ASTR 5300
Ion Outflow

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NOAA/NGDC

Special thanks to:
W.K. Peterson, A. Yau, R. Mcgranaghan

http://spidr.ngdc.noaa.gov/art/?special=chapman2011 Poker Flat, February 2011

Outline

- What is ion outflow?
- Why study?
- How formed? What processes?
- Observations and Models
- Summary

What is ion outflow?

The big picture:

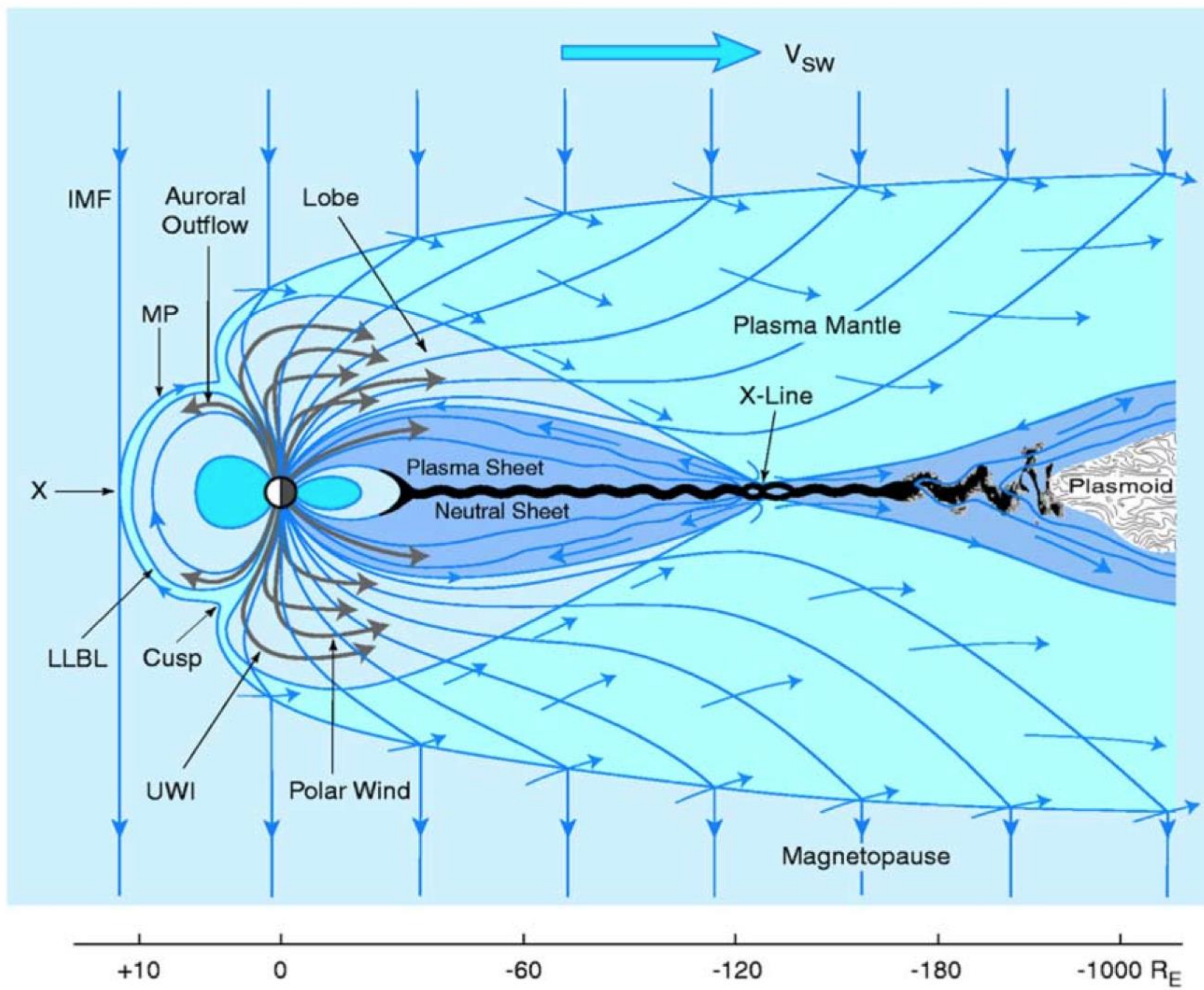


Figure 2. Global circulation of plasmas in Earth's magnetosphere, in the noon-midnight meridian. After *Hultqvist et al.* [1999] with kind permission of Springer Science and Business Media.

(Moore and Horwitz, 2007)

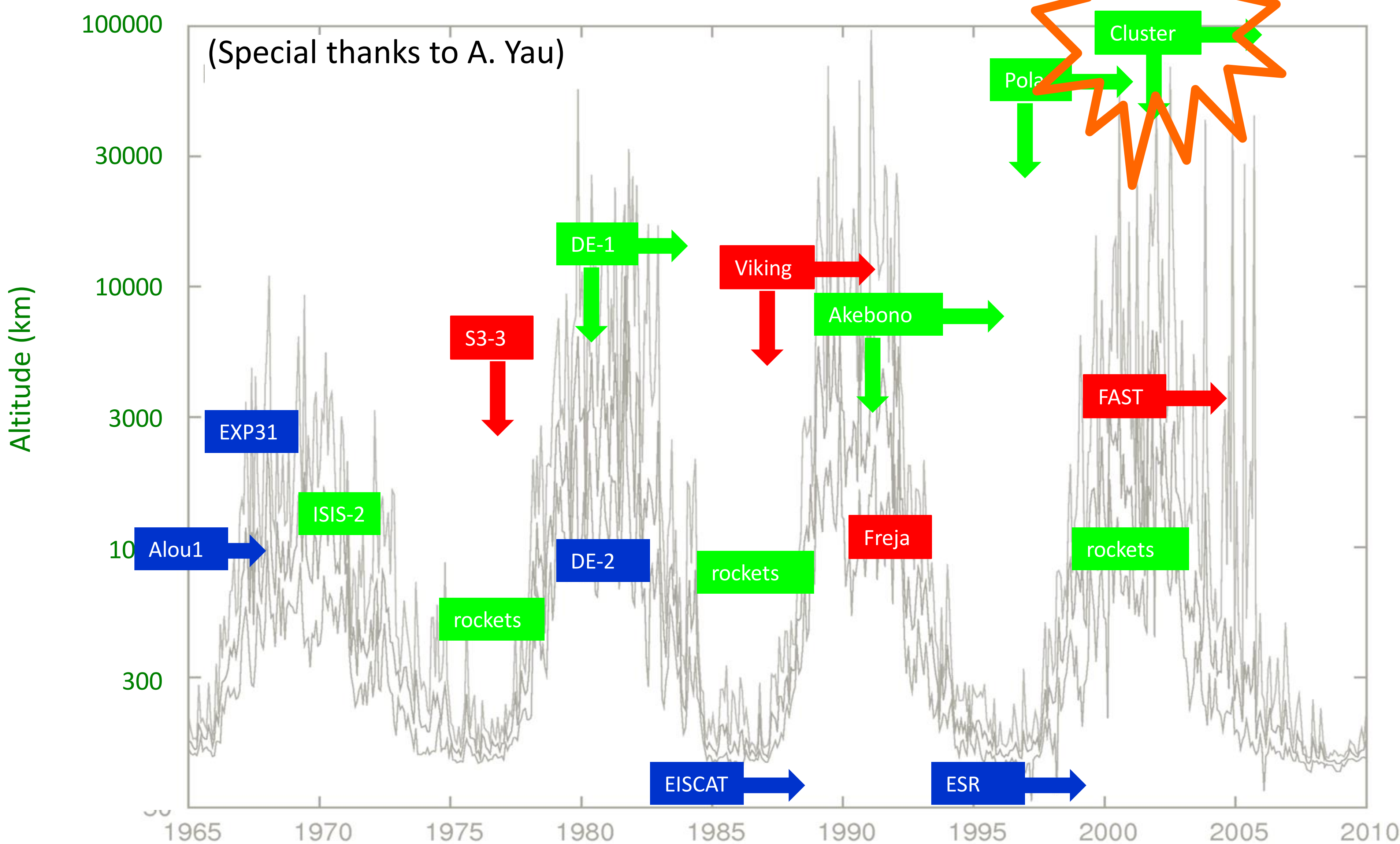
Observations: Historical Perspective

Satellite and radar observations over 3 Solar Cycles

Thermal: polar wind, auroral bulk flow

Suprathermal: beam, conic, transverse ion (TAI) upwelling ion/cleft ion fountain (UWI/CIF)

Thermal-Suprathermal



Who cares?

- Why ion outflow (H^+, He^+, O^+) is important?
- Supply magnetosphere (e.g. discovery of Shelley et al., 1972)
- Stellar ablation of planetary atmospheres
  - Primary planetary atmospheric loss mechanism (Moore and Horwitz 2007)
  - Interplanetary low-energy ions (< 10's eV) originate from Earth's ionosphere and several planets and moons (Andre and Cully, 2012)
- What about O^+?
  - Much more massive (16 amu)

Who cares? *Why Study O^+?*

- Energetic O^+ ions have important dynamic effects on the pressure of the ring current (Lotko et al., 2007, JASTP)
- Changes the reconnection rate in the magnetopause and magnetotail (Shay and Swisdak, 2004. Phys. Rev. Lett.)
- Significant populations of O^+ have been observed in the plasma sheet even during quiet times (Peterson et al, 2006, JGR)
- O^+ increases plasma sheet density, thermal pressure, slows convection, decreases CPCP (Winglee et al., 2002, JGR)
- Affects the development of substorm sawtooth oscillations in magnetospheric convection (Brambles et al., 2011, Science)

Who cares? *Why Study O^+?*

- Outflow Impacts to Substorms
  - Recall sawtooth events are representative of the stretching and contraction of the magnetotail with a subsequent release of an earthward plasmoid as the field returns to a more dipolar state.
  - Magneto-hydrodynamic (MHD) simulations using the LFM model show a strong dependence of the periodicity and magnitude of sawtooth oscillations on the existence and MLT location of the outflow of O^+ ions by mass loading [Brambles et al., 2012].

How formed?

- Note about energy to overcome gravitational potential:

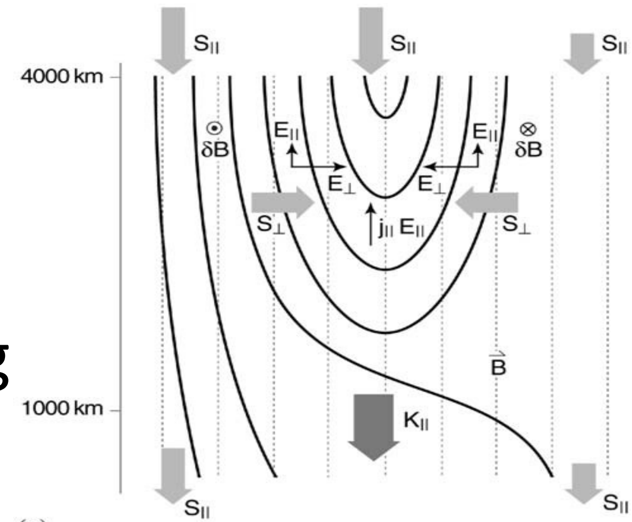
	Altitude (km)	Gravity (m/s^2)	Velocity Escape (km/s)	Energy (eV) [1:4:16]		
				$^{1}H^{+}$	$^{4}He^{+}$	$^{16}O^{+}$
	300	8.94	10.9	0.62	2.49	9.97
DMSP →	850	7.63	10.5	0.58	2.30	9.21
	2500	5.06	9.47	0.47	1.87	7.50
	6000	2.60	8.03	0.34	1.34	5.38
	9000	1.69	7.20	0.27	1.08	4.33

- At 850 km, O^{+} is ~ 0.01 to 0.1 eV
- H^{+} and He^{+} have high thermal energies → sufficient to escape to inner magnetosphere w/o additional energization → Jean's Escape
- Considerable energy needed to convert low altitude thermal O^{+} bulk flows to outflows!

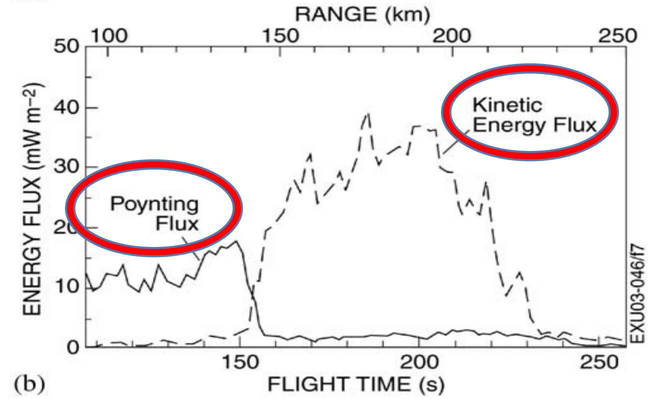
Essential Processes

- Photoionization
  - Ambipolar electric field
- K.E. - Soft particle precipitation
- EM.E. - Poynting flux, Joule heating
- Parallel electric field $E_{||}$
  - Up / Down Current Regions
    - Filamented by potential structures
- Wave particle interactions
- Centrifugal
- Misc: e.g. ponderomotive

Thayer and Semeter, JASTP, 2004



(a)



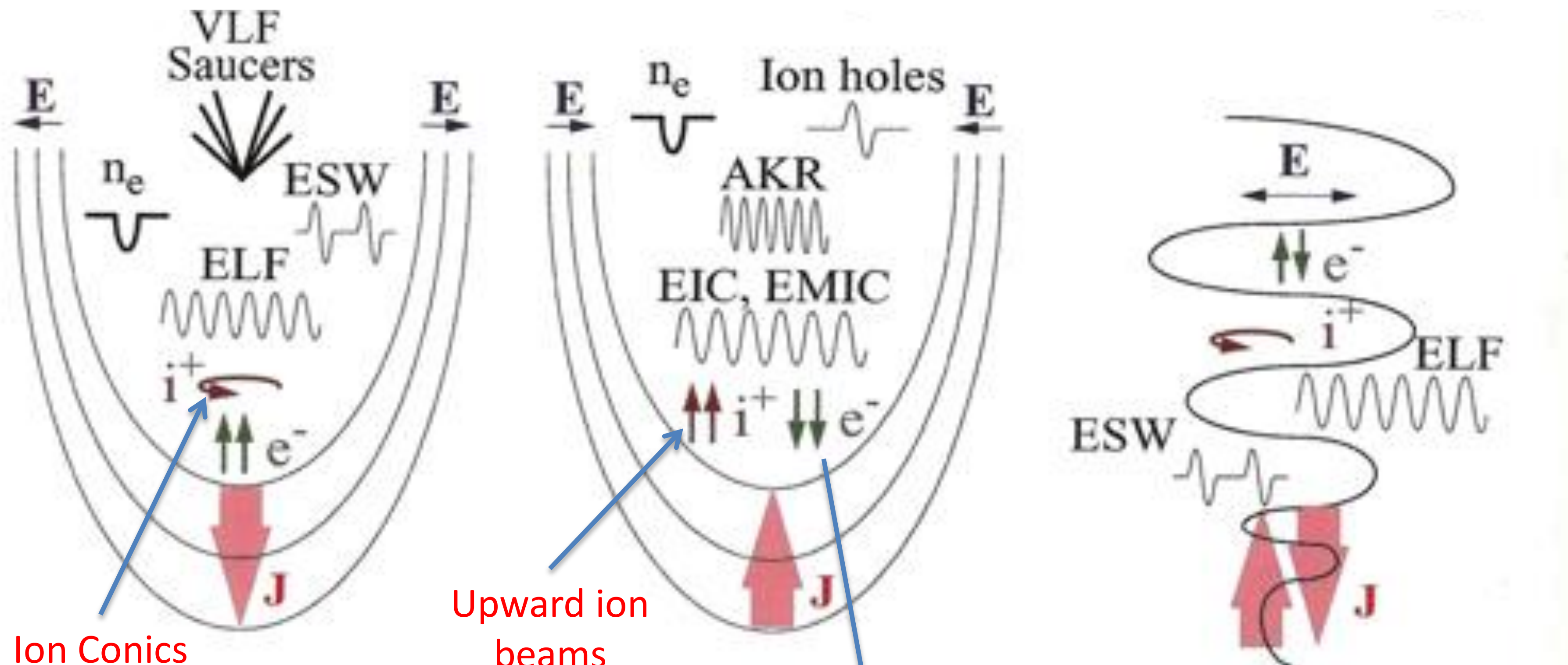
(b)

Evans et al, JGR, 1977

Energizing O^+

Waves and $E_{||}$ => Conics and Beams

Downward Current Structure | Upward Current Structure | Polar Cap Boundary Acceleration Region



Ion Conics
"Pressure Cooker"
Conic => Pitch angle ≠ 0 or 180

Upward ion beams
Beam => Pitch angle ≈ 0, 180

Monoenergetic / Discrete Aurora Observed below

Carlson et al. (1998b)

Perpendicular Heating → Conics

- Ion cyclotron resonance: ions can exchange energy and momentum with low frequency plasma waves

$$\omega - k_{\parallel} u_{\parallel} - l\omega_{ci}/\gamma_{rel} = 0, \quad \omega_{ci} = qB/m$$

- Ion heating rate quasi linear approx. (Chang et al., 1986)

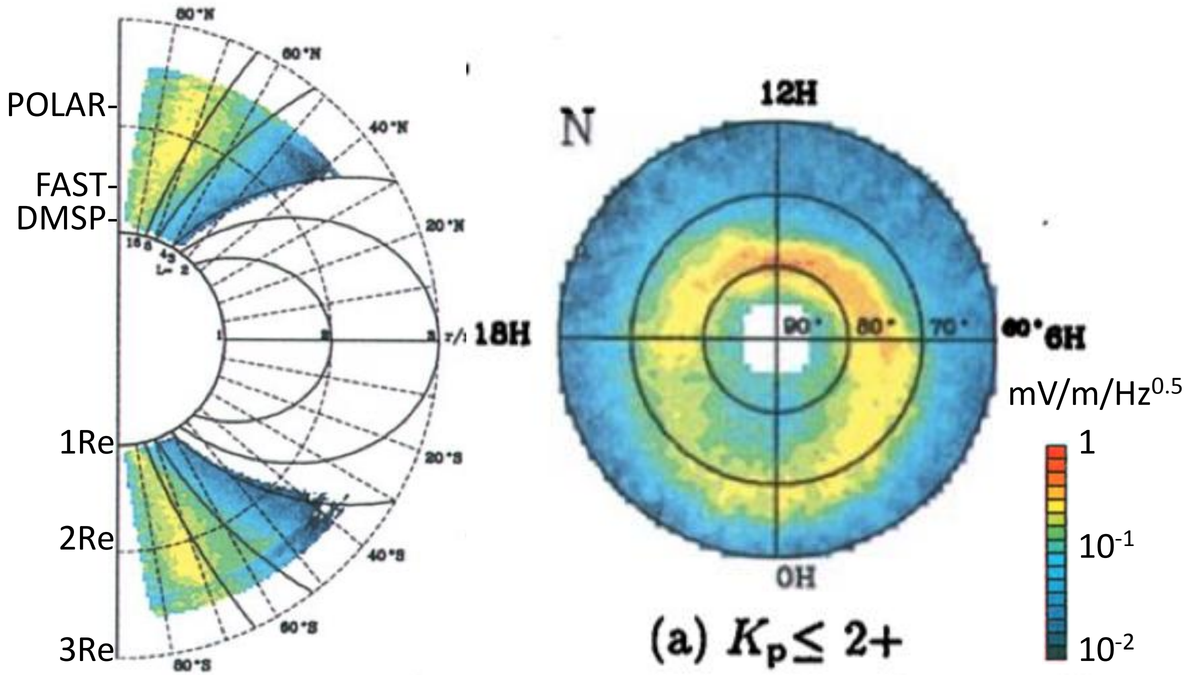
$$dW_{\perp}/dt \approx S_L(\omega_{ci}) q^2/2m$$

  - $S_L(\omega_{ci})$ is the spectral energy density ($V^2m^{-2}Hz^{-1}$) at the ion-cyclotron frequency ω_{ci}
- Magnetic mirror force $F_m = -\frac{W_{\perp}}{B}\frac{\partial B}{\partial z}$ → transfer of $v_{\perp}$ to $v_{\parallel}$
  - Good references: Lysak et al. (1980) and Paschman et al. (2002)
- Thus, perpendicular heating results in conics → ion velocity distribution looks like cone in velocity space

Perpendicular Heating

Measuring wave power…

5 Hz broadband noise power altitude profile from Akebono:



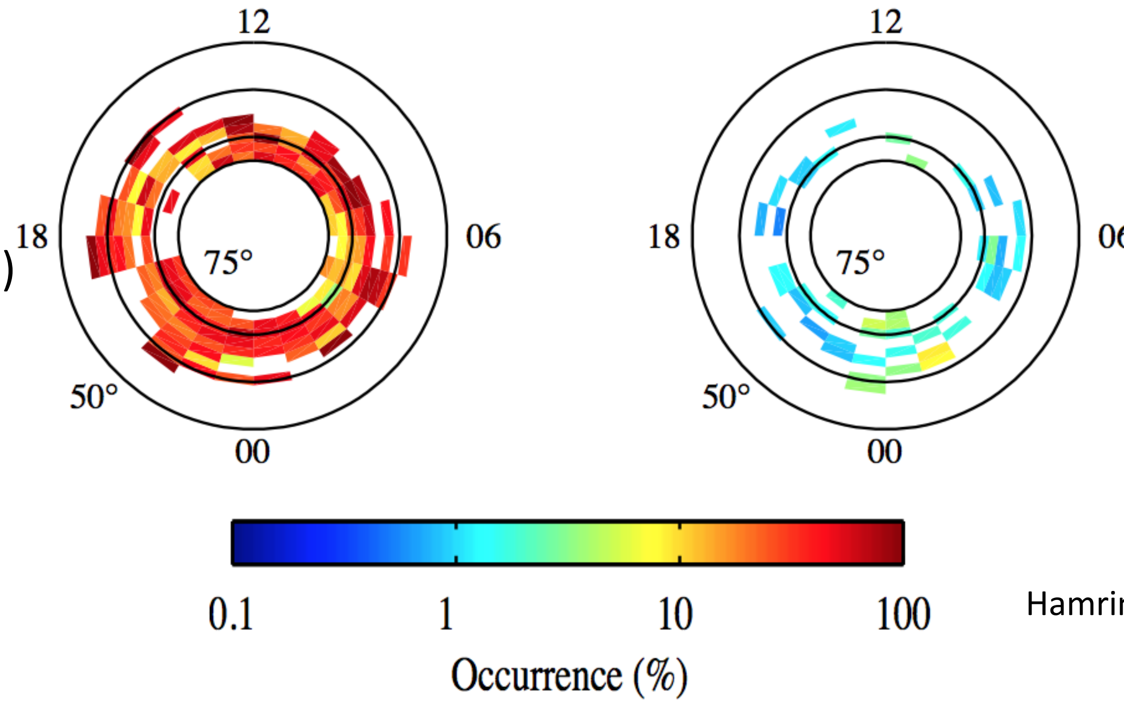
(Akebono, Kasahara 2001)

- Most intense in the cusp (constant 270-10,000km)
- Dawn > Dusk

Perpendicular Heating of O^+

- Observations at 1500 km (via Freja)
- Heated O^+ ⇔ Resonant waves
  - Resonant = Wave frequency ≈ Gyro Frequency

O⁺ when:
Strong Waves
(BB-ELF, EMIC, or
near lower hybrid)



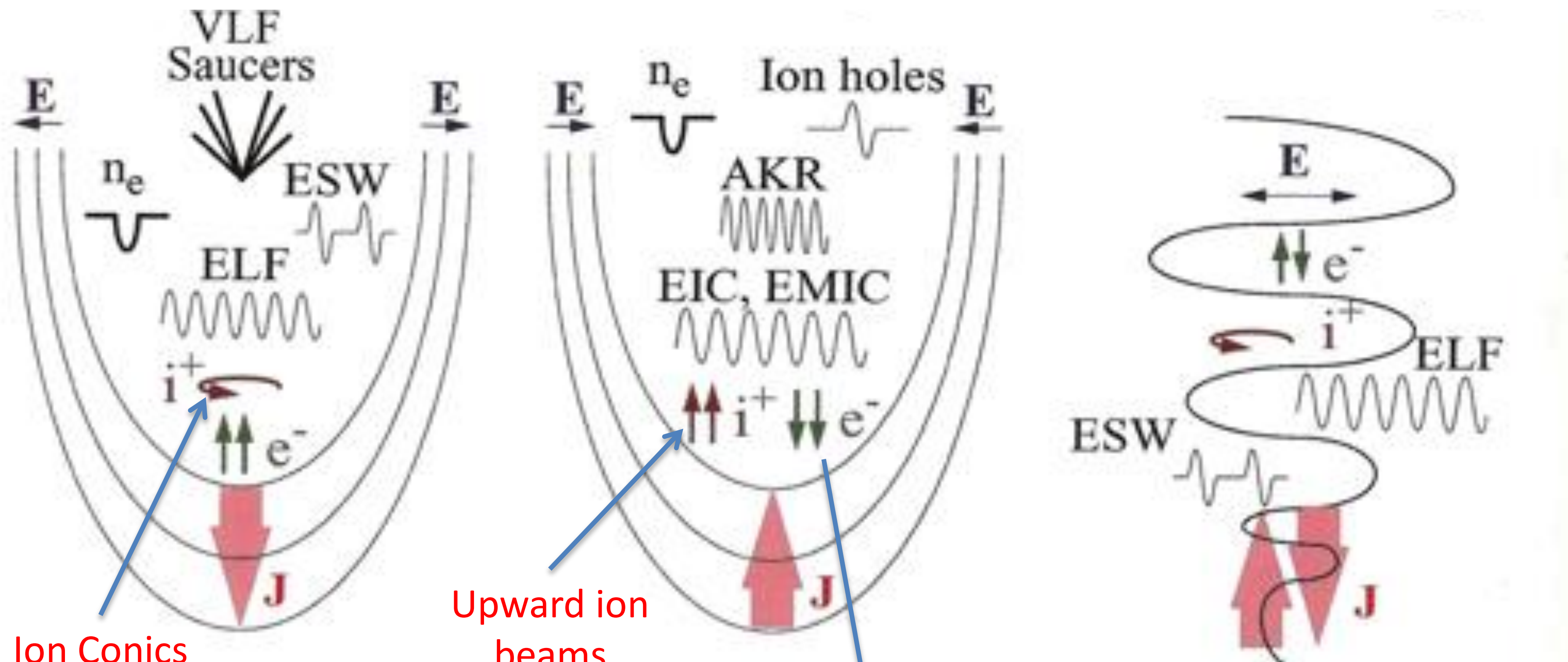
O⁺ when:
No Waves

Hamrin et al (2002a,b)

Energizing O^+

Waves and $E_{||}$ => Conics and Beams

Downward Current Structure | Upward Current Structure | Polar Cap Boundary Acceleration Region



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Monoenergetic / Discrete Aurora Observed below

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Parallel Energization and Quasi-static Potential Structures

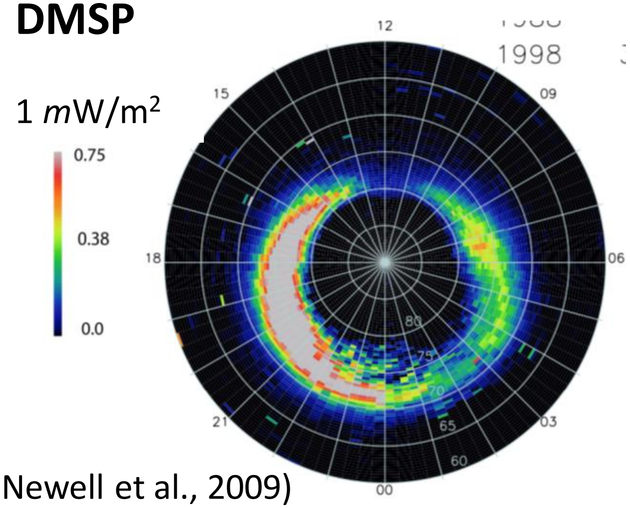
Observations on VIKING and FAST

→ structures with $E_{||}$ ↑ usually appear at higher altitudes:

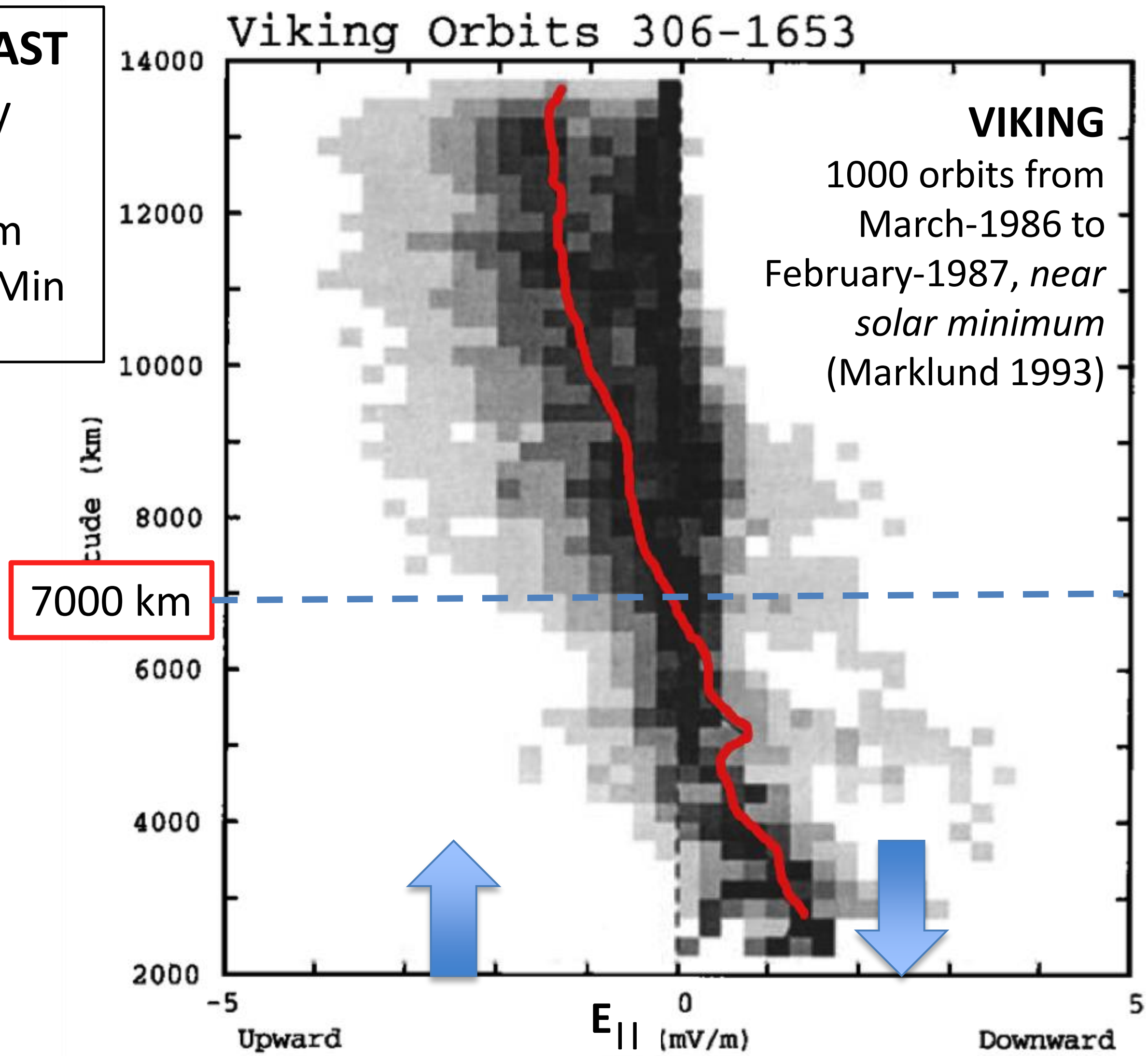
VIKING (on right): above 7000km

FAST (not shown): during Solar Min

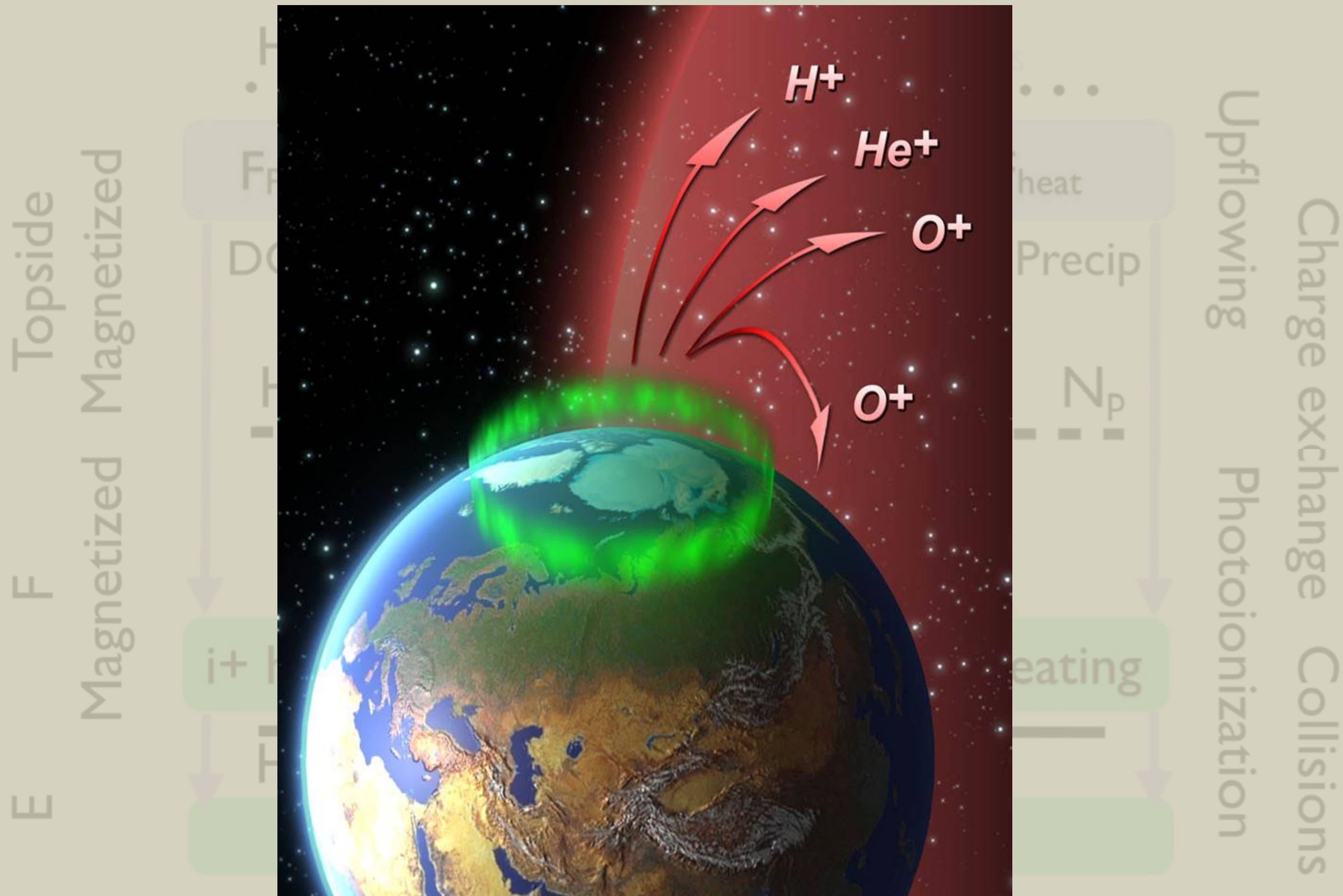
Auroral *signature* of $E_{||}$ from DMSP



(Newell et al., 2009)



Processes Summarized



Observations, Models

- How do we measure outflows?
- What have we observed?
  - What have we learned?
- What models and tools have we created?

Observations Low-energy Ions (mostly H^+)

- Low energy ions (< 10's eV) more prevalent than previously thought
- Dominant energy in magnetosphere 50-70% of time at 10^{25}-10^{27} ions/s
- Lowers V_A $(= B/(\mu_o\rho)^{1/2})$
  - Lowers dayside reconnection rate
- Smaller gyroradii
  - Better access to separatrix in magnetopause reconnection
  - Play important role in acceleration of ions from magnetosphere into reconnection jet

Observations Low-energy Ions
(mostly H^+)

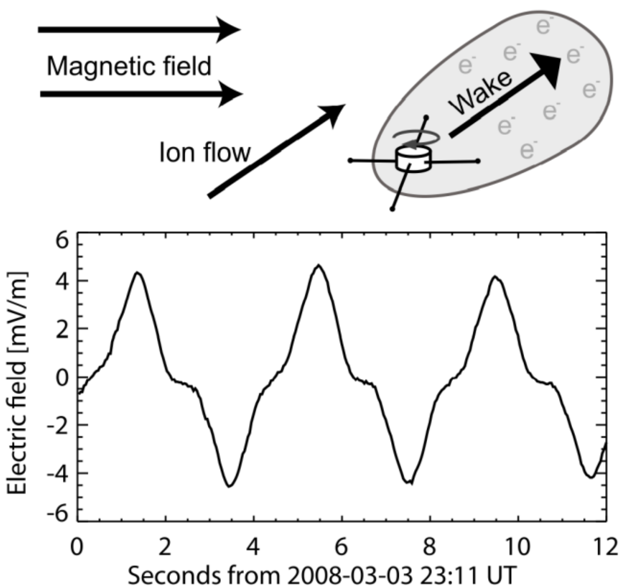


Figure 1. (top) Sketch of the wake behind a positively charged Cluster spacecraft, caused by a supersonic flow of cold ions [see *Engwall et al.*, 2009b]. (bottom) Non-sinusoidal electric field measured by the electric field booms on Cluster 3, with a spin period of 4 s, in a cold plasma [*André et al.*, 2010].

From Andre' and Cully (GRL, 2012)

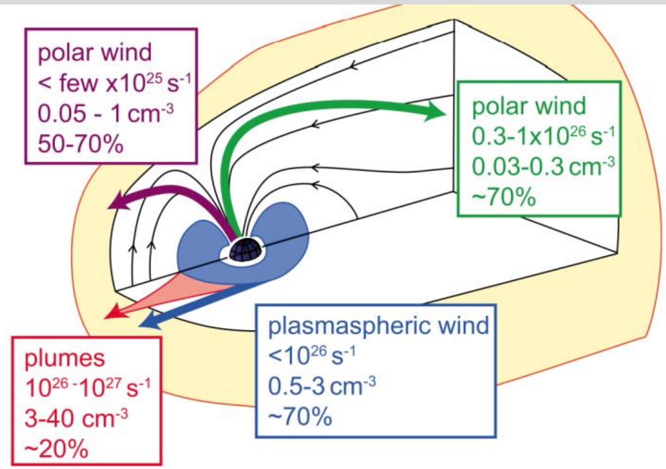
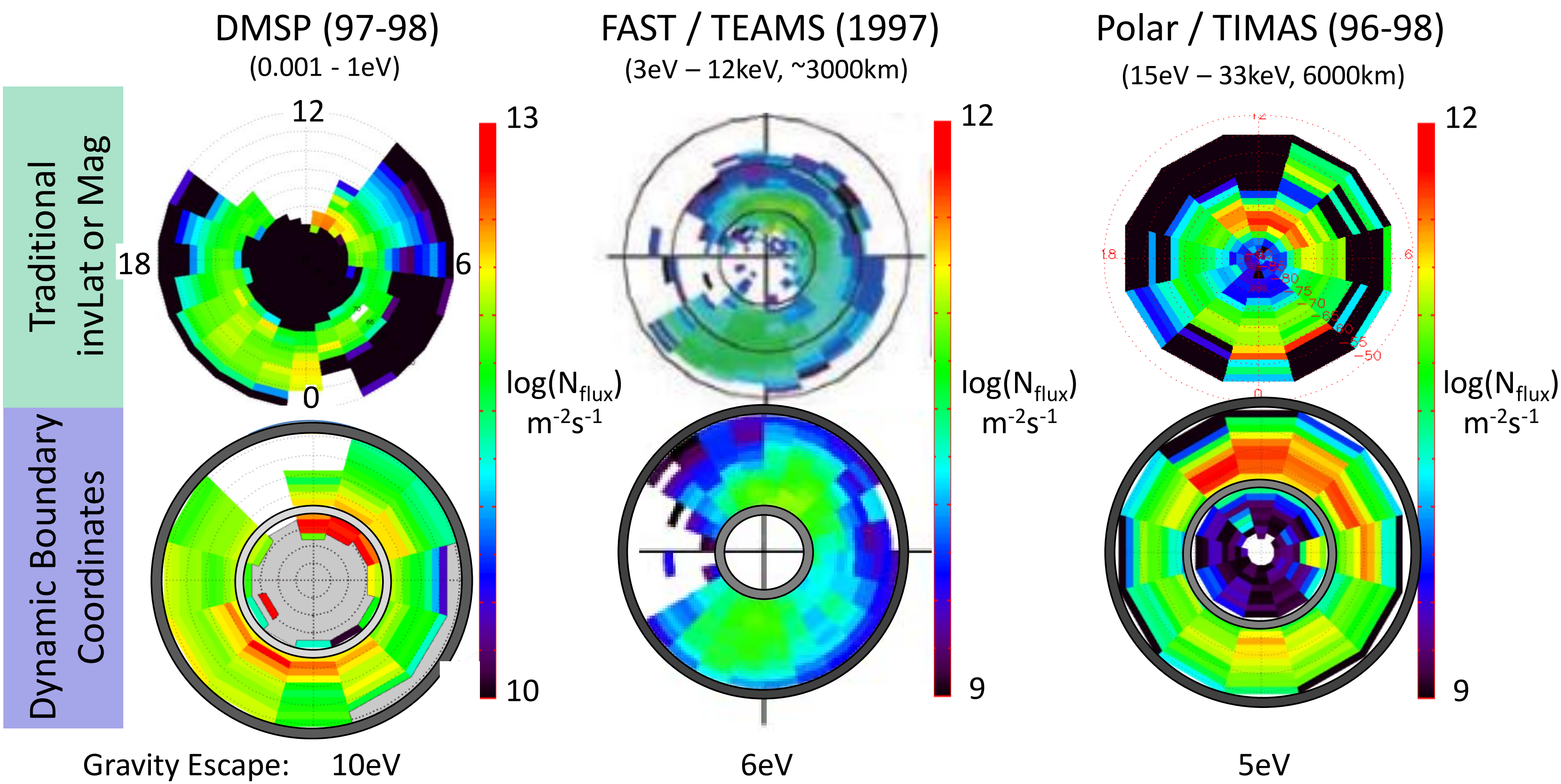


Figure 5. Sketch of regions where the density is dominated by low-energy ions, including sources, order of magnitude outflow rates and densities, and percentage of the time that low-energy ions dominate outside the ionosphere and plasmasphere. The polar wind mostly flows into the tail with a typical outflow rate somewhat less than 10^{26} s^{-1}. Some tens of percent of this flow are diverted through the dayside magnetopause for southward IMF. The plasmaspheric wind contributes an outflow comparable to the polar wind, but only through a limited area of the magnetopause. Dayside plumes occur much less frequently, but transfer a large mass of ions when they do occur.

Observations O^+ Low to High

Auroral Boundary Coordinates



The **light** and **dark gray** circles represent statistical auroral zone based on precipitation.
Dynamic boundaries = tracing of mass transport from upward to outflowing ions.

Observations

What have we learned?

- Variations with activity, SZA, MLT, Invariant Lat
  - From Cully 2003
    - H+ accelerated between 9000 and 16,000 km
    - O+ accelerated below 9000 km
      - Strangeway 2005 refined this to infer significant acceleration below FAST altitudes
    - Both H+ and O+ are dependent on Kp
    - While O^+ is more dependent on F10.7 than H^+ (partially open question)
- Escaping number flux quiet time (~6000 km)
  - noon ≈ midnight ≈ dawn + dusk (Peterson et al., 2009)

Observations *New*

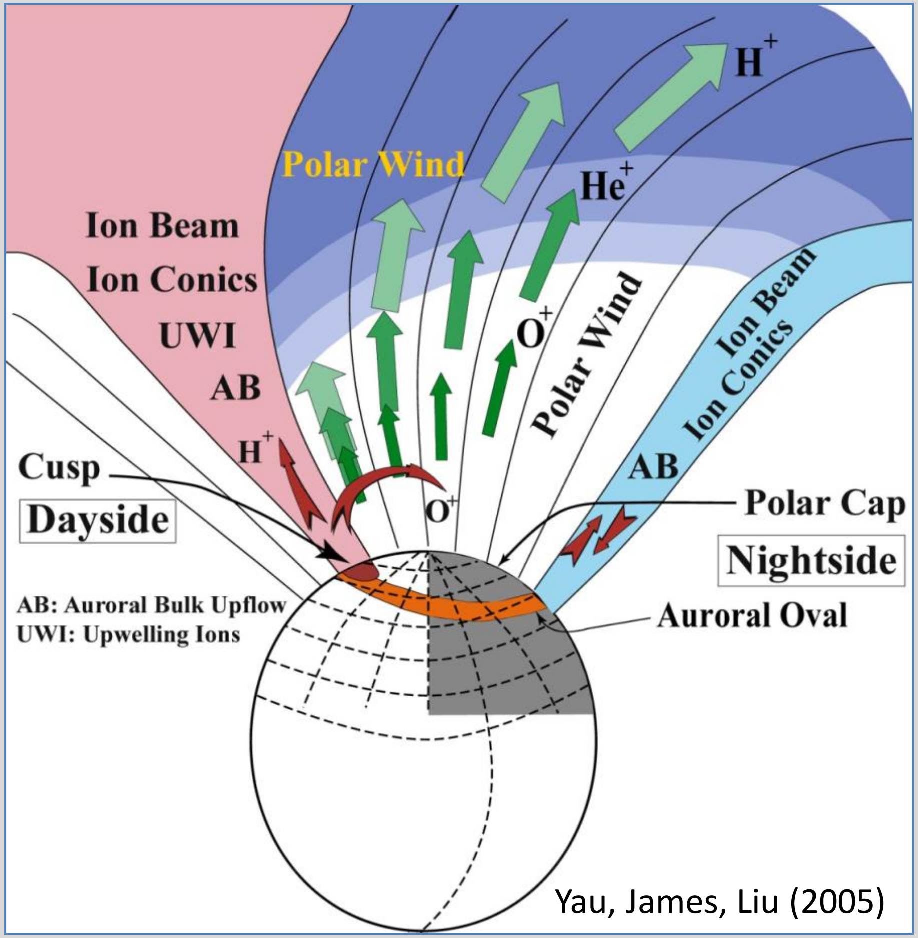


Fig. 26.2 Schematic depiction of planned investigation of important ion outflow populations in the polar ionosphere

Models

- Empirical
  - Yau (1988) – parameterized by AE, Kp, F10.7
  - Strangeway (2005)

$$F_{O^+} = 1.022x10^{9\pm0.341} n_{ep}^{2.200\pm0.489}$$

$$n_{ep} = 2.134x10^{-14} f_{en}^{3/2} / f_{ee}^{1/2}$$

Relates O+ fluence to precipitating e-'s

- Physics Based
  - Field Line Interhemispheric Plasma (FLIP)
    - Two stream fluid; Solves for n, T, v of many species
  - Polar Wind Outflow Model (PWOM)
    - MHD; Part of SWMF; Multiple convecting flux tubes
  - Dynamic Fluid Kinetic (DyFK)
    - Fluid + Kinetic; Analytical Expressions
  - Lyon-Fedder-Mobarry (LFM) Magneosphere Model

What's needed is an O^+ {Kp, MLT, iLat} model validated against real observations.

Some Open Questions

- What's the relative importance of Solar Zenith Angle, solar EUV and geomagnetic activity? (Peterson 2006, JGR)
- What's the contribution of plasma pressure gradients vs. ambipolar electric field (from escaping photo-electrons) to the Polar Wind generated outflow? (Andre and Yau, 1997)
- What is the alt dependence of the acceleration of the Polar Wind versus solar cycle? (Yau 2007)
- Why is O+ more efficiently energized than H+ below 2 Re?
- What explains the assymetry in Dayside upward flows? [Possibly explained by Redmon et al., 2013]

Summary

- O^+ outflows are important for ring current dynamics, magnetic reconnection rates, convection speeds and modulating substorm features
- O^+ has been observed by various platforms for the last 35+ years (e.g. S3-3, DE1, Akebono, FAST, Polar, DMSP)
- Empirical relationships of limited activity and spatial parameterization have been developed
- Physics based models implementing the processes thought to be most important have been developed with mixed levels of validation against observations
- Efficacy of controlling processes needs further study (e.g. e-POP on CASSIOPE)

Some Useful *Review* References

- Paschmann, G., Haaland, S., Treumann, R. (Eds.), 2002. Auroral Plasma Physics. Kluwer Academic Publishers, Boston/Dor- drecht/London.

- Lotko, W. (2007), The magnetosphere-ionosphere system from the perspective of plasma circulation: A tutorial, Journal of Atmospheric and Solar-Terrestrial Physics, Volume 69, Issue 3, Global Aspects of Magnetosphere-Ionosphere Coupling, Global Aspects of Magnetosphere-Ionosphere Coupling, March 2007, Pages 191-211, ISSN 1364-6826, DOI: 10.1016/j.jastp.2006.08.011.

- Yau, A.W., Peterson, W.K., Abe, T., Influences of the Ionosphere, Thermosphere, and Magnetosphere on Ion Outflows, Article in "The Dynamic Magnetosphere" to be published by Springer, 2011.

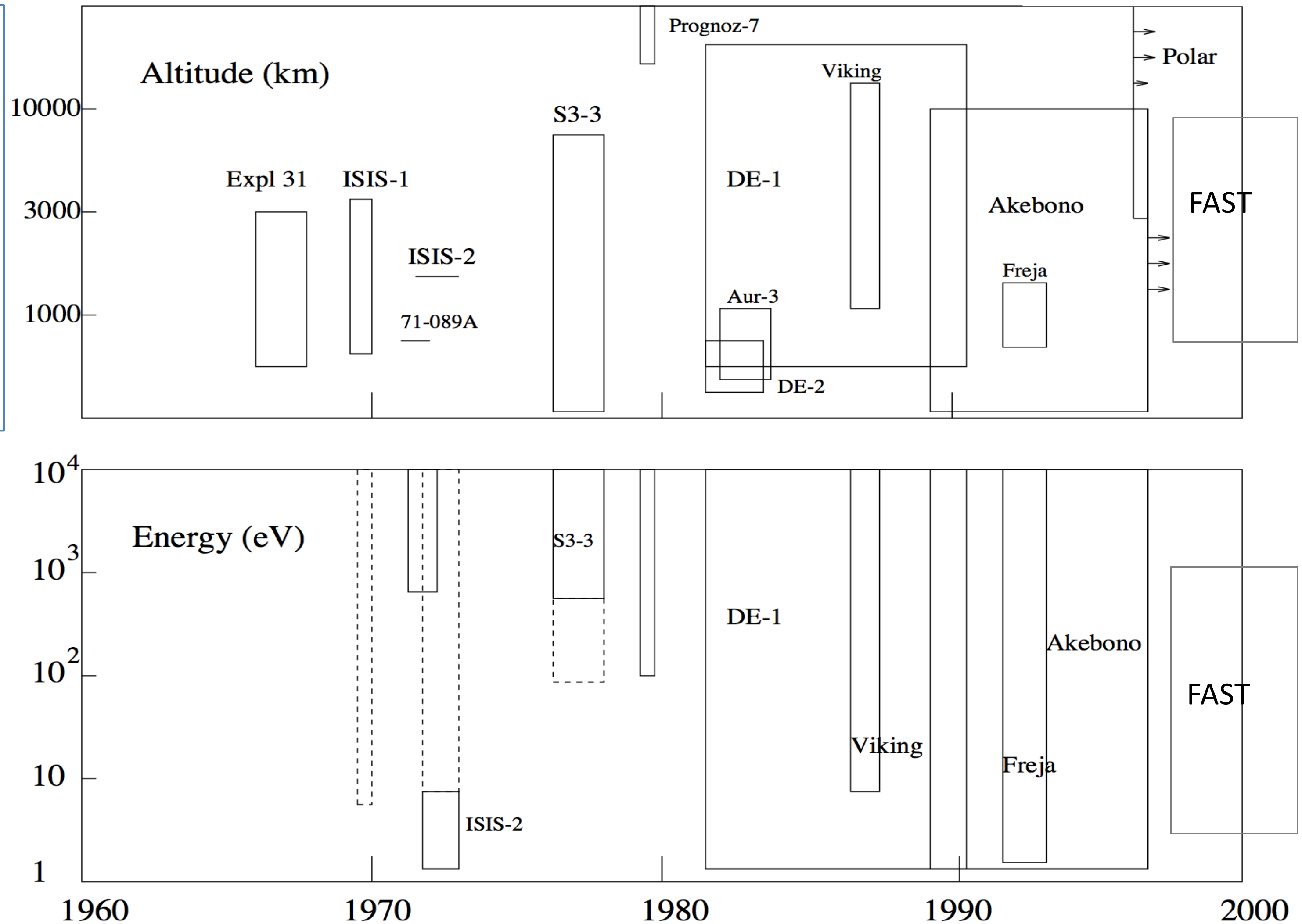
- J.P. Thayer, Joshua Semeter, The convergence of magnetospheric energy flux in the polar atmosphere, Journal of Atmospheric and Solar-Terrestrial Physics, Volume 66, Issue 10, Upper Atmosphere Tutorials from the 2001 Joint CEDAR SCOSTEP Meeting, July 2004, Pages 807-824, ISSN 1364-6826, DOI: 10.1016/j.jastp.2004.01.035.

Questions?

Backup Slides

Observations

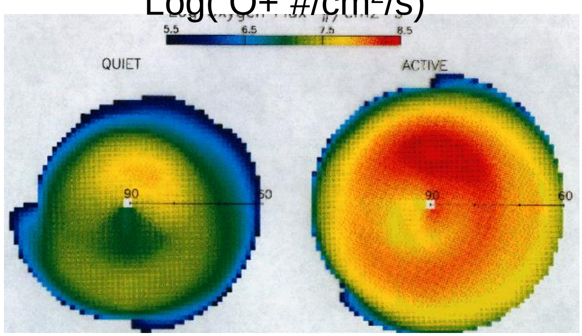
Altitude and energy coverage of missions over 3 solar cycles



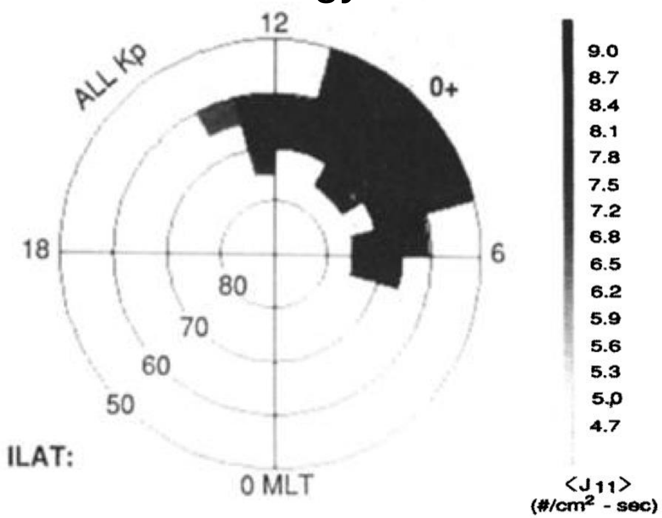
Observations: Dawnward Bias

DE1 EICS (<20,000 km; 1981)

Log(O+ #/cm²/s)

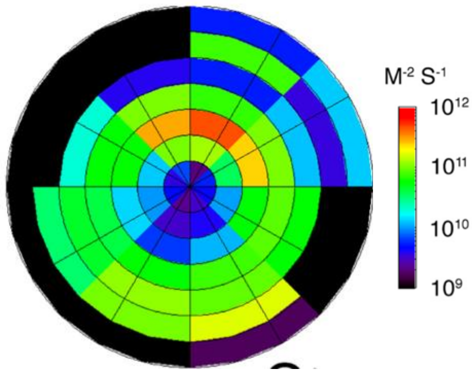


DE1 RIMS
Low Energy O+



~1.5-2 Re.
Pollock 1990

Polar TIMAS
Suprathermal 15eV-33keV



< 9000 km, Quiet Solar Min. Peterson (2006)