Global Aspects of Alfvén-Wave-Driven Ion Outflow

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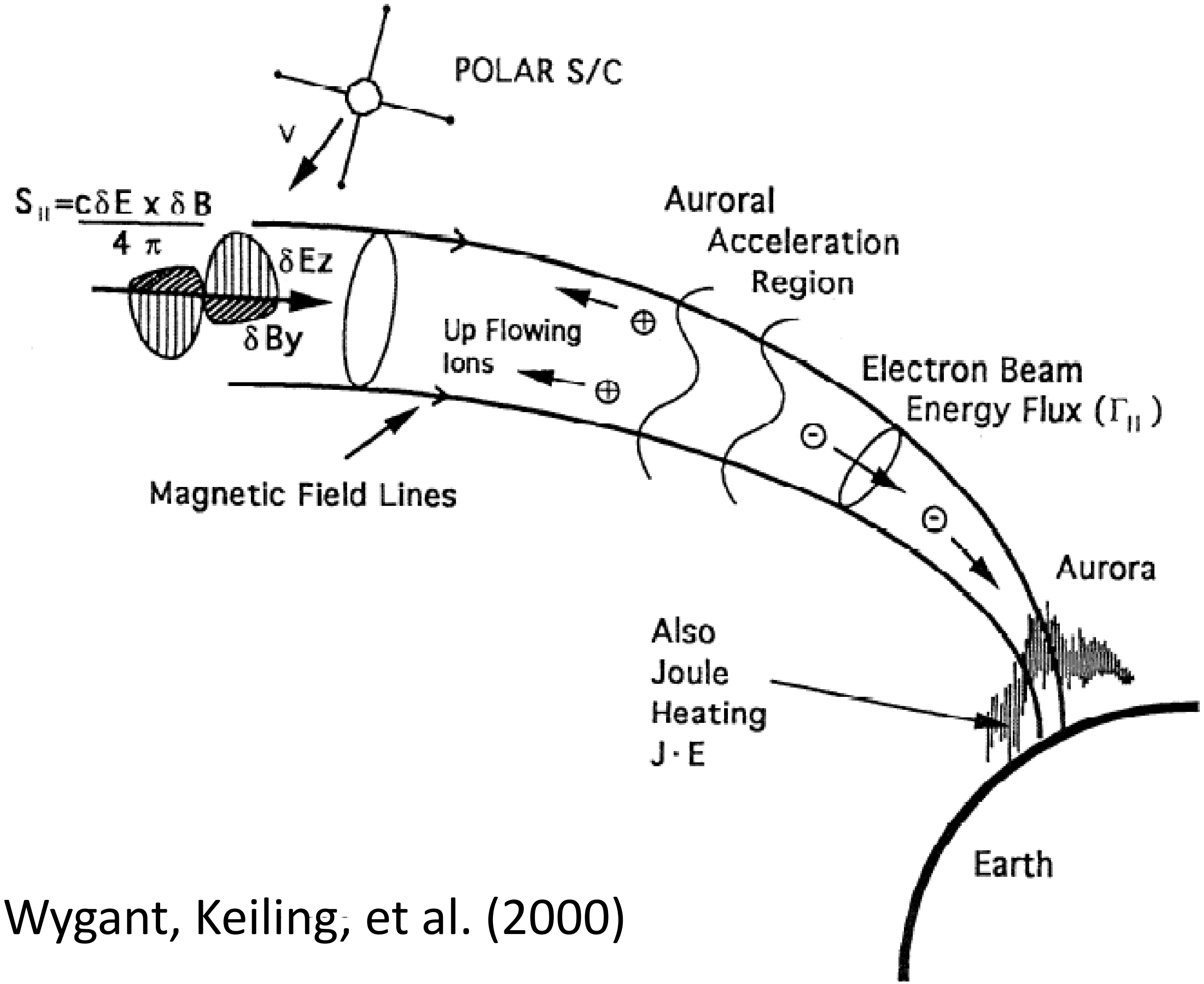
What is the relative importance of Alfvén waves in controlling/driving ion upflow/outflows?



Wygant, Keiling, et al. (2000)

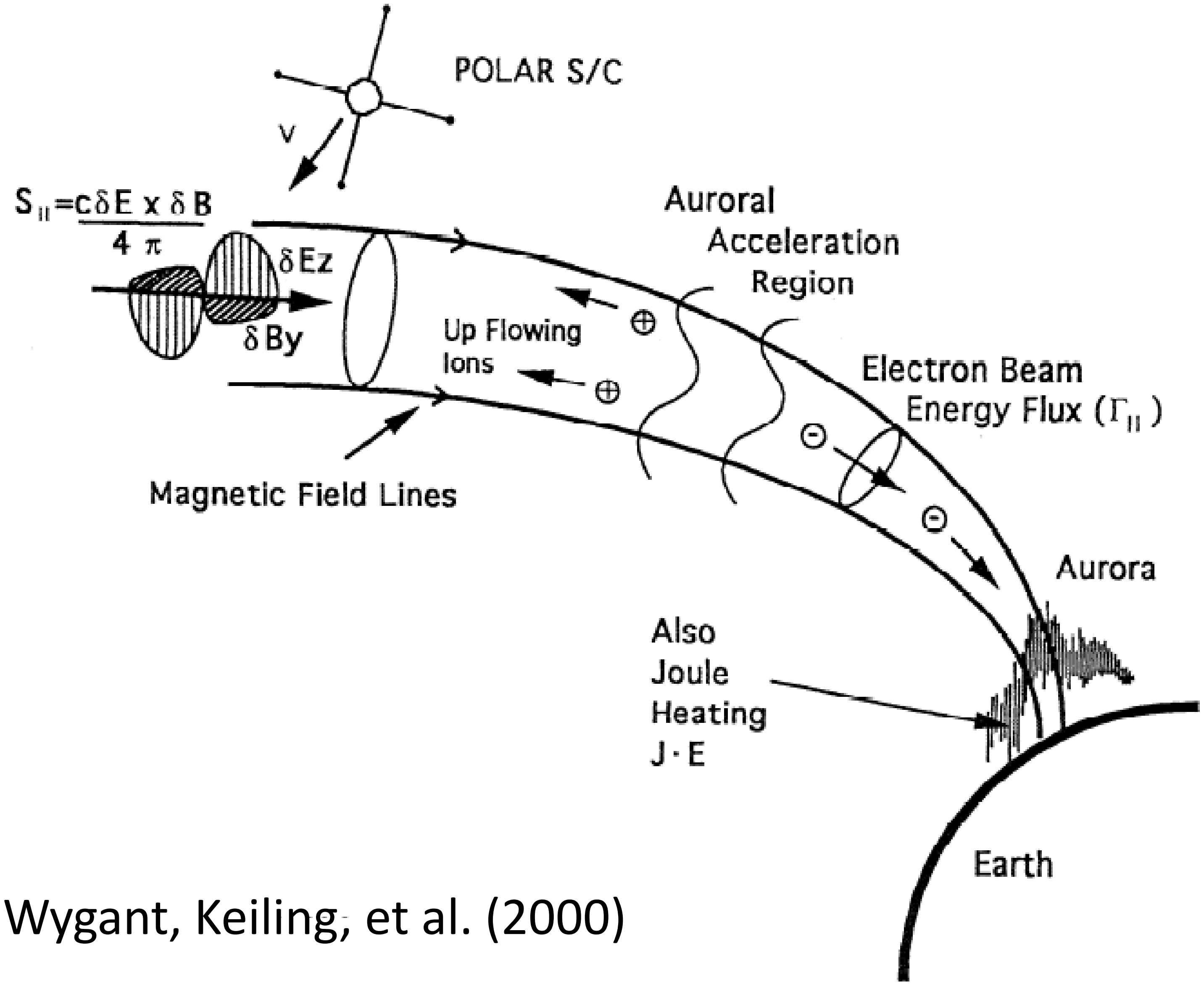
Global Aspects of Alfvén-Wave-Driven Ion Outflow

Introduction

Three case studies

Global patterns

Questions



Wygant, Keiling, et al. (2000)

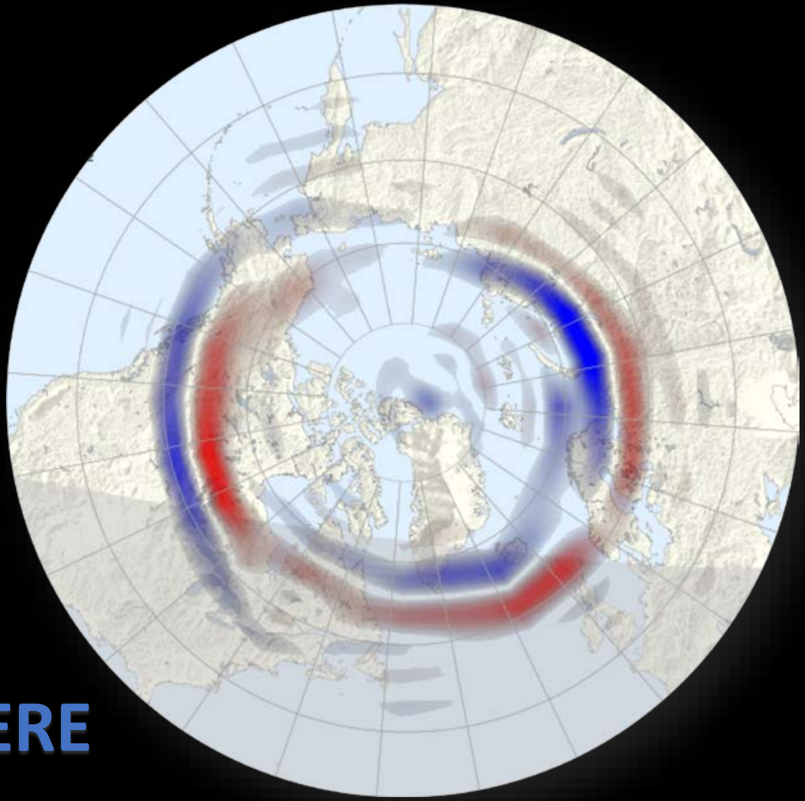
Importance of Alfvén waves in the dynamic magnetosphere

Lysak et al. (2009) wrote:

- The importance of Alfven wave propagation to energy transport between the tail and the auroral zone has been emphasized by observations at the **plasma sheet boundary layer** by Polar, Cluster, and FAST (Wygant et al., 2000, 2002; Keiling et al., 2000, 2001, 2002, 2003, 2005; Angelopoulos et al., 2002; Nakamura et al., 2004; Dombeck et al., 2005).
- These observations show that the Poynting flux carried by shear Alfvén waves can be the **dominant energy flow along auroral field lines**, especially during substorm times.
- Standard models of substorms have generally emphasized convective flows as the major source of energy and momentum transport; however, **Alfvén wave propagation can also be an important transport mechanism**.

Electromagnetic M-I Coupling over the Polar Region

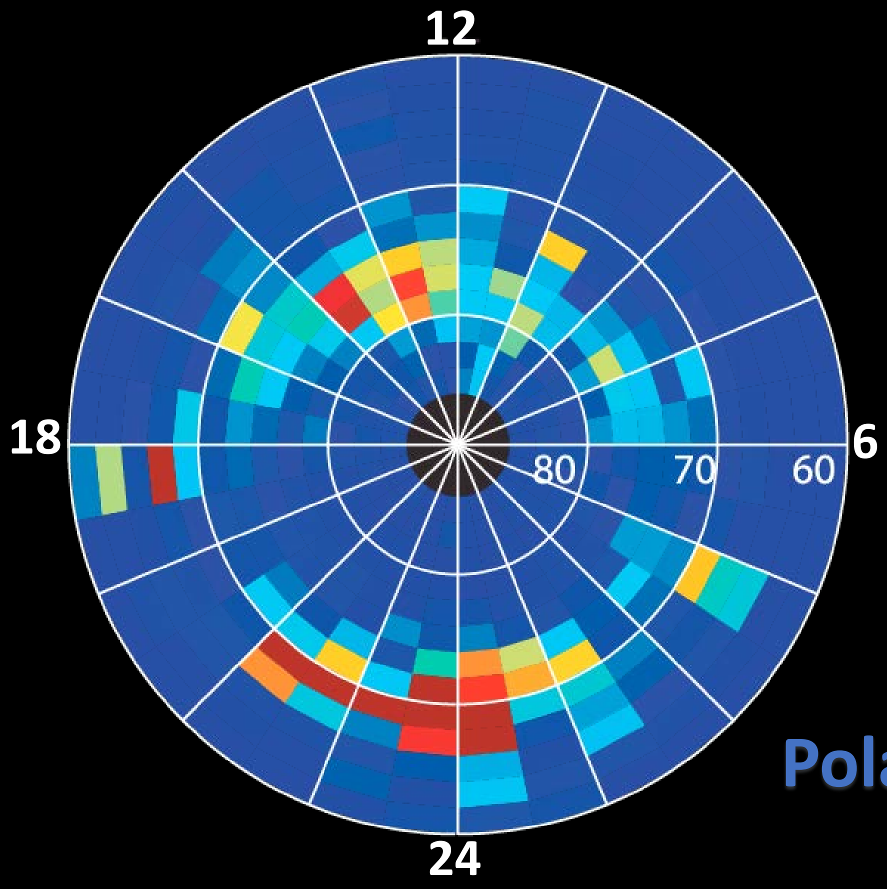
Static FAC
(Birkeland Currents)



AMPERE

1976

Time-dependent FAC
(Alfvén Waves)

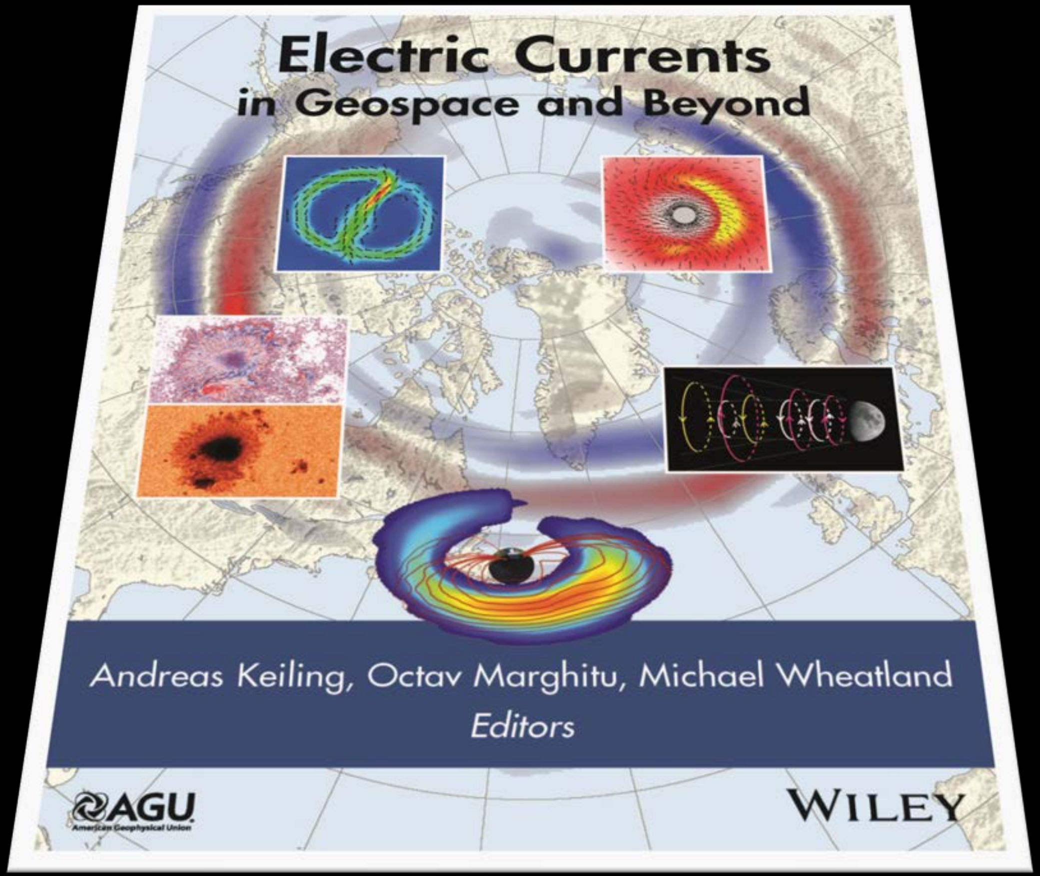


Polar

2003

Electromagnetic M-I Coupling over the Polar Region

Static FAC
(Birkeland Currents)



Time-dependent FAC
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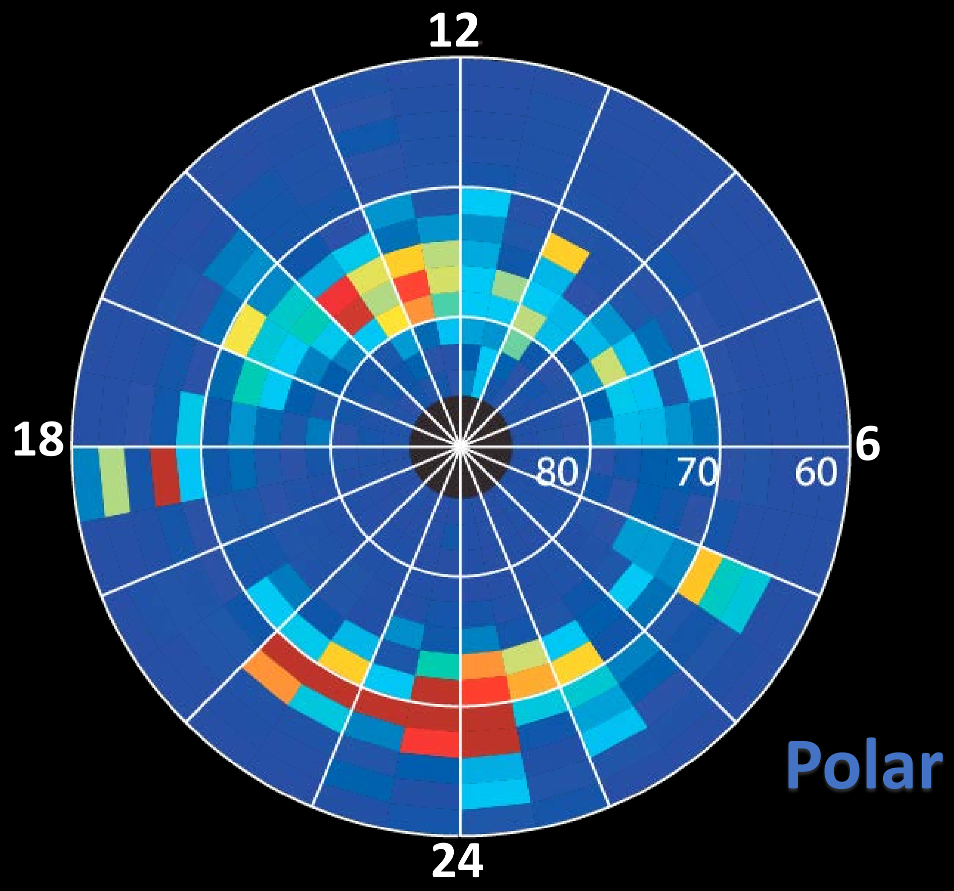
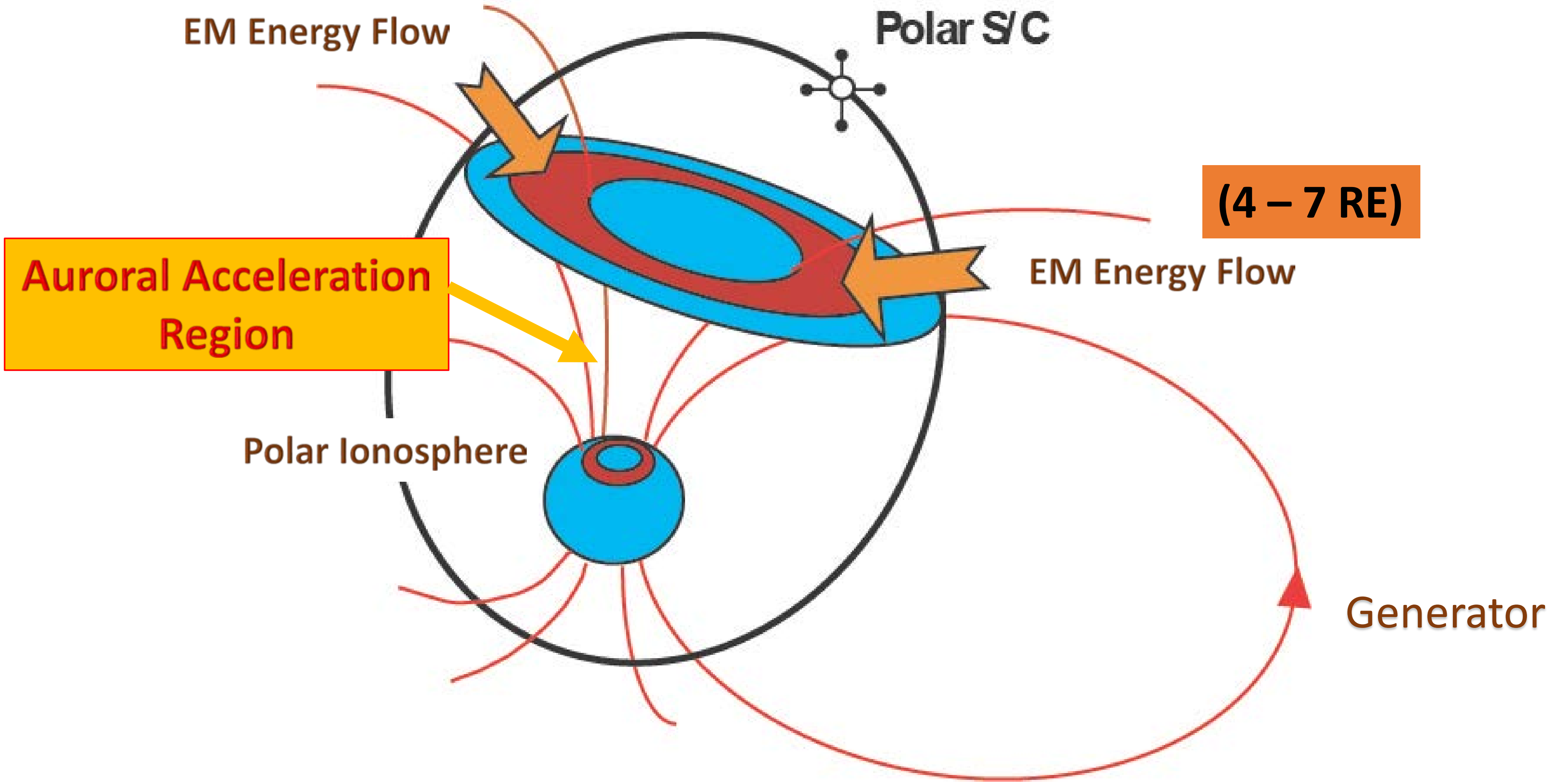
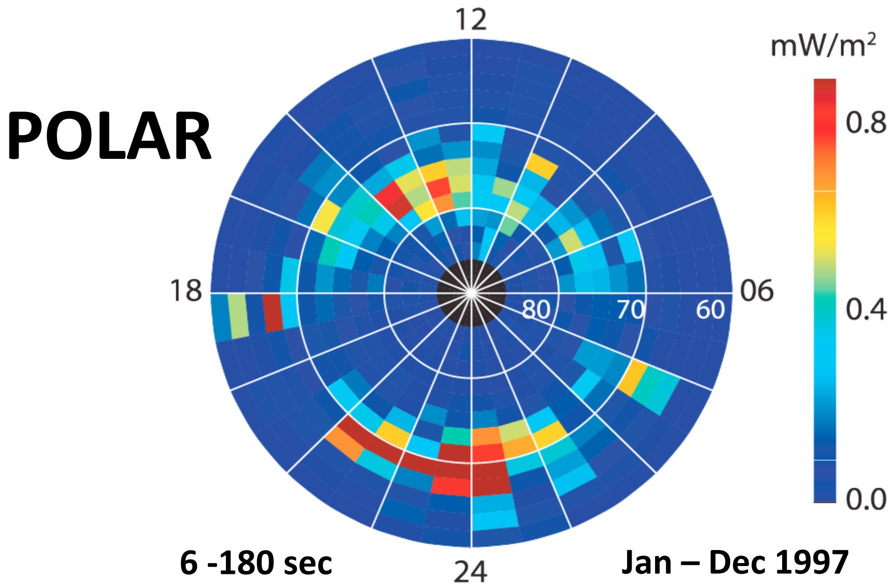


2003

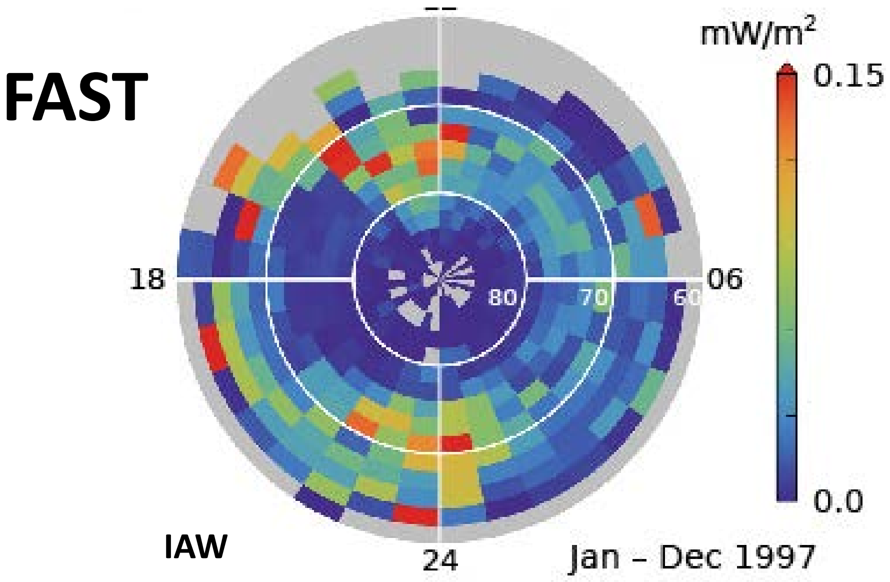


Keiling et al. (2003)

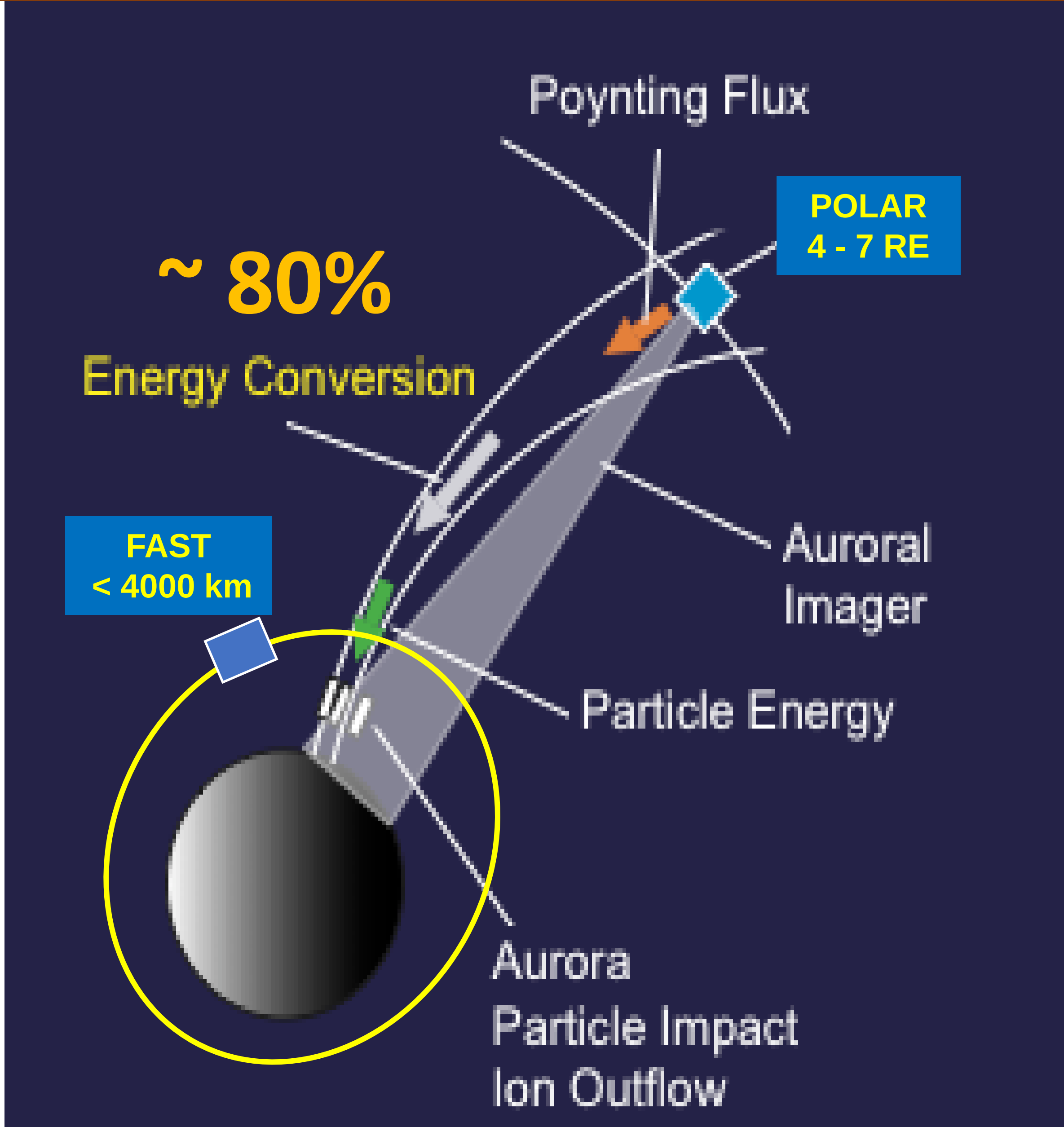
Alfvénic Coupling through the Auroral Acceleration Region



Keiling et al. (2003)



Hatch et al. (2017)



Ionospheric outflow

- Large fraction of inner magnetospheric energy density is supplied by ionospheric ions during geomagnetic storms (review by Daglis et al., 1999)
- Ions at source are ~1 eV, but in ring current >100 keV

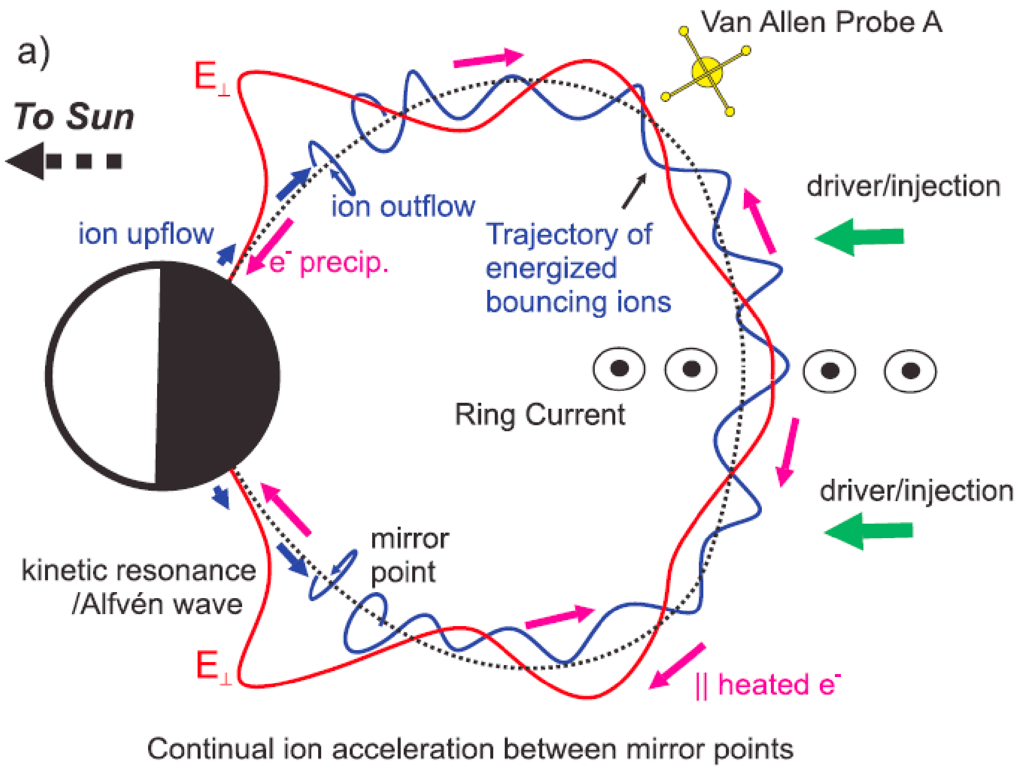
Challenge:

(1) ion extraction from ionosphere
(2) transport to ring current
(3) acceleration up to large energies

Mechanism

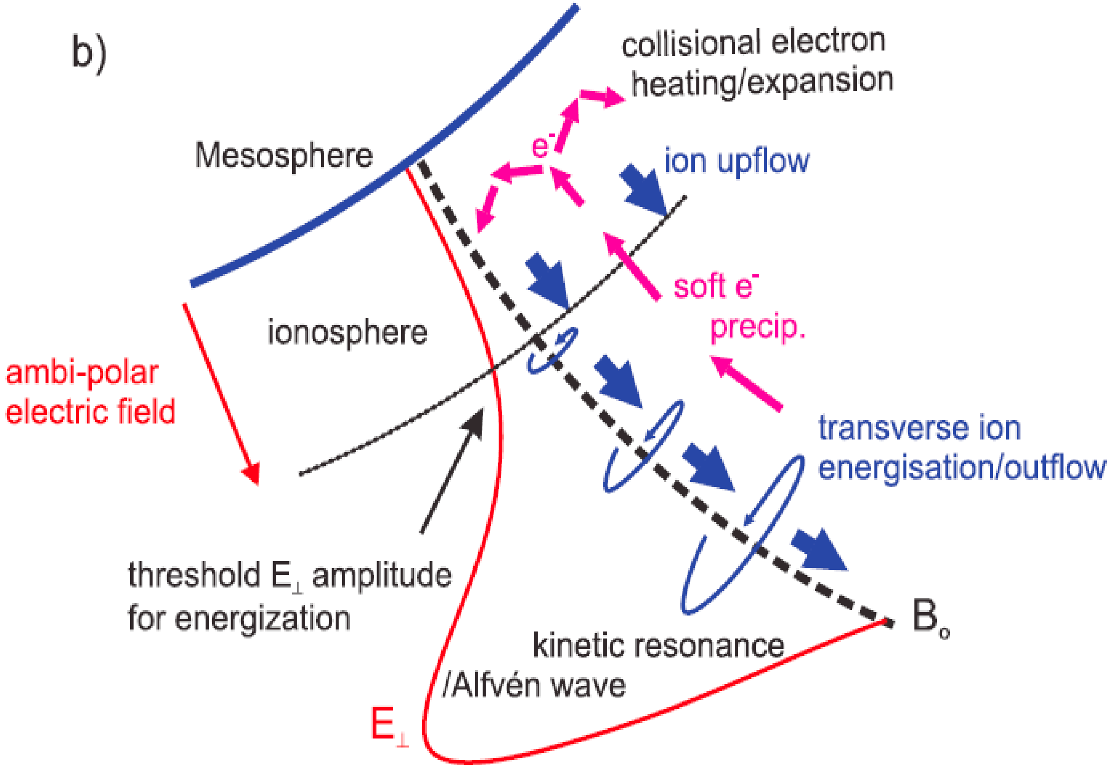
Chaston et al. (2015) wrote:

- The process begins with the driving of dispersive Alfvén waves in the dipolar magnetosphere presumably as a consequence of the **injection process** and their precursors in the form of **fast flows** in the plasma sheet. [Chaston et al.,2012; Ergun et al.,2015, Wright and Allan, 2008; Lysak et al., 2009; Lee and Lysak, 1991; Rankin et al., 1993; Lee et al., 2012].
- Phase mixing, refractive focusing [Mann et al., 1995; Rankin et al., 2005], and nonlinear processes [Rankin et al., 1993] will produce **large-amplitude dispersive scale Alfvén waves**.



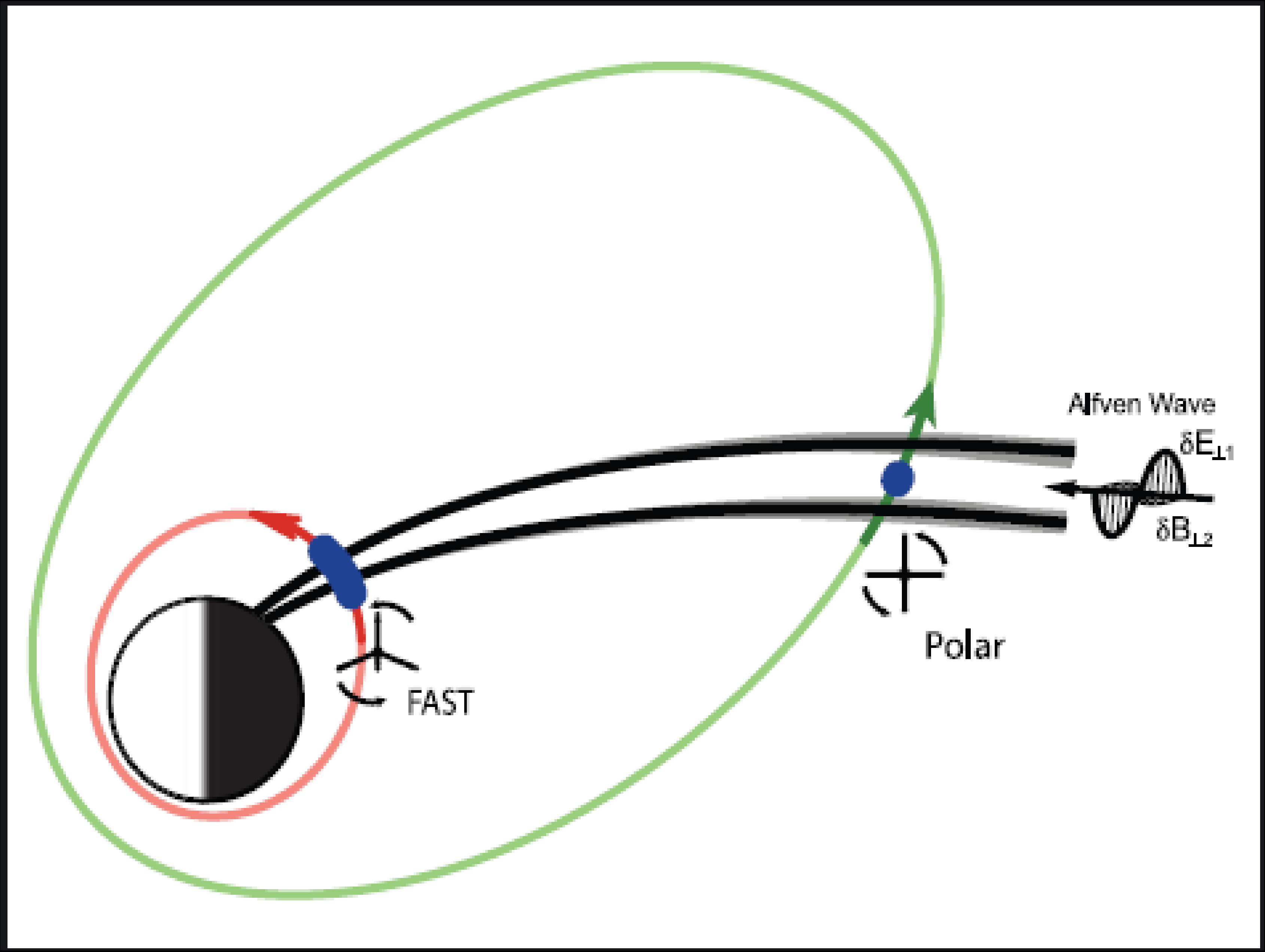
Chaston et al. (2015)

- Observations performed within the ionosphere by radars [Wahlundetal., 1992; Kaganetal., 1996] and rockets [Whalen et al., 1978; Lynch et al., 2007] along with modeling [Sydorenko and Rankin, 2013] have shown ***HOW*** electron precipitation at energies typical of those observed in dispersive Alfvén waves drive collisional heating and outward expansion of ionospheric electrons leading to ion upflows.
- These upflows may supply ionospheric ions to altitudes where they can **experience electric fields in the Alfvén wave** sufficient to drive trapping in the wave potential [Lysak, 1986] and/or the breakdown of gyromotion [Cole, 1976; Johnson and Cheng, 2001; Chen et al., 2001], causing transverse acceleration followed by ionospheric outflow due to the mirror force.

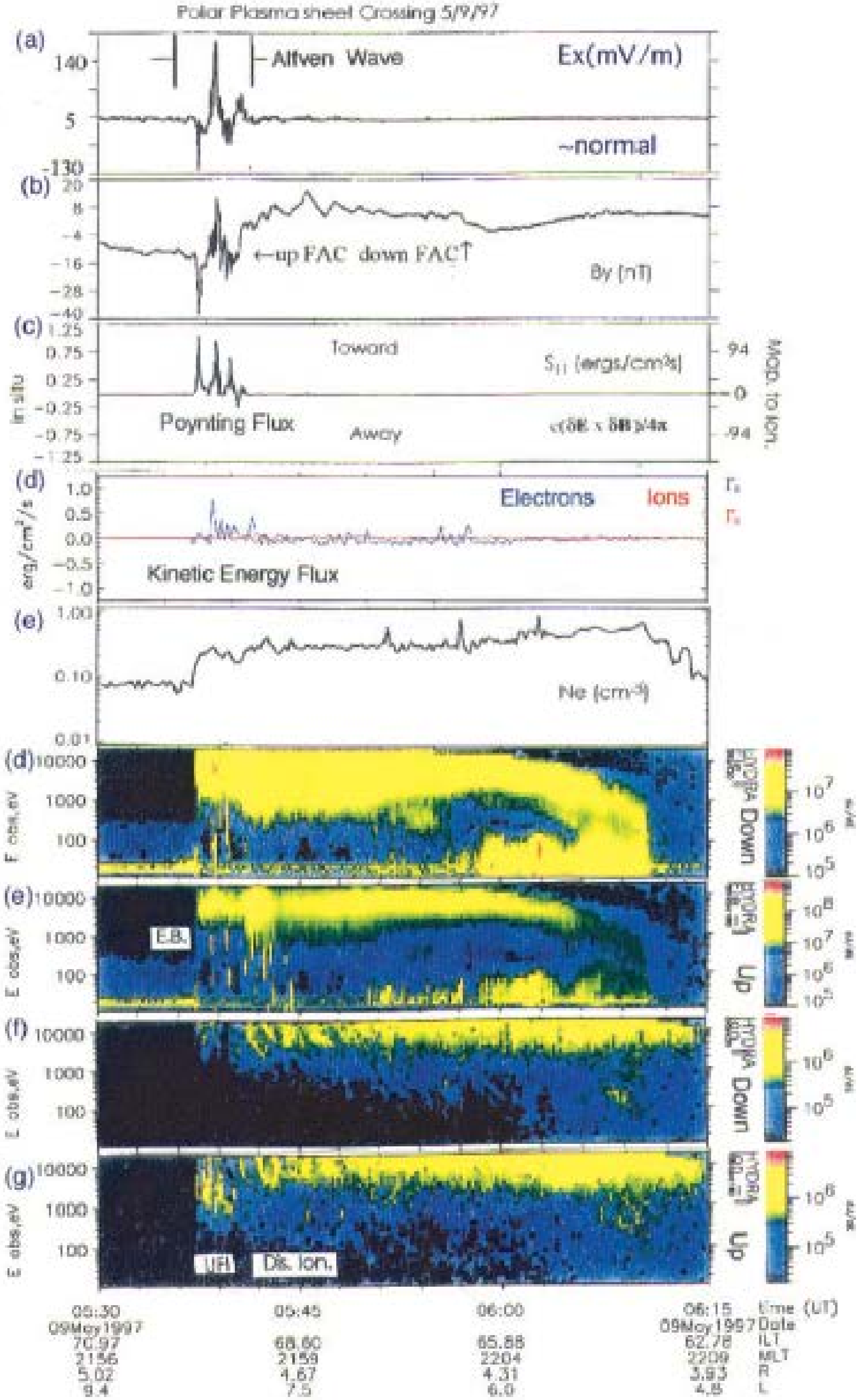


Chaston et al. (2015)

Case studies



Wygant et al. (2000)



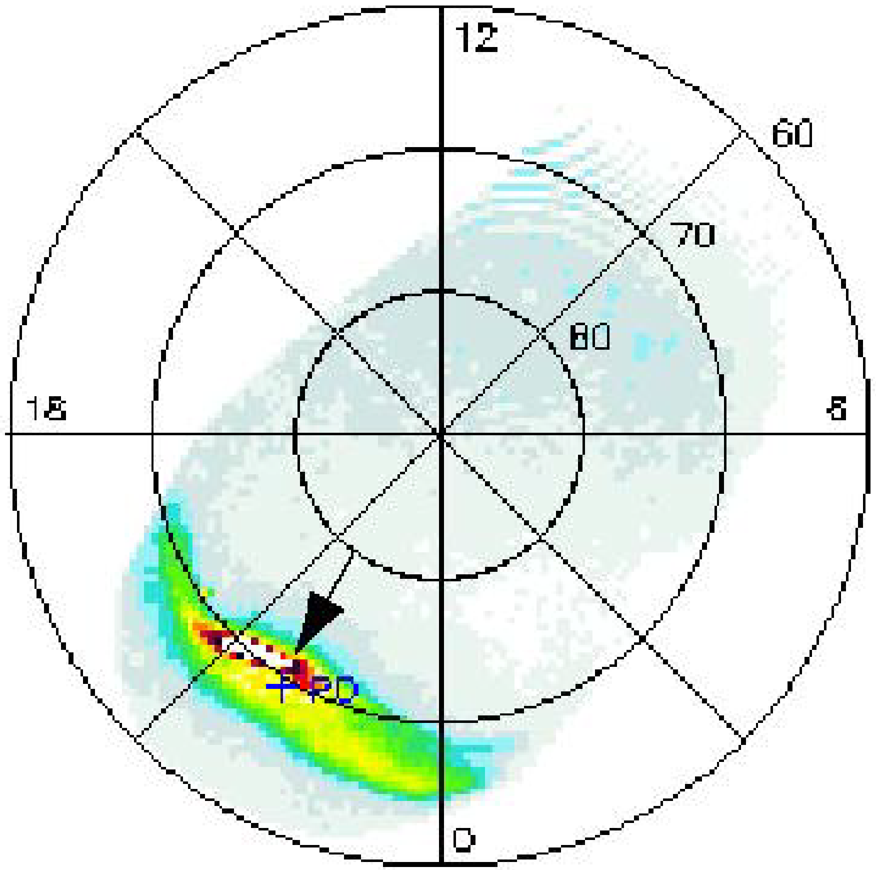
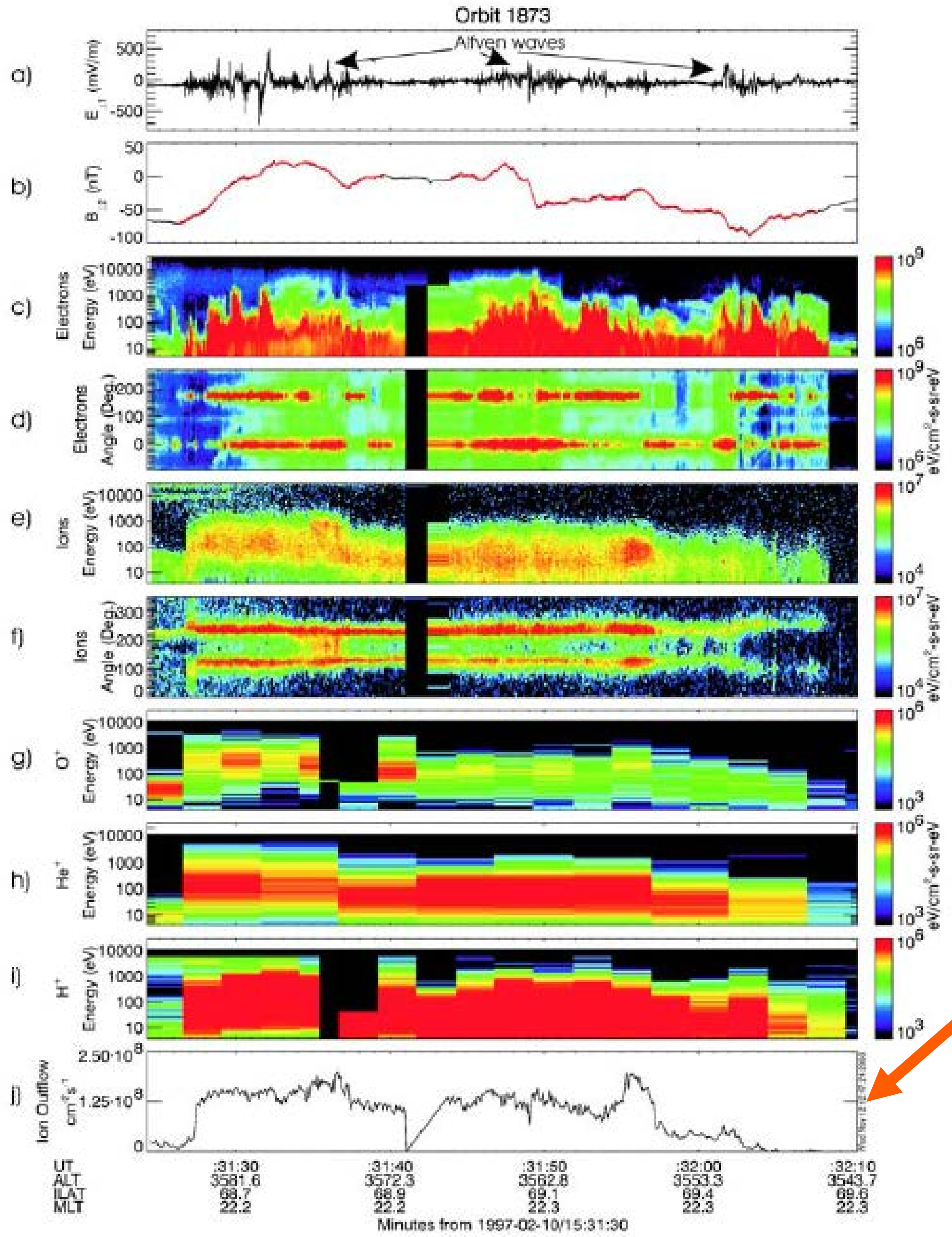


Figure 1. Polar measurements through the plasma sheet tail lobe boundary. (a) *Ex* component of the electric field (northward, normal to average plasma sheet boundary and nearly perpendicular to the magnetic field). (b) *By* component of magnetic field (eastward perpendicular to the magnetic field nominally in the plane of the plasma sheet). (c) Field-aligned component of the Poynting flux (positive is earthward). (d) Electron (blue line) and ion (red line) kinetic energy flux derived from the Hydra particle measurements. (e) Electron density. (f–k) Ion and electron fluxes for pitch angles between 150 and 180° (away from the Earth), 75 and 105 °, and 0 and 30° (toward the Earth).

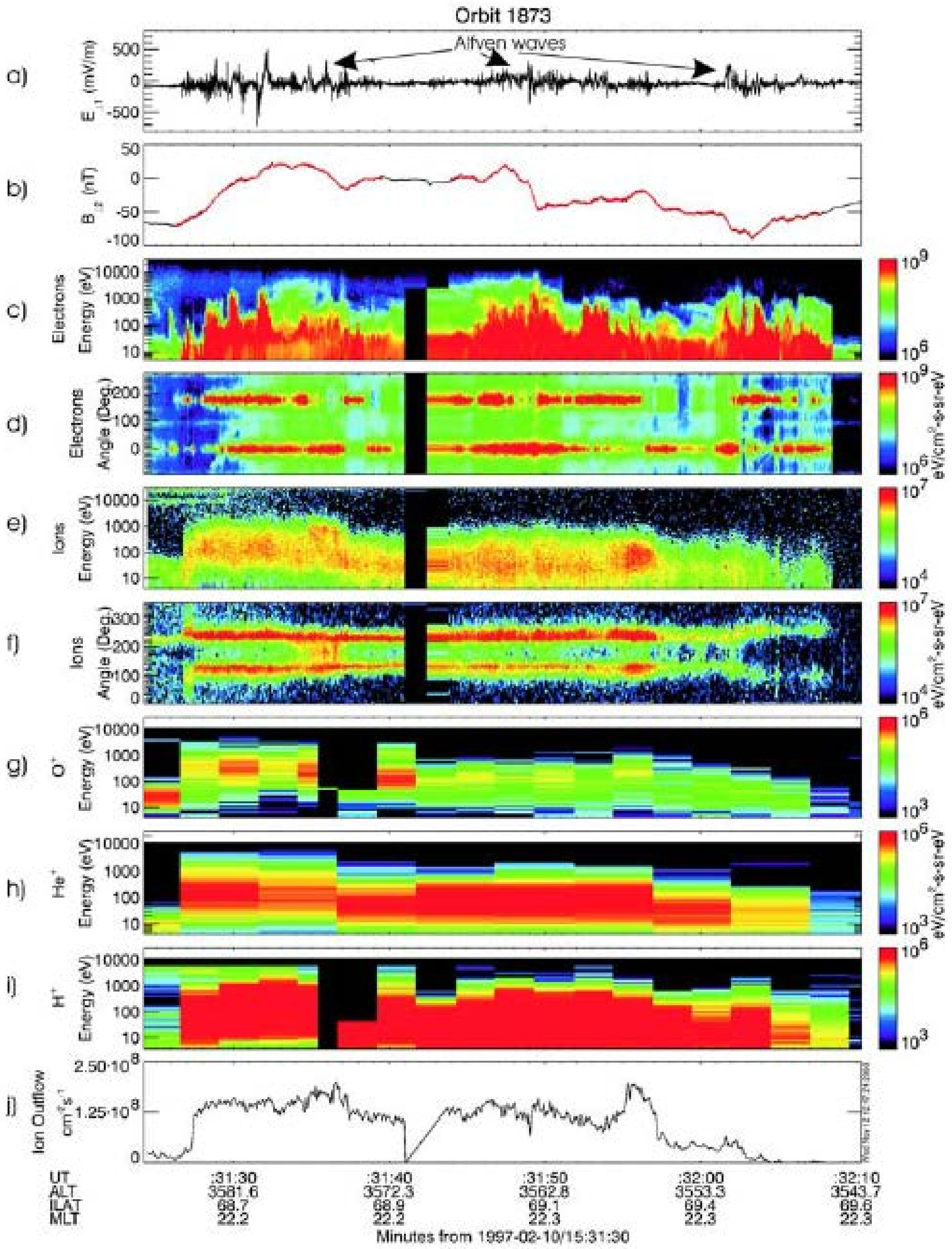
Chaston et al. (2004)

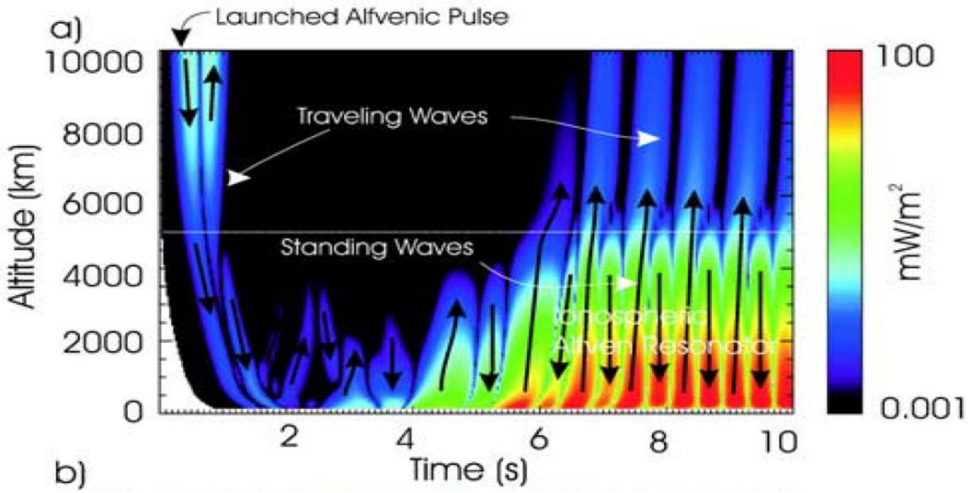


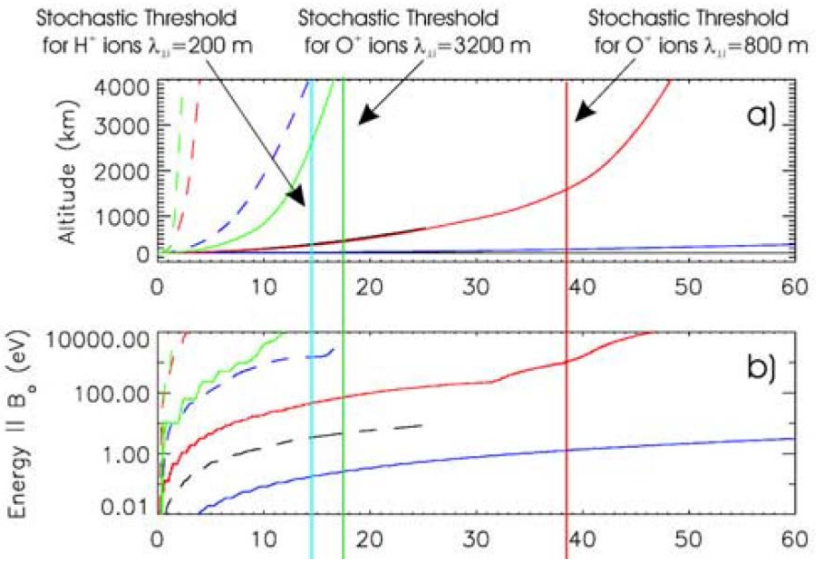
Ion outflow

Figure 1. Observations from FAST on the polar cap boundary. (a) The electric field along the spacecraft trajectory or roughly north-south ($E_\perp 1$). (b) The magnetic field measured transverse to the spacecraft trajectory and Bo, pointing roughly east-west ($B_{\perp 2}$). The red lines show high-resolution search coil data. (c) The energetic electron spectra. (d) The energetic electron pitch-angle spectra with 0° pointing downward. (e) The ion energy spectra. (f) The ion pitch-angle spectra with 90 and 270° pointing transverse to Bo. (g)–(i) The O^+, He^+, and H^+ ion energy spectra and (j) the total integrated outflowing ion flux.

Chaston et al. (2004)







→ Tracing ion motion over many wave periods from an initial altitude and transverse energy of 200 km and 1 eV, respectively.

Storm event - Van Allen Probes

Chaston et al. (2016)

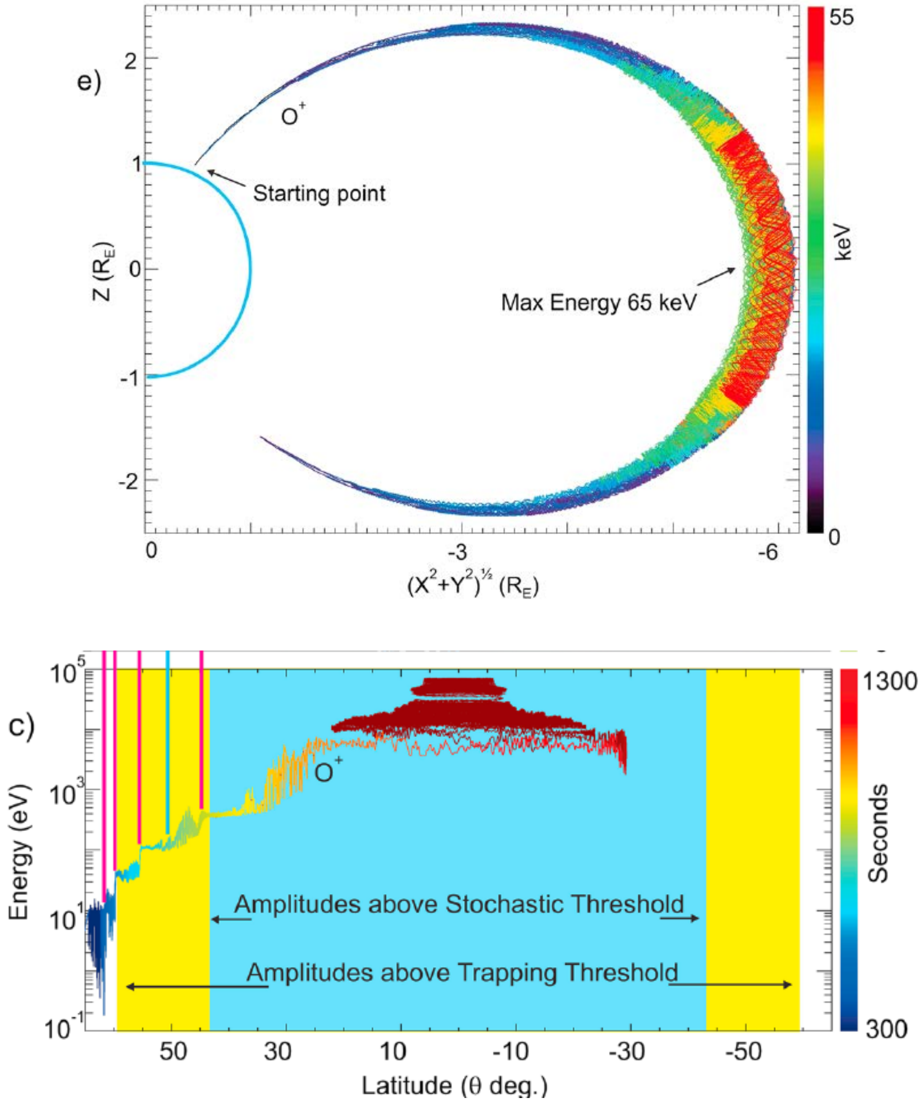


Figure 2. (a and b) Slices through Φ in dipole coordinates at constant φ and L. Blue and white traces show two O^+ ion trajectories from an ionospheric source. (c) Energy of the "white" ion shown in Figures 2a and 2b. Time is indicated by line color. (d) Transverse slice through Φ at $\theta = 37°$. (e) Trajectories of the ions in geophysical coordinates.

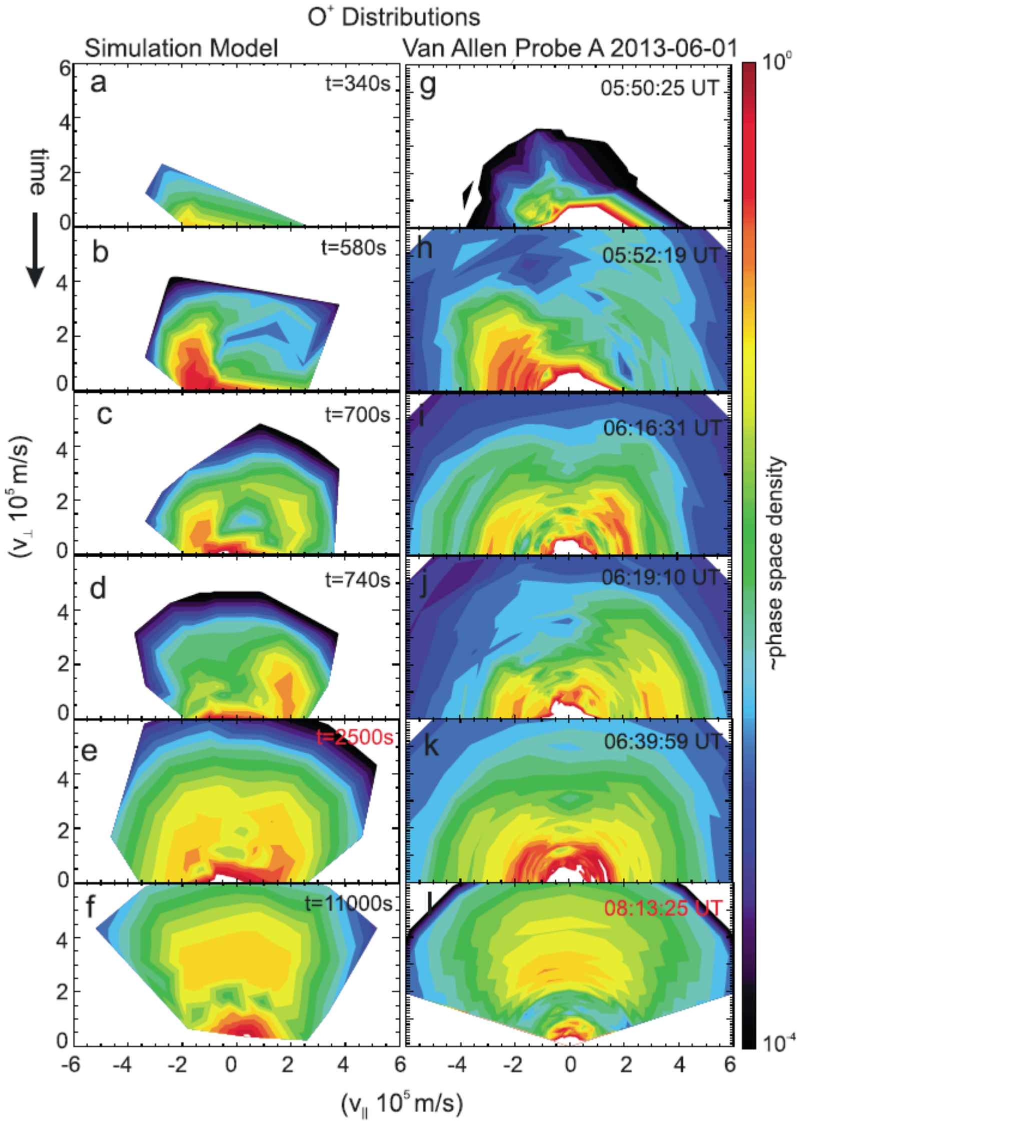
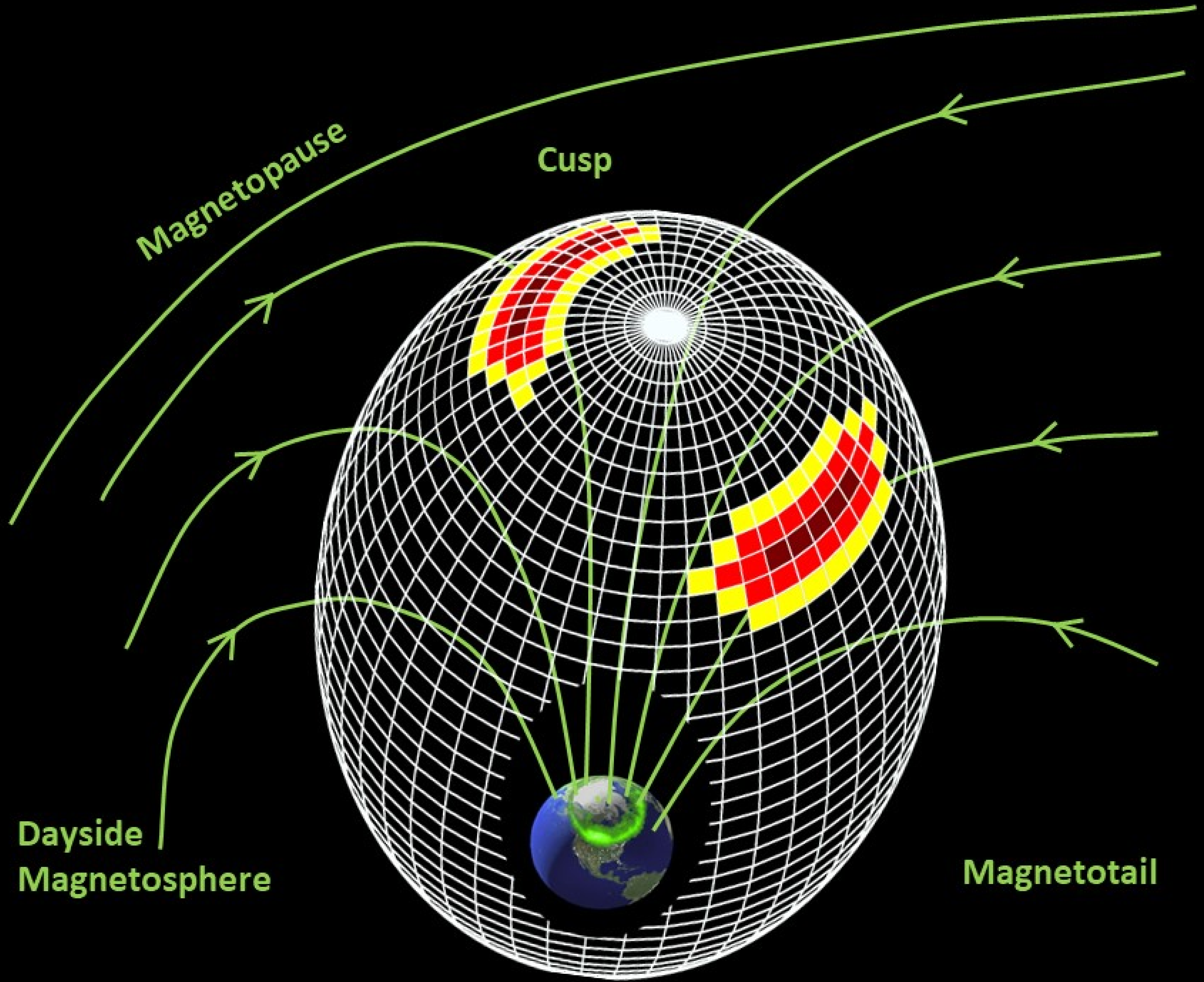
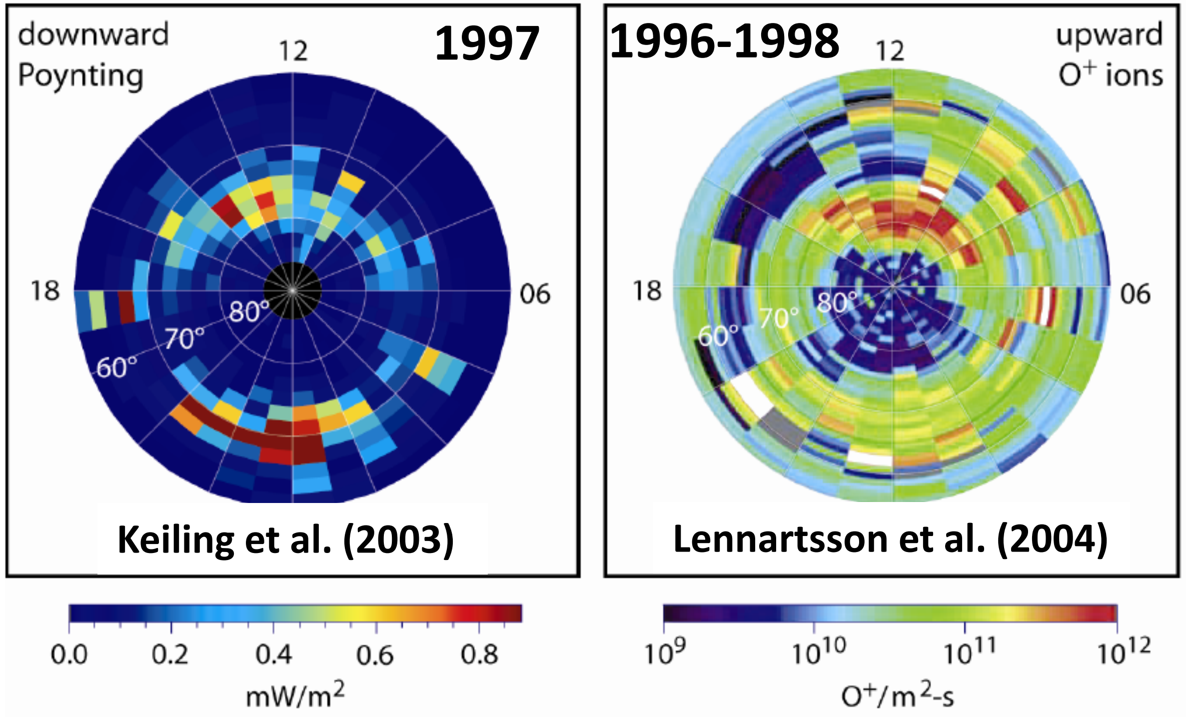


Figure 4. (a–f) Simulated evolution of O^+ distributions in the equatorial plane. (g–l) Observed evolution of O^+ distributions from 1 June 2013 storm on Van Allen Probe A.

Global studies





Lotko et al. (2006) wrote:

- Keiling et al. (2003) have shown that the cusp and premidnight boundary plasma sheet regions at **4-6 RE** statistically are the principal sites of intense Alfvénic Poynting fluxes
- The statistical pattern of intense Alfvénic activity exhibits some similarities to the observed statistical pattern in the number flux of outflowing O+ derived from Polar-satellite perigee passes near **1-RE altitude** by Lennartsson et al. (2004).
- The regions of greatest Alfvénic activity and **O+ outflow** occur in approximately the same local time sectors.
- Some of the Alfvénic power is absorbed by transversely accelerated ions (TAIs), producing keV ions at FAST altitudes (Chaston et al., 2004). The action of the mirror force on the TAIs produces the observed ion outflows.

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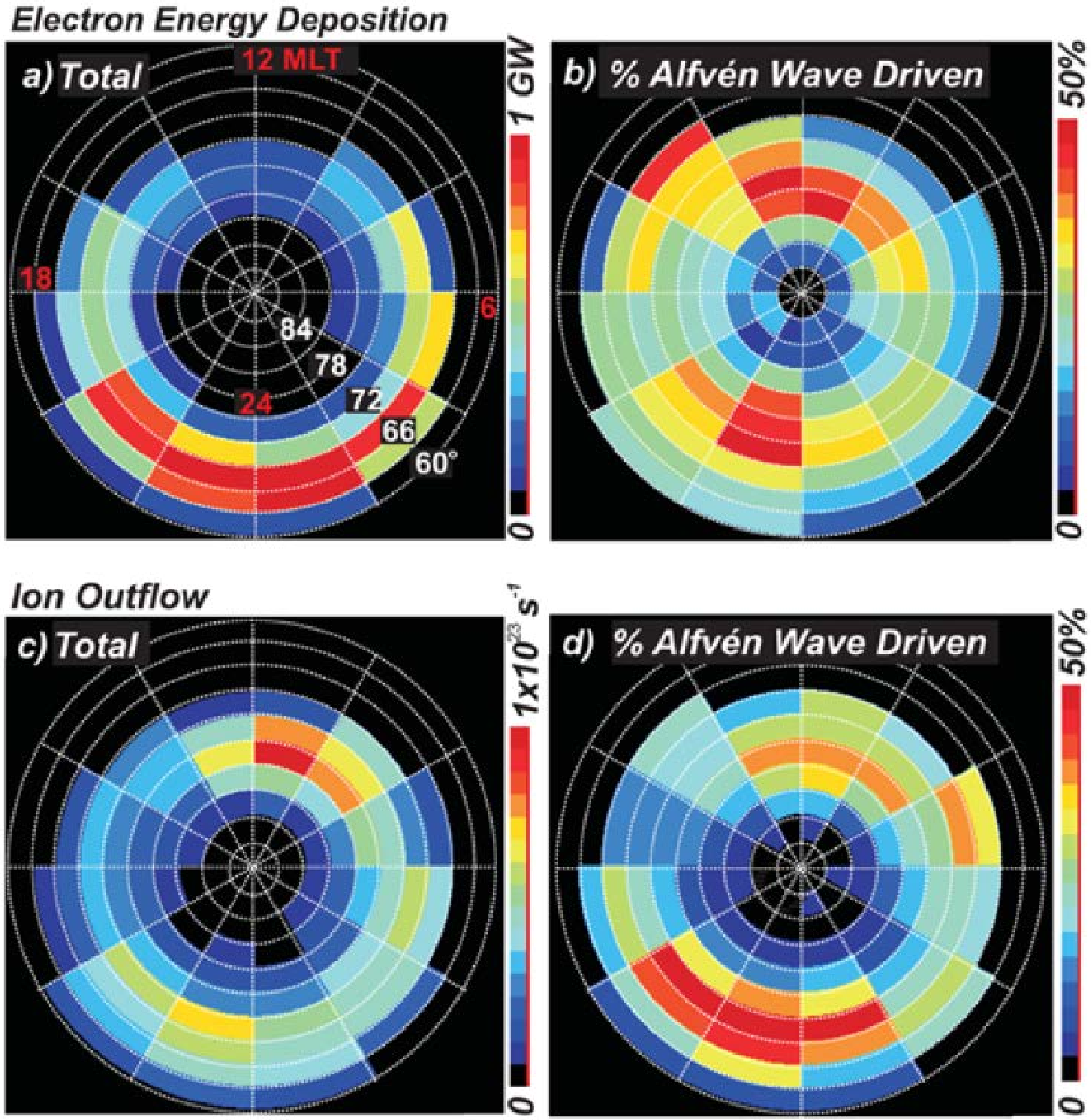
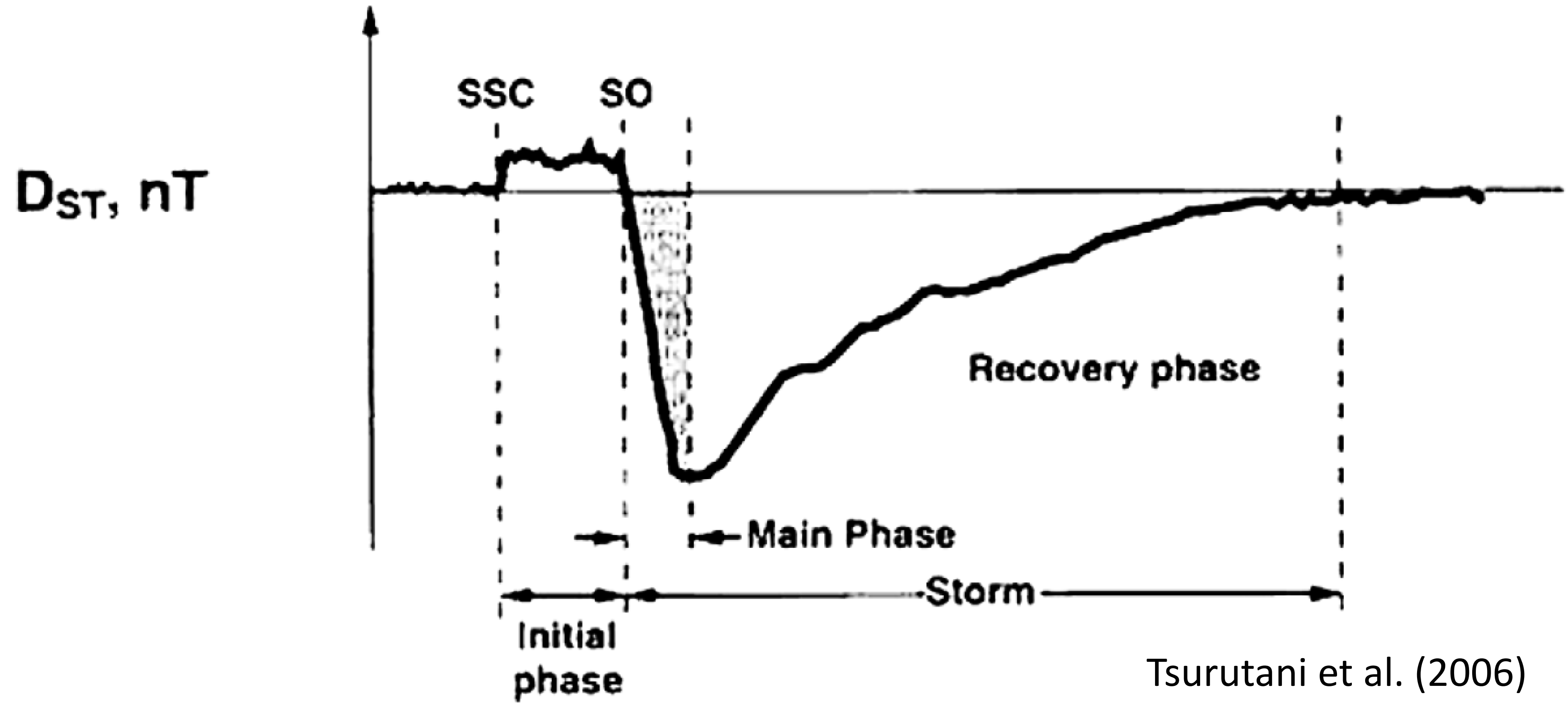


How important are dispersive Alfvén waves for auroral particle acceleration?

(Chaston et al., 2007)

- Combining coincident satellite measurements of fields and particles.
- As functions of increasing auroral activity on average 15–34% of total energetic ion outflow may be attributed to the action of DAWs.
- In the vicinity of the polar cusps and pre-midnight auroral oval, DAWs may provide the dominant means for powering electron and ion acceleration during active times.

Now on to storms….



Tsurutani et al. (2006)

→ Ion outflow is geomagnetic activity dependent (Yau et al., 1985)

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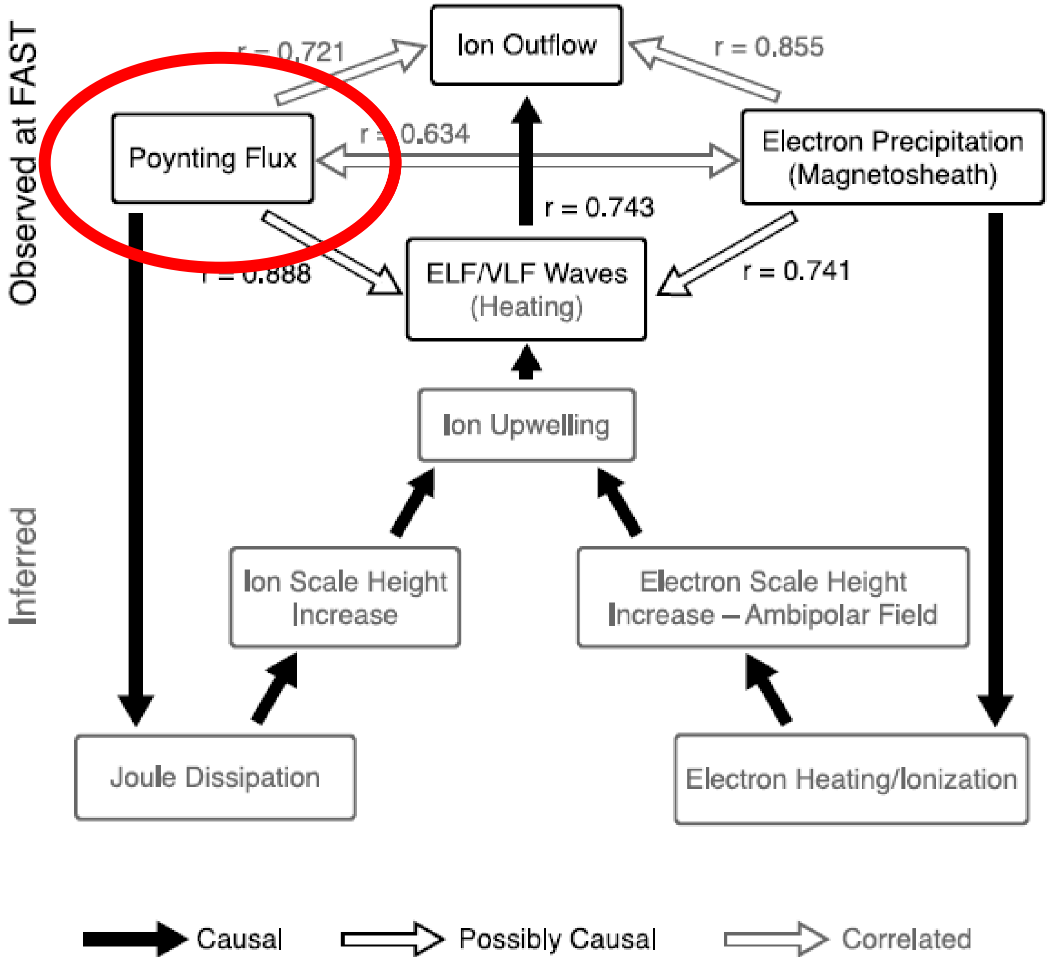
Finally



Strangeway et al. (2005)

Zheng et al. (2005) wrote (Polar data):

- Poynting flux may be associated with field-aligned currents or/and low-frequency Alfvén waves.
- Since AW enhance soft electron precipitation, the two controlling factors (Poynting flux and precipitating electrons) are not independent of each other.
- Poynting flux will be converted to heat in the ionosphere through Joule dissipation
- The resulting increase in ionospheric scale height will increase the column density of ions at altitudes where transverse heating occurs.
- Thus the electromagnetic energy flux in the form of Poynting flux is not the sole cause for the ion outflows, but it is the necessary first step.

→ Both studies ignore direct transverse acceleration of ions by Alfven waves, leading to outflow via the action of the mirror force (as discussed in previous slides).

Some Questions

- Is there community acceptance for the Alfvén wave picture of ion outflow? (→ Moore & Horwitz, 2007)
- How much of the Poynting flux in Strangeway's diagram is Alfvénic?
- Are there estimates of global kinetic energy flux (in GW) for outflowing ions?
- Etc.