermal	Atmospheric sputtering	around and above exobase (M, V>E)	m^0
non-thermal ions	Large-scale momentum transfer & instabilities	magnetospheric boundary (E>M~V)	m^0
non-thermal	**Ion energisation by EM waves and $E_{//}$**	upper ionosphere & magnetosphere (E>M>V)	?
non-thermal	**Plasmaspheric wind, plasmaspheric plumes**	plasmasphere (E>M~V)	m^0
non-thermal	Boundary shadowing	ring current (E)	m^0

Conclusion

O^+-N^+ escape from the Earth ~ $10^{25\text{-}27}$ s^{-1}.

The past escape is much more, and we might still underestimate the past escape.

Total escape on geological scale could have even affected the biosphere.

Thank you

Outline

(1) Escape routes through different destinations

(a) Directly to the solar wind
(b) Through the magnetotail
(c) First entering the inner magnetosphere/plasmasphere
(d) Returning from the tail but eventually escaping

(2) Cluster Instruments that contributed

(a), (b), (c), (d)

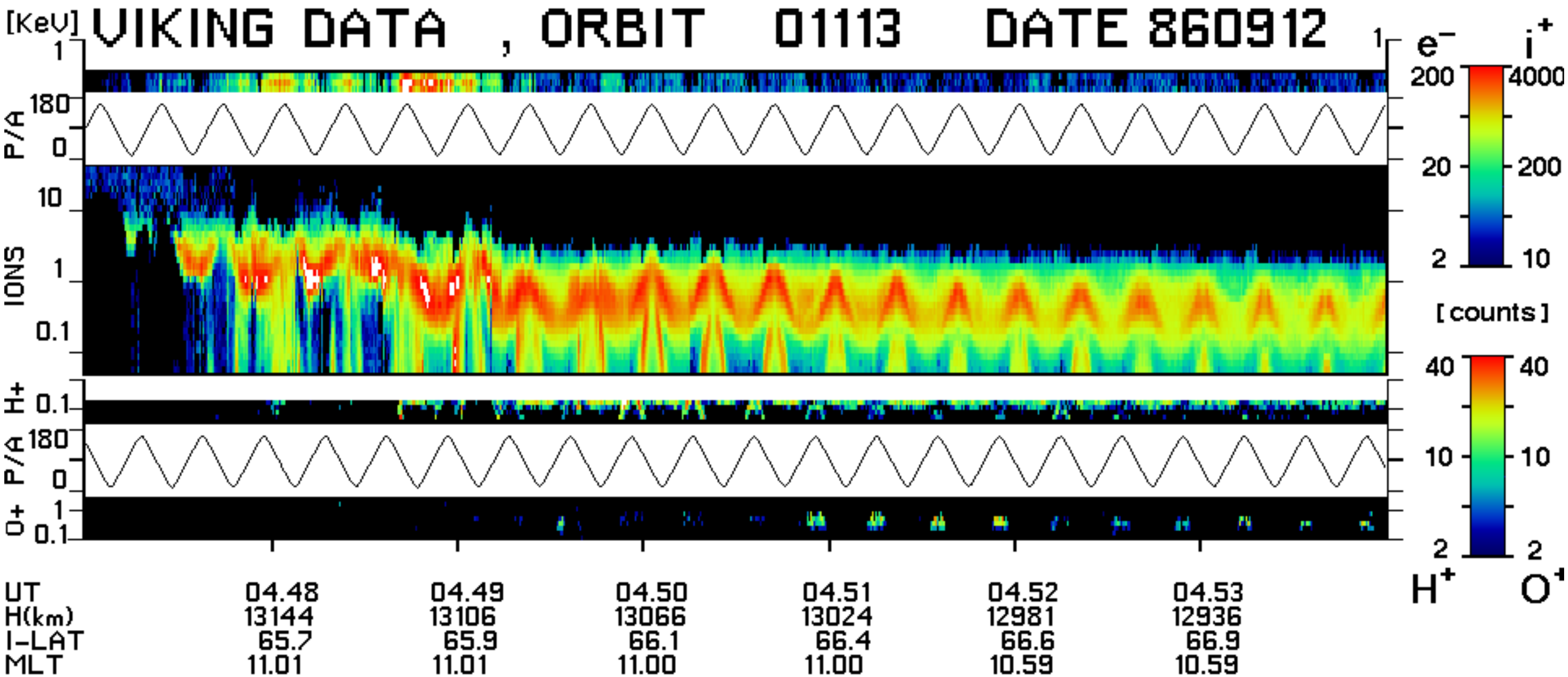
(3) Short-term effect by directly escaping ions

(e) Feedback effect by escaping ions (not circulating ions)

(4) Geological-scale evolution

(f) Extreme events as proxy of the past
(g) N^+ vs O^+
(h) What is missing / Future measurements

O+ outflow in precipitation region



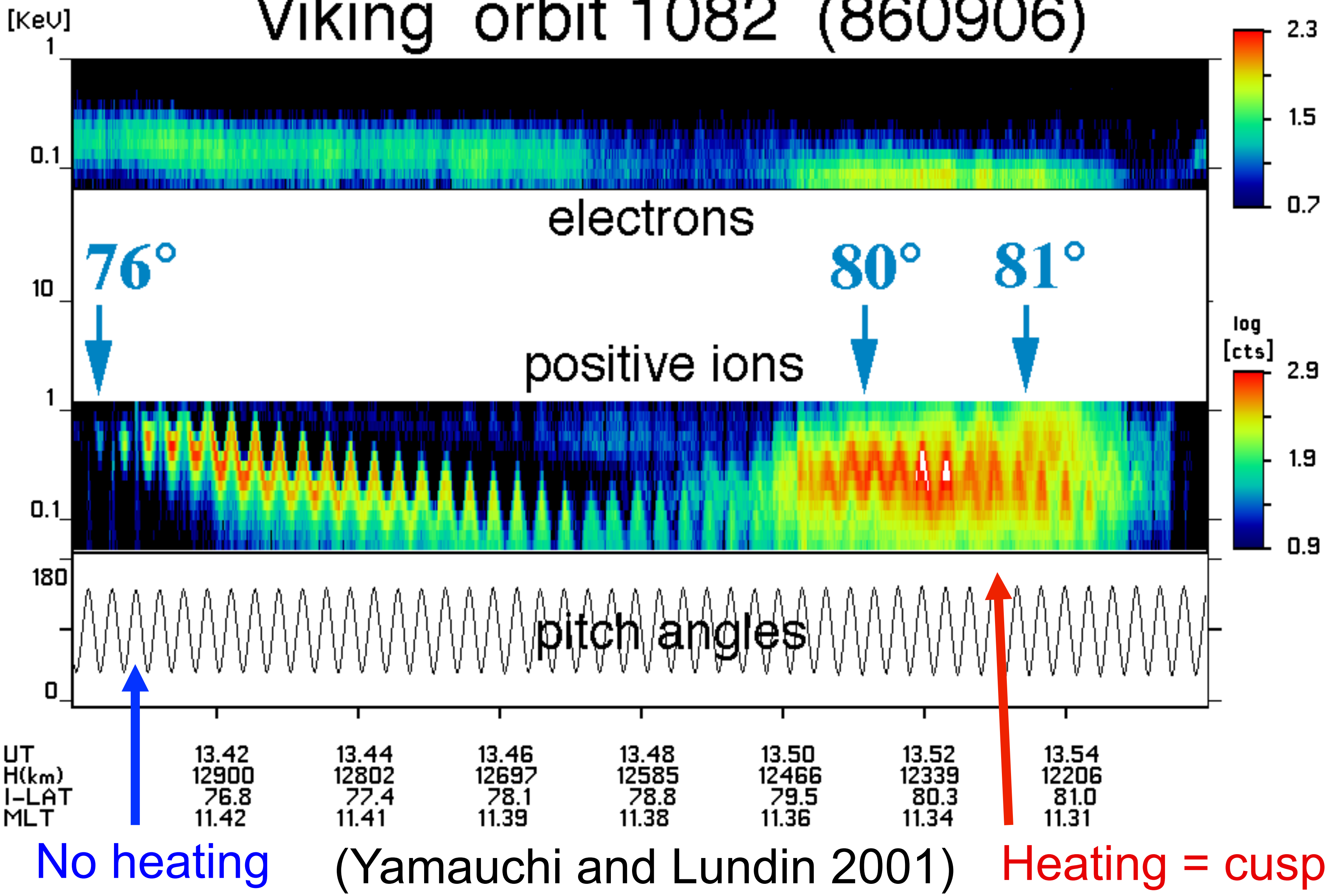
Even low-energy input like cusp, that is enough to cause non-thermal outflow (even starting with conic)

$n_H >> n_O$

heating (IMF Bz>0) only in the cusp @ 3Re

FTE + cusp : breathing magnetosphere

Viking orbit 1082 (860906)



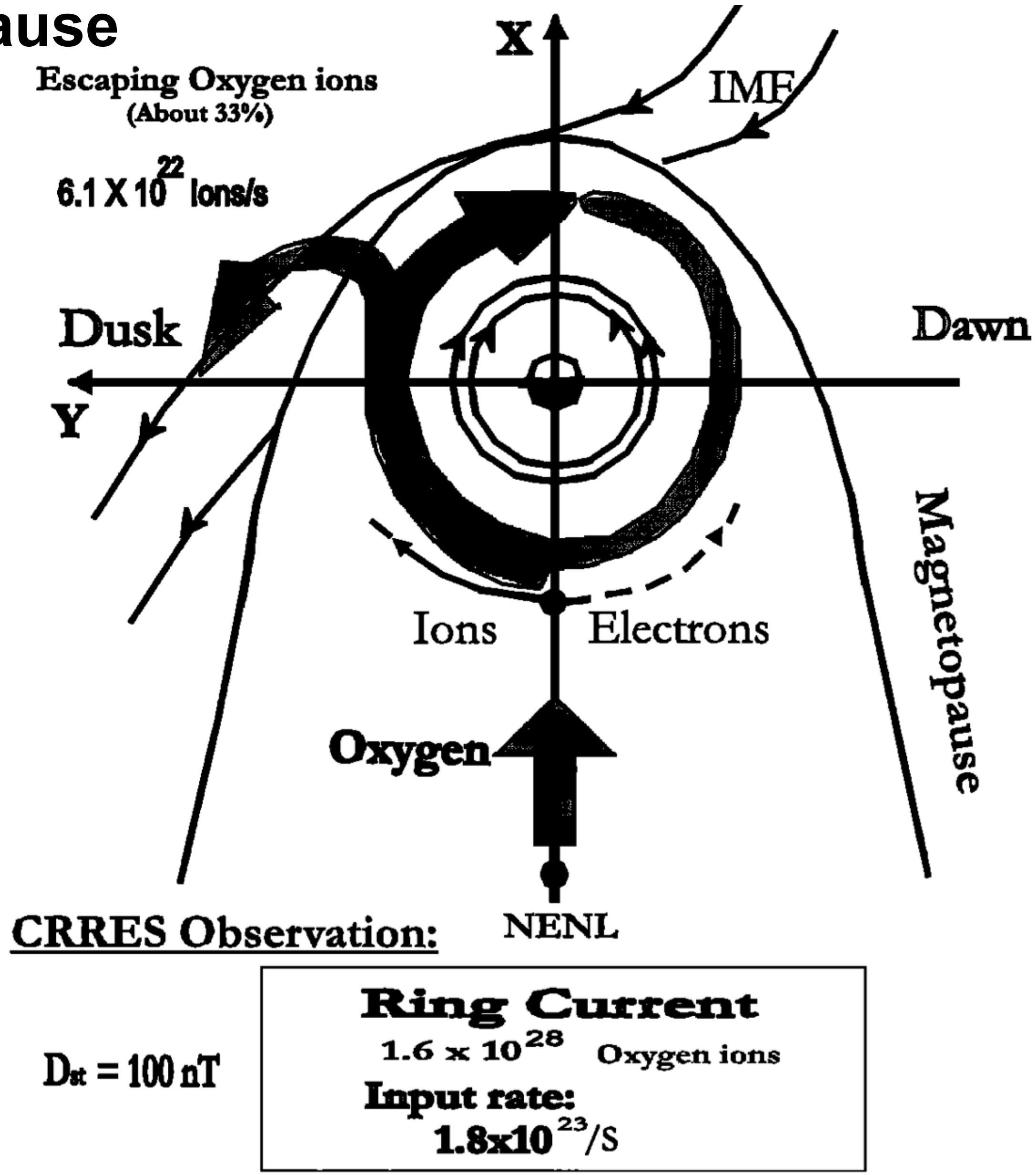
(Yamauchi and Lundin 2001)

(d1) Return/Ring Current (MP shadowing)

Leak through Magnetopause (model+Geotail obs)

about 1/3 of input O^+ during storm

(Zong et al., 2001)



Oxygen from opposite cusp

Strong IMF By ⟹ **a very narrow spot** (Rodger et al., 200)