Magnetospheric Currents

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Currents in a Plasma: B-V vs J-E

At home, I flip the switch and a current flows to the light bulb according to the relationship V=IR.

But in space plasmas the fundamental quantities are V and B. The forces on the plasma tell the plasma how to move and the magnetic field is frozen (generally) into the plasma. The resulting field configuration tells you what the current has to be from Ampere's Law. Ohm's law is $\mathbf{E}+\mathbf{V}\times\mathbf{B}=0$, so $\mathbf{E}$ is frame-dependent.

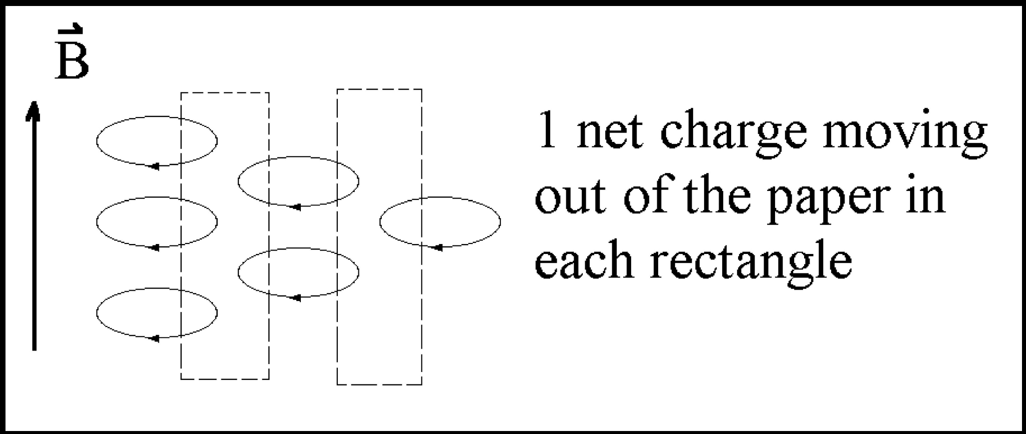
See Vasyliunas [2005, Ann. Geo.].

For an isotropic plasma

$$\rho \frac{d\vec{V}}{dt} = -\nabla P + \vec{J} \times \vec{B}$$

and in force balance

$$\vec{J}_{\perp} = \frac{\vec{B} \times \nabla P}{B^2}$$



Pressure gradient driven current

Chapman-Ferraro Current

From Chapman and Ferraro [1931]

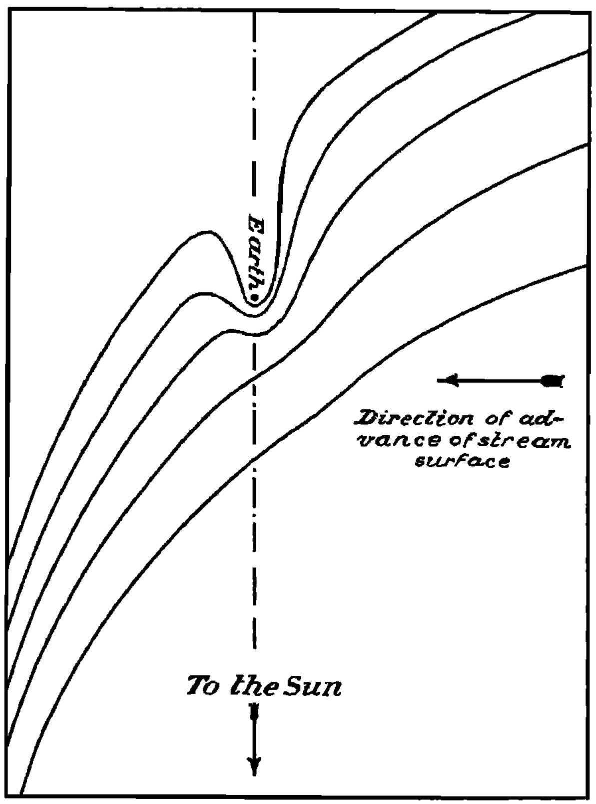


FIG. 2—Successive equatorial sections of the surface of advancing stream

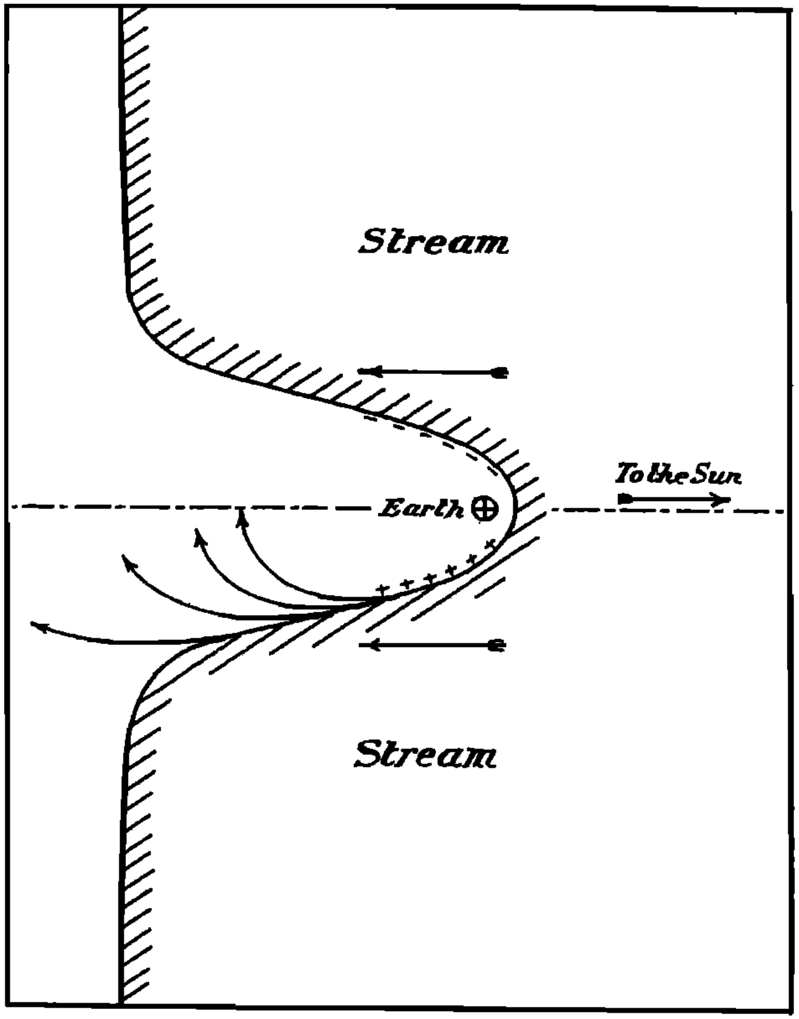
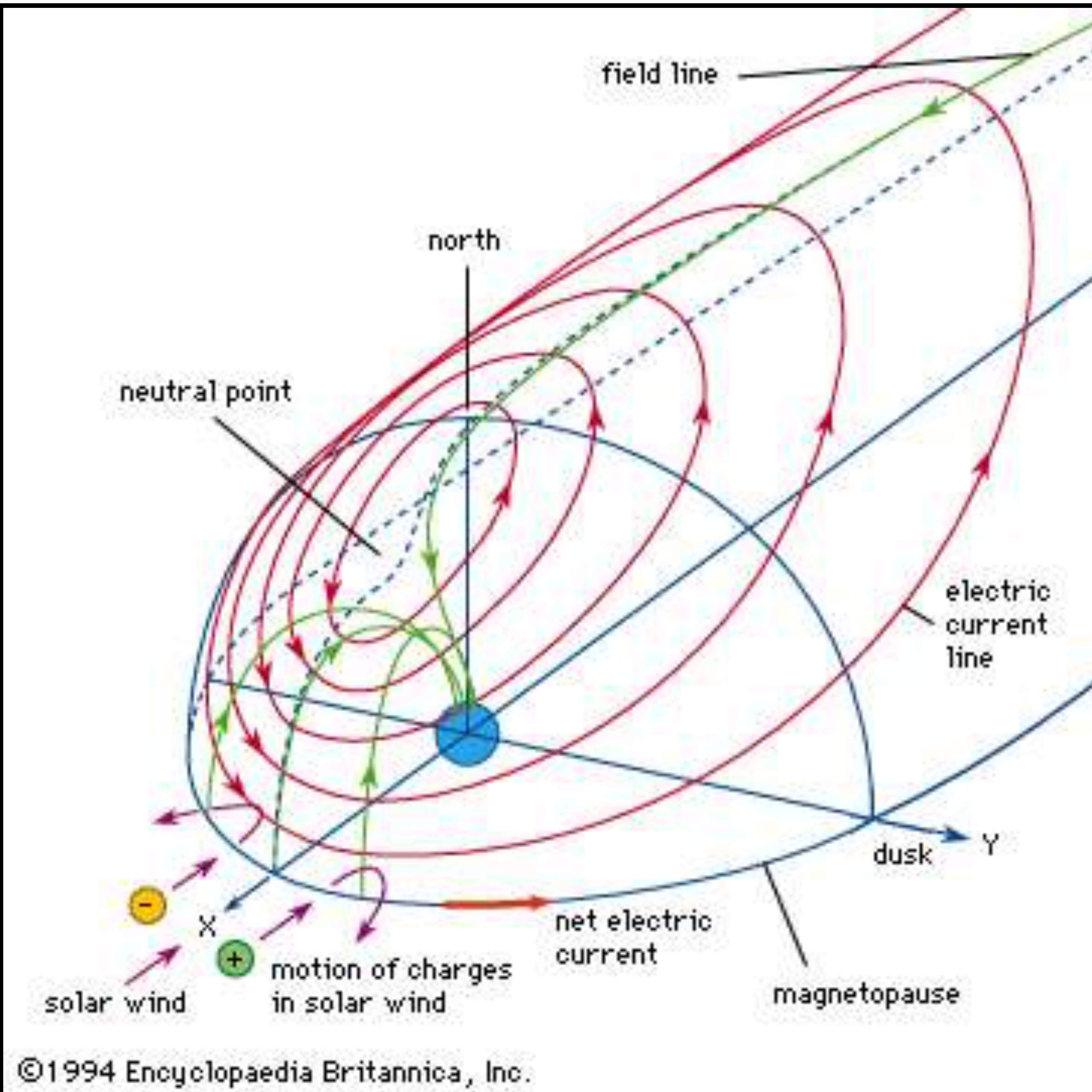


FIG. 5—Equatorial section



By the 1990's this picture was in encyclopedias.

For southward IMF
E = VBz (dusk-direction)

J•E > 0 at low latitude

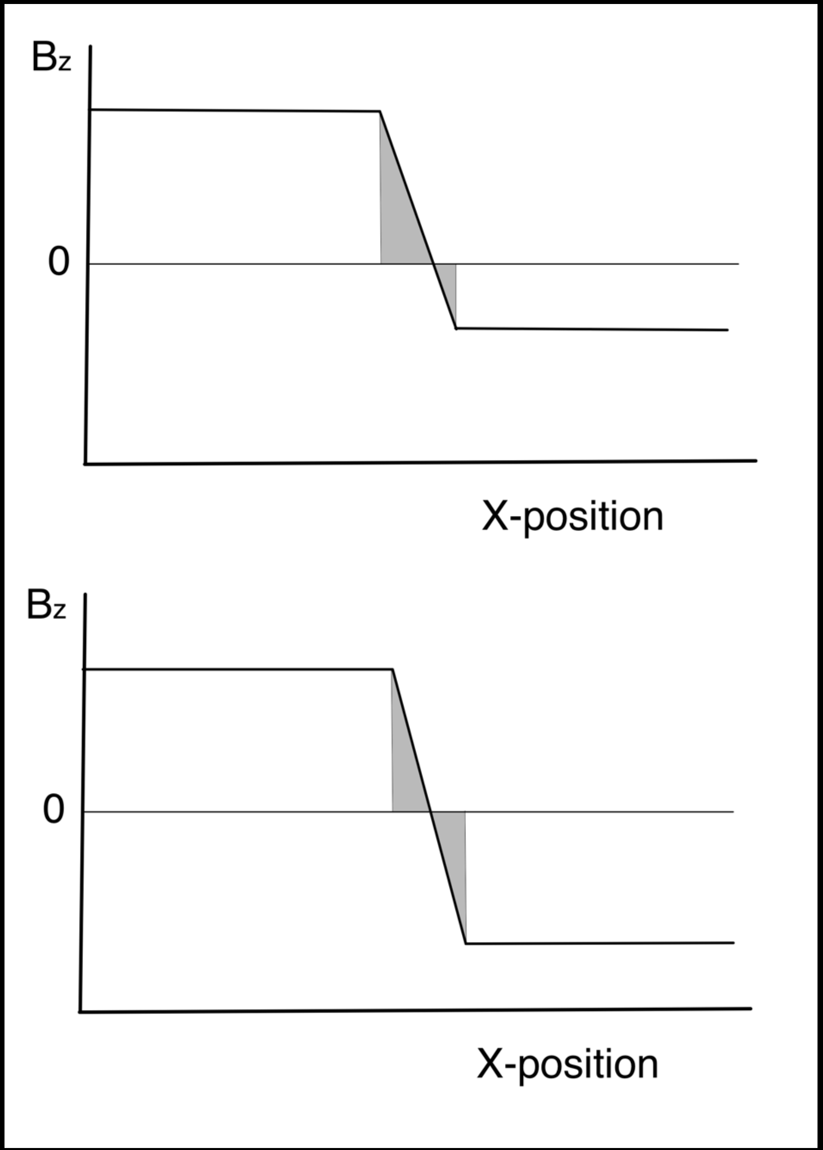
J•E < 0 at high latitude (the mantle region)

C-F current exerts outward **JxB** force on solar wind

The External Chapman-Ferraro current

- Moderate southward IMF - In this case there is a net outward JxB force and most of the C-F current flows inside the magnetosphere.

- Large southward IMF - In this case there is no net JxB force and the C-F current flows 1/2 in the magnetosphere and 1/2 in the magnetosheath.

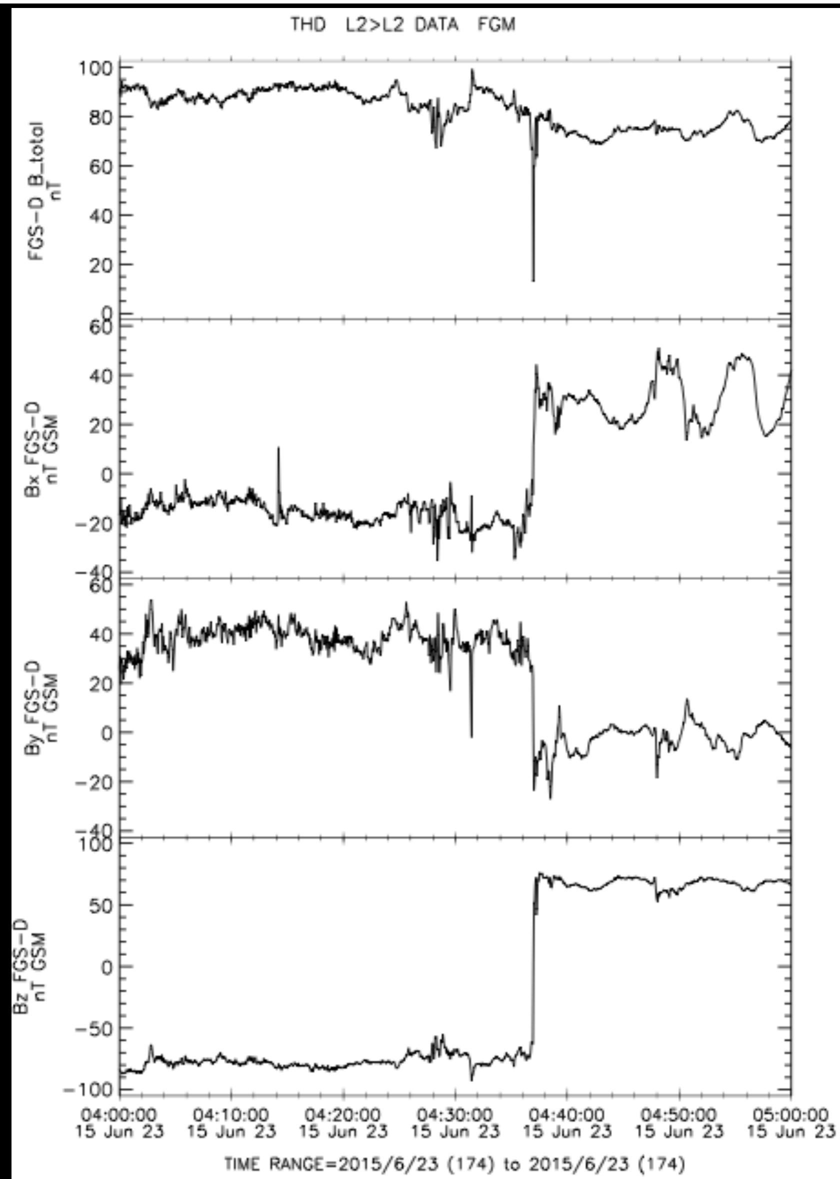


Lopez and Gonzalez [2017, GRL]

- Magnetopause crossing at 0437 UT, THEMIS D at (7.74, -0.96, -0.62) R_E in SM coordinates
- B_{dipole} ~ 63 nT, and B_{obs} ~ 68 nT (1.84 nPa)
- $B_{outside}$ ~ -72 nT (2.09 nPa)
- $P_{magnetosphere}$ = 0.34 nPa
- $P_{magnetosheath}$ = 0.36 nPa

No JxB force from C-F?

Siscoe et al. [2002]



Region 1 and 2 Birkeland Currents

and Region 0 (NBz)

Birkeland [1908]

The Norwegian Aurora Polaris Expedition 1902-1903

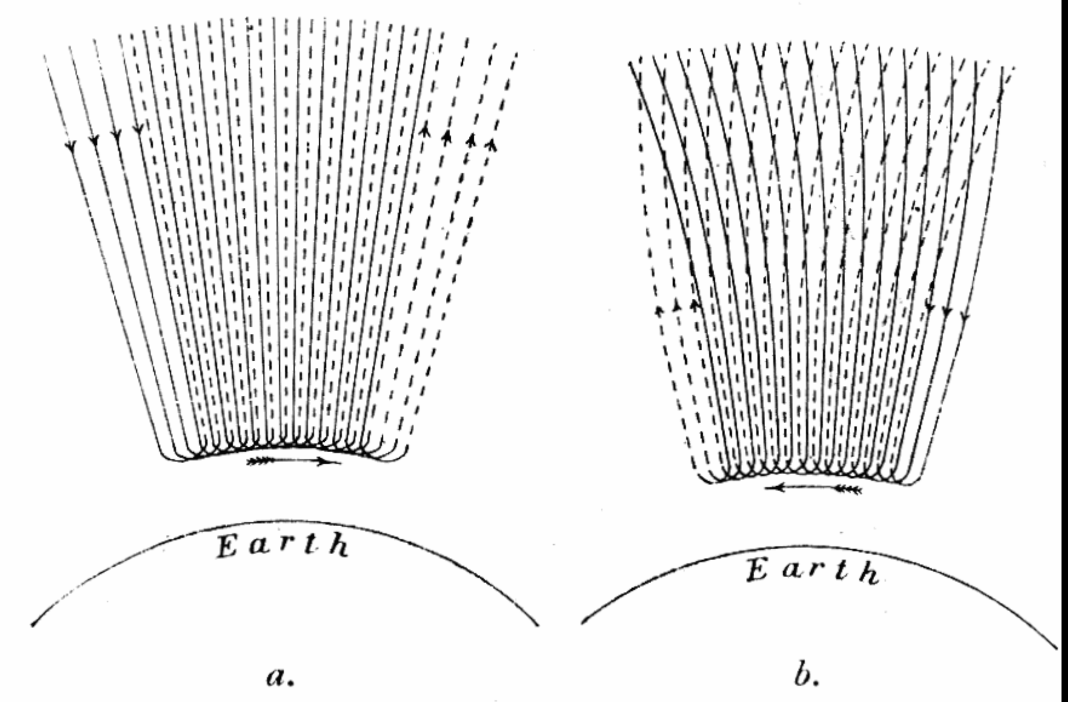


Fig. 50.

(See A. J. Dessler, *Science*, 1970; *Magnetospheric Currents*, 1984)

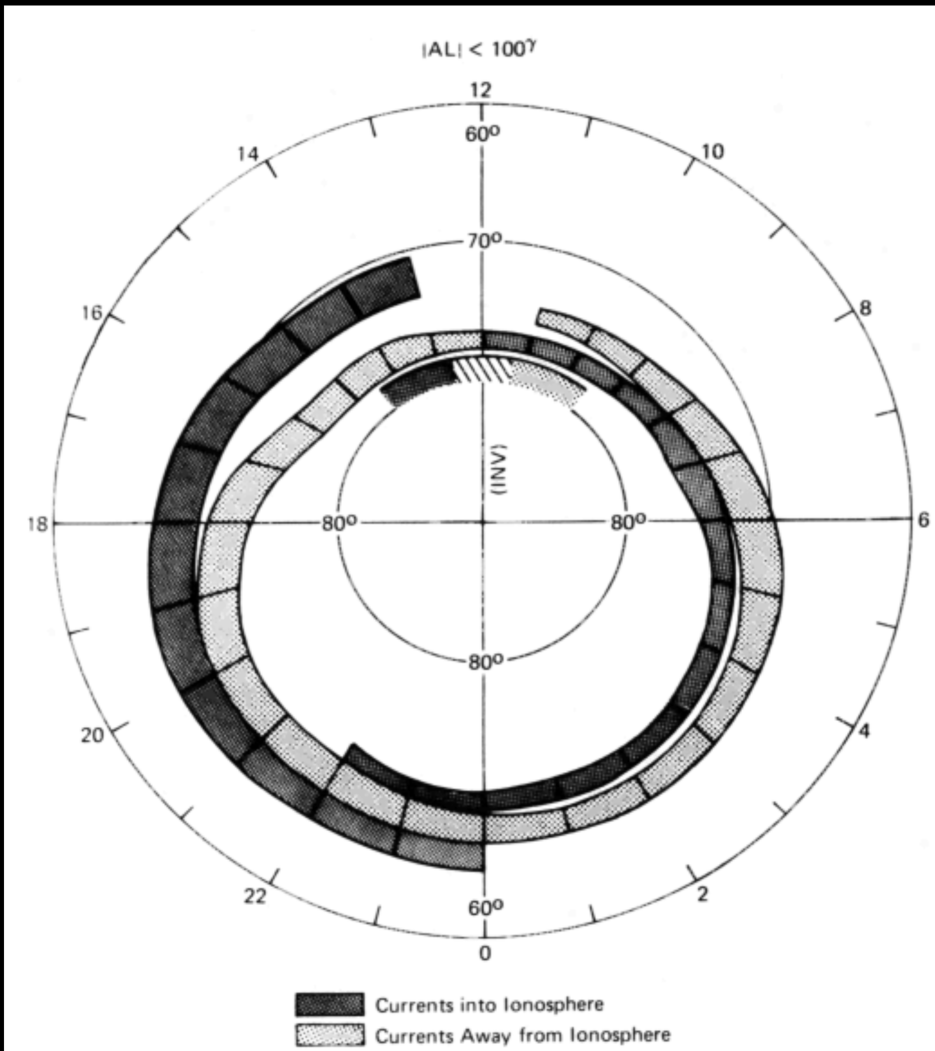
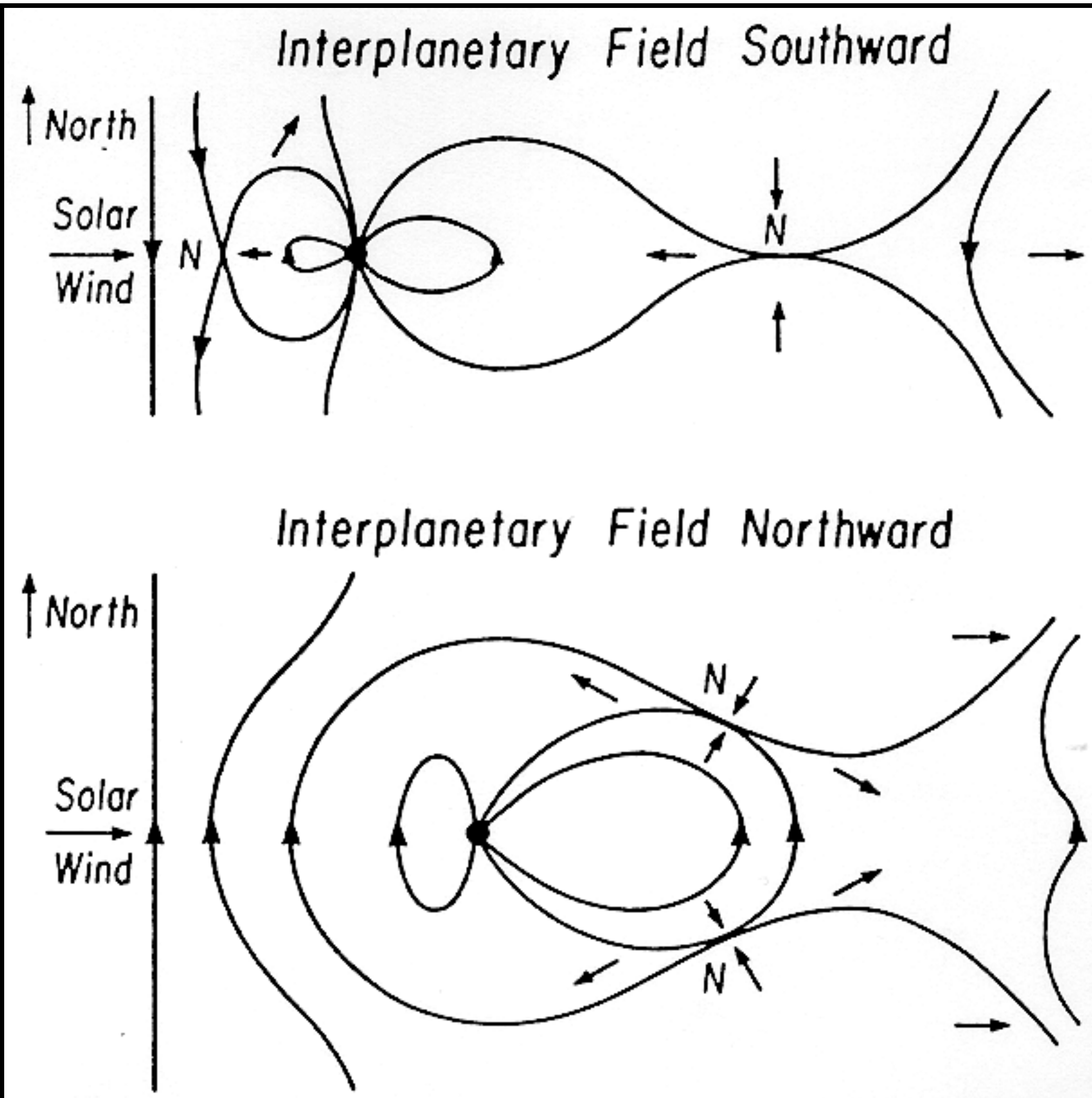


Figure 2 from Iijima and Potemra [1976]

Using TRIAD data, Iijima and Potemra [1976] identified the large-scale Region 1 and 2 current system.

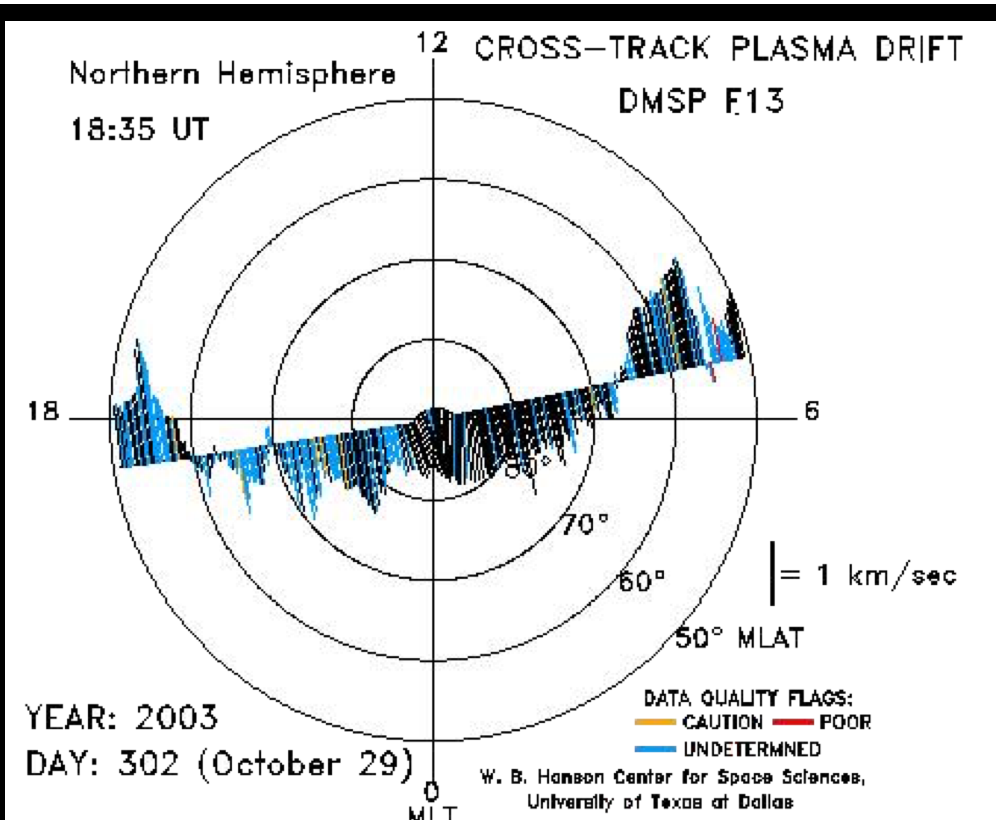
They also identified a higher-latitude system, with polarity reverse to Region 1, associated with northward IMF, Region 0 or NBz currents.

What drives these currents?

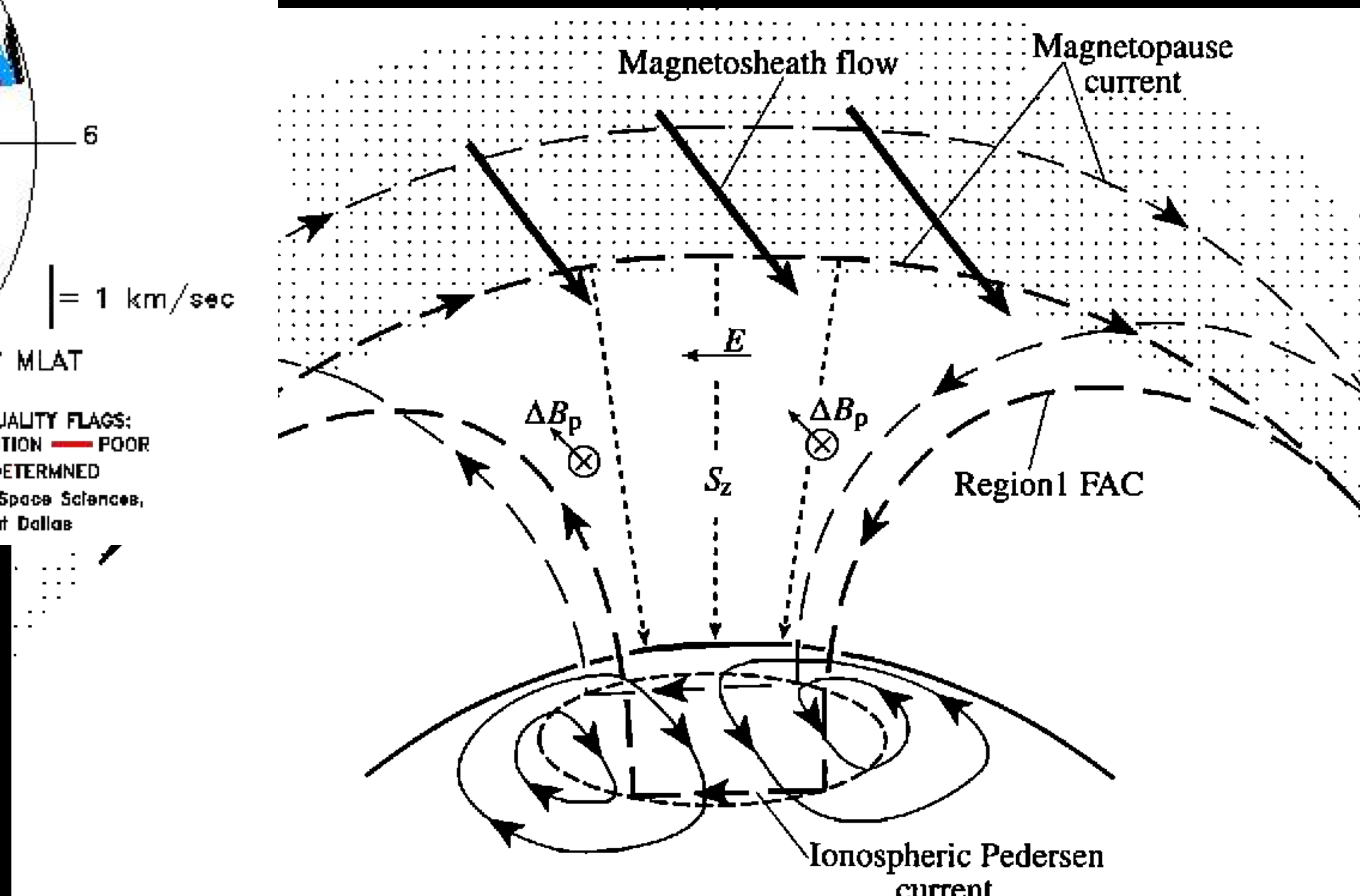


Dungey (1961) introduced the idea of magnetic merging and reconnection to transfer solar wind tangential stress across the magnetopause.

DMSP plasma drift data provided by the W. B. Hanson center for Space Sci., UTD



From Cowley [2013]



For southward IMF, the polar cap flow is from day to night

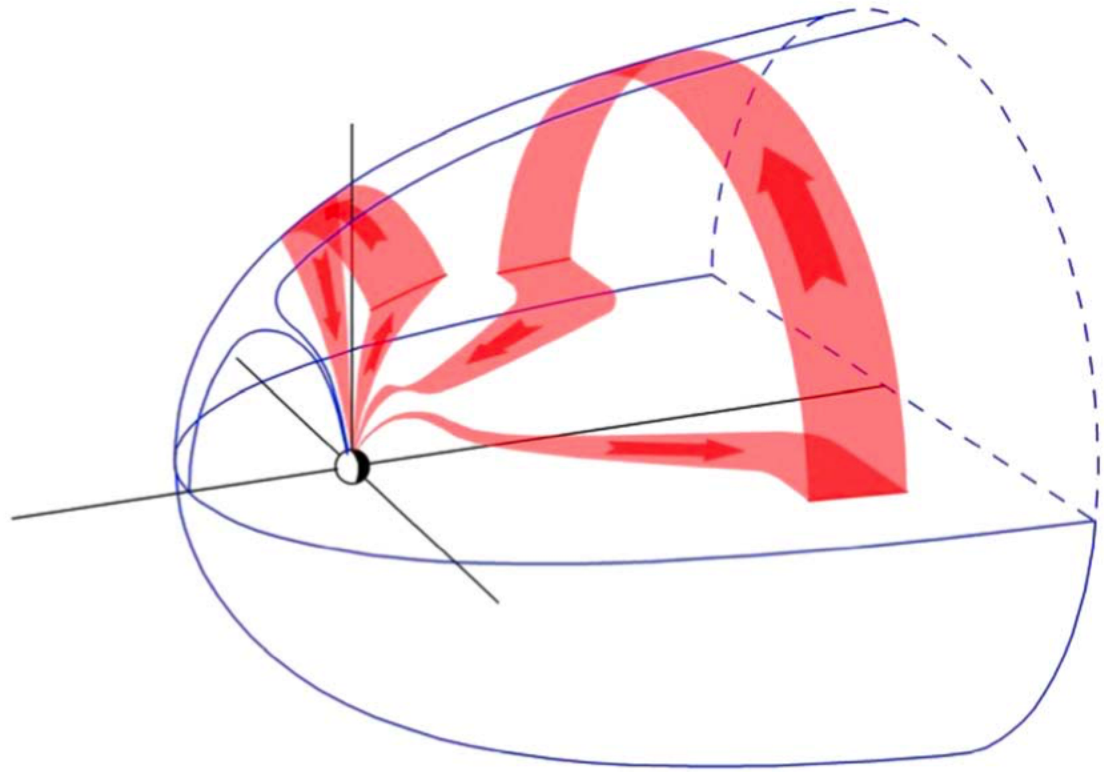
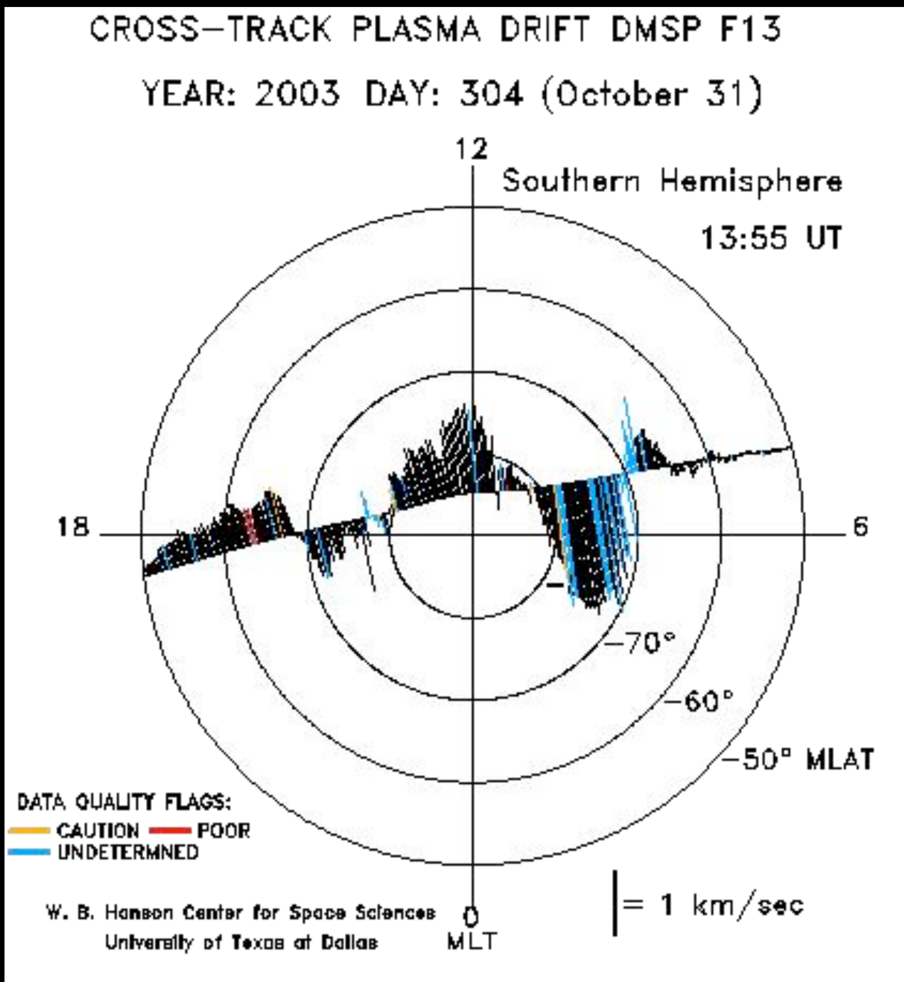
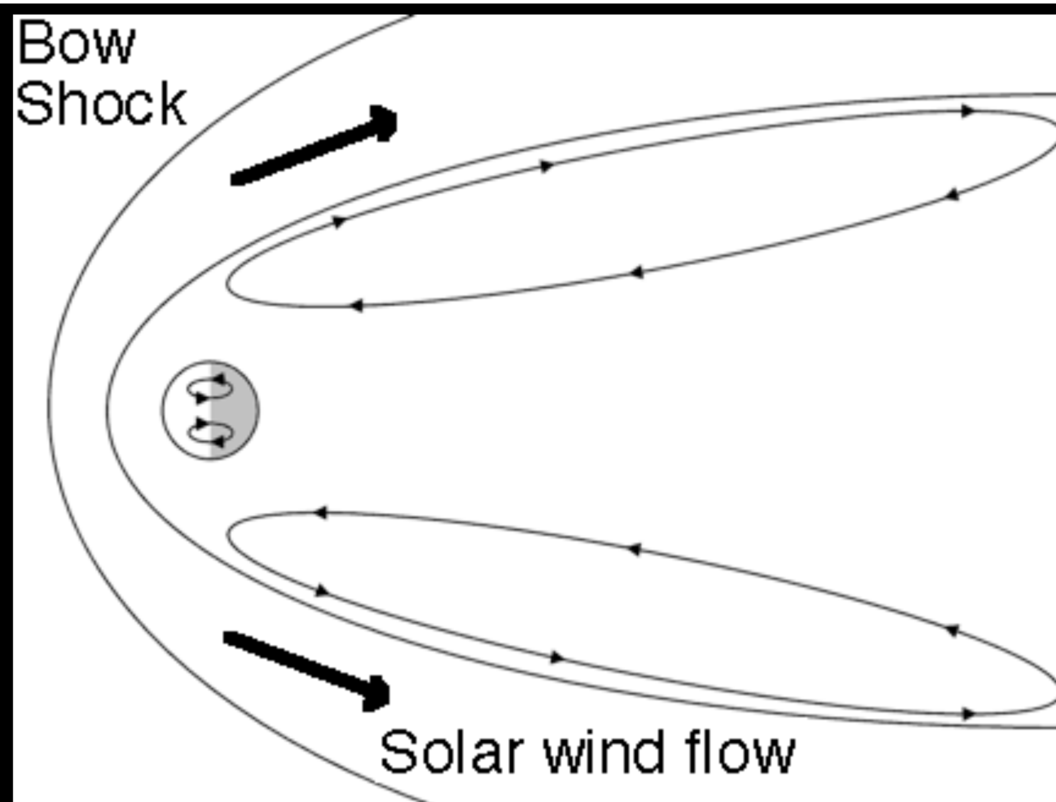


Figure 4. Region 1 field-aligned currents, shown as the red bands, including the two possible closure paths: directly to the magnetopause and via the far tail plasma sheet.

From Ganushkina et al., [JGR, 2017]

4-cell convection with NBz/Region 0 currents

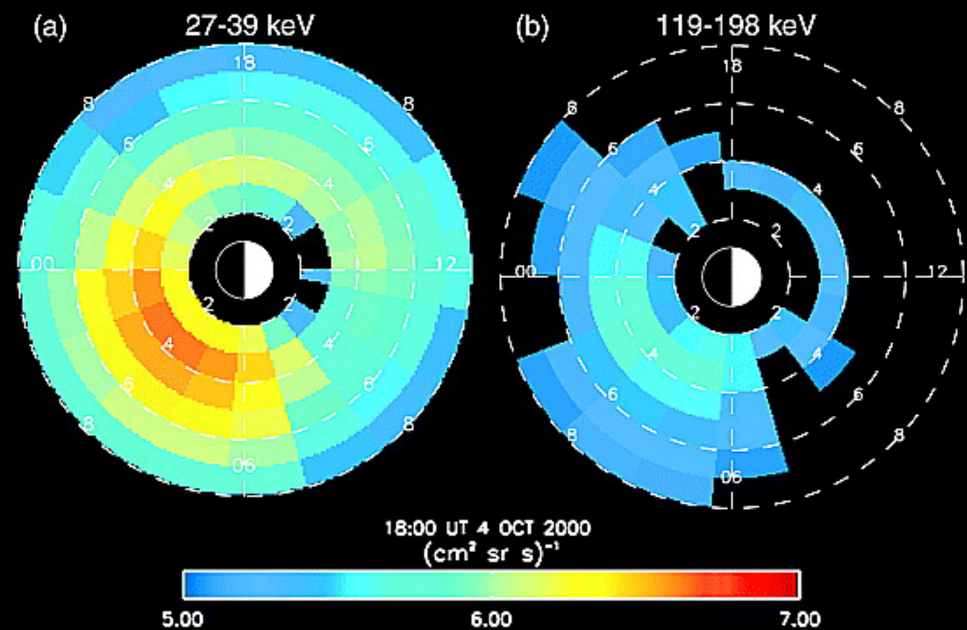




Viscous interaction produces Region-1 polarity current on closed field lines (Axford and Hines, [1961]).

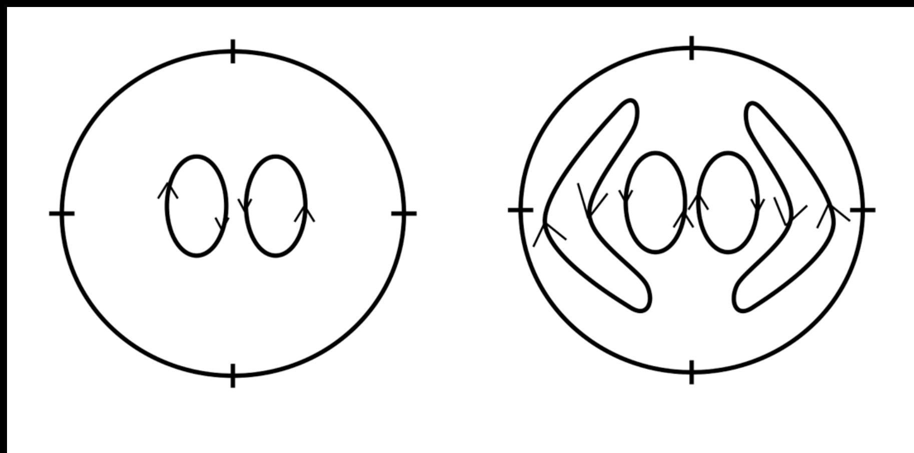
What about Region 2 currents?

- Driven by pressure gradients in the inner magnetosphere
- Plasma pressure and current maximize near the center of the tail
- Particularly visible during storm times



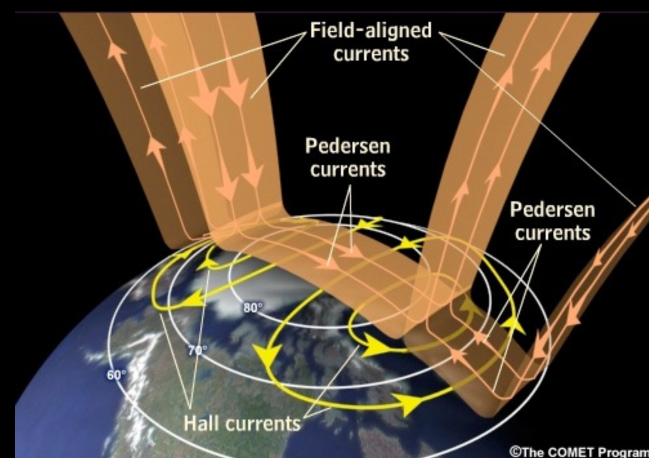
ENA inversion showing plasma pressure peak on nightside (Fig. 1 from Brandt et al. 2002, GRL)

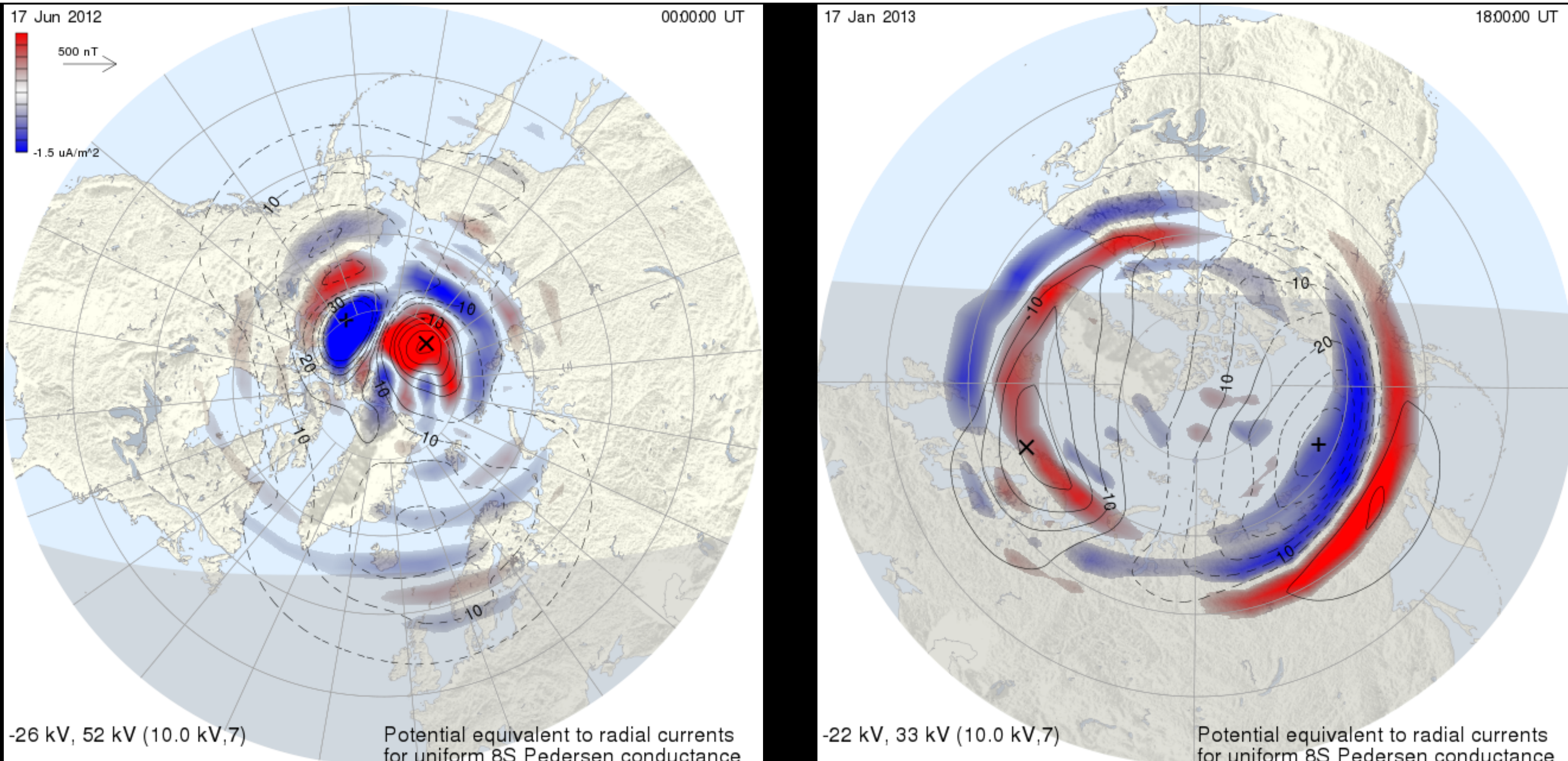
Southward IMF leads to 2-cell convection



Northward IMF leads to 4-cell convection

The overall transpolar potential is a global indicator of solar wind-magnetosphere coupling





IMF Bz = +34 nT, V = 510 km/s, n = 40 cm^{-3} IMF Bz = -12 nT, By = -10, SYM-H = -55 nT

AMPERE data provided courtesy of JHU/APL

The cross-tail current
and
the substorm current wedge

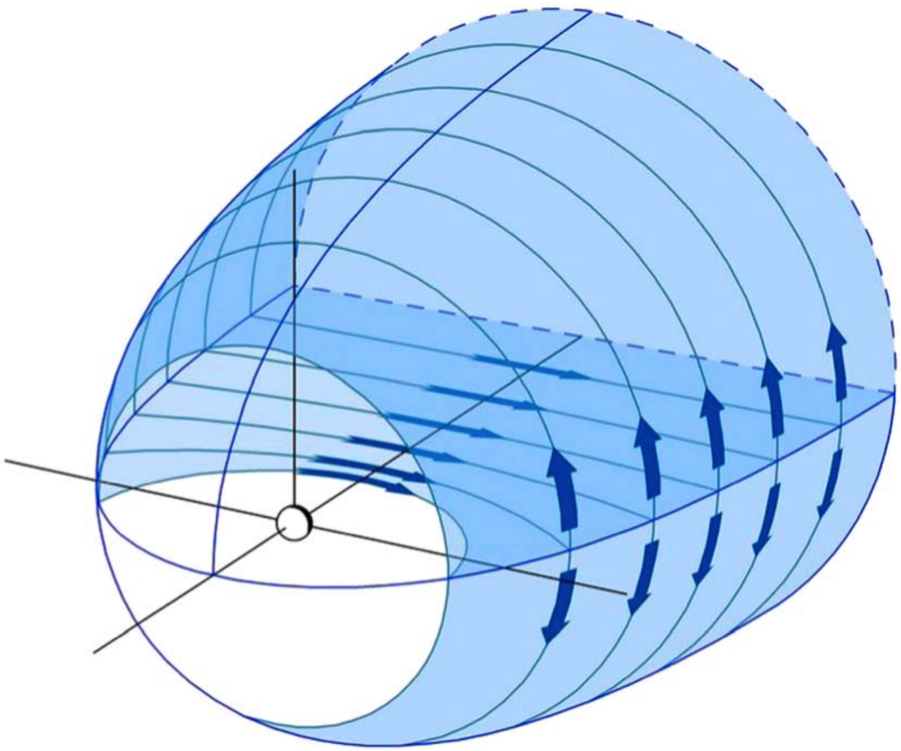


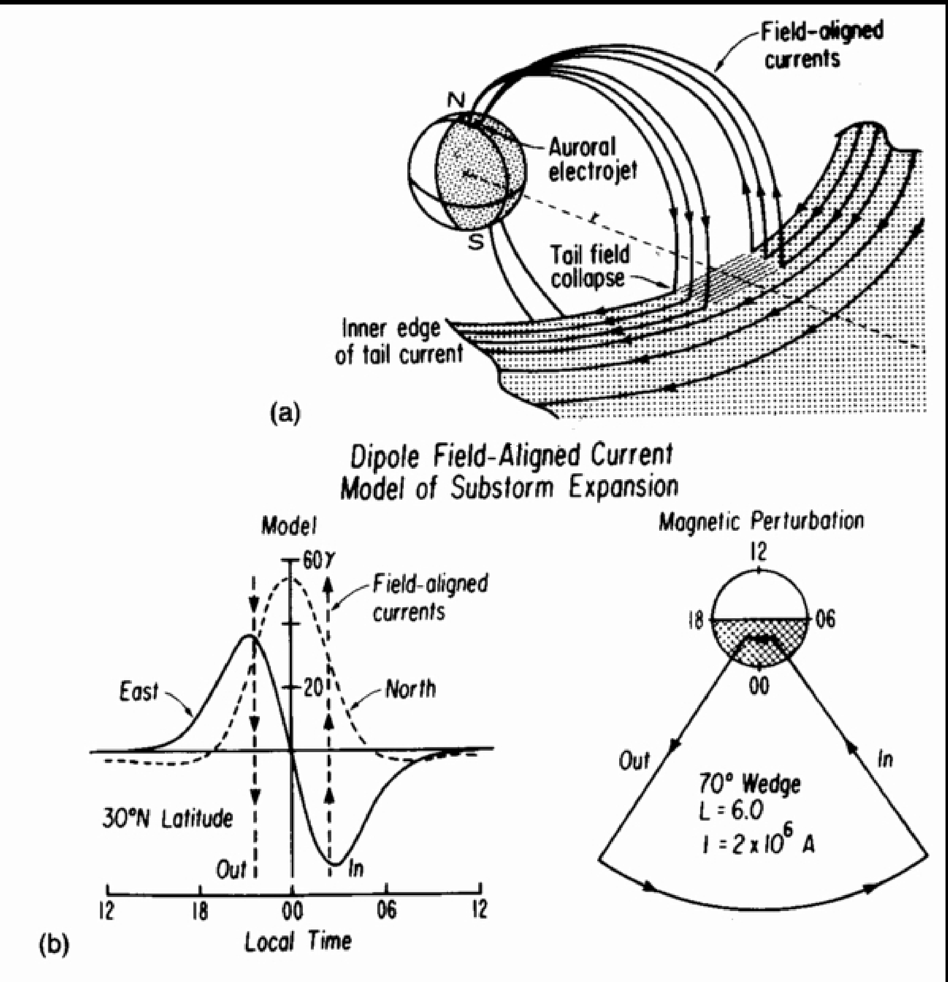
Figure 3. The tail current with closure via return current on magnetopause shown in light blue on the wire diagram of the magnetopause, as in Figure 2.

From Ganushkina et al. [2017]

The cross-tail current is driven by the earthward pressure gradient, so that the JxB force balances the pressure gradient. It closes via the boundary currents.

For southward IMF, as the Region 1 current increase, flux is transferred to the tail lobes and the solenoidal current increases. This leads to a substorm.

The Substorm current wedge McPherron et al. [1973]



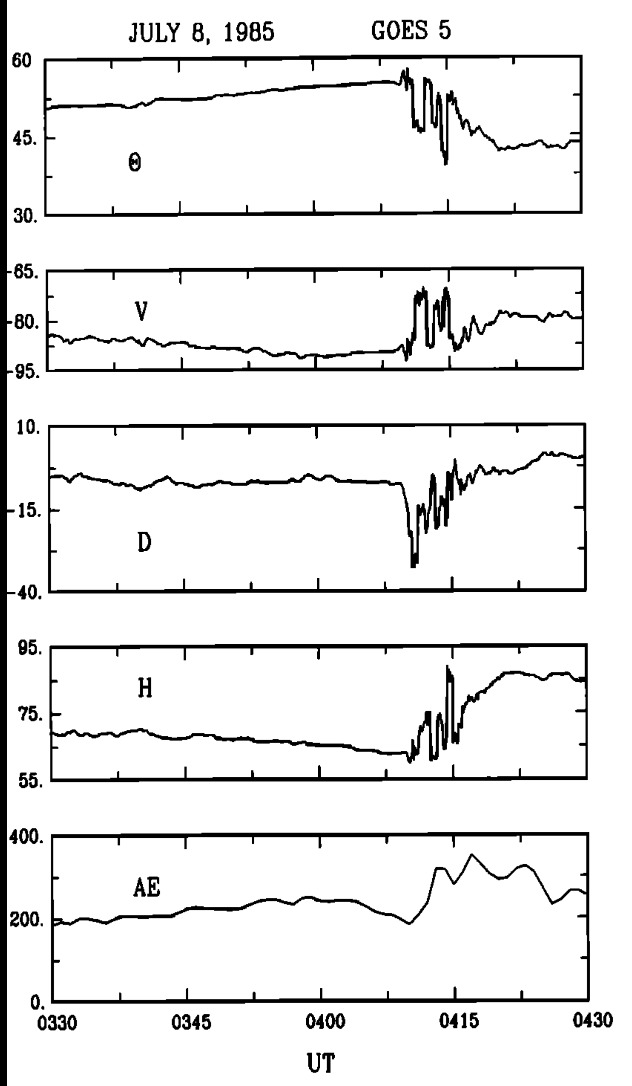


Fig. 3. GOES 5 data for the July 8 event.

The near-Earth magnetotail relaxes to a more dipolar field as the cross-tail current is reduced.

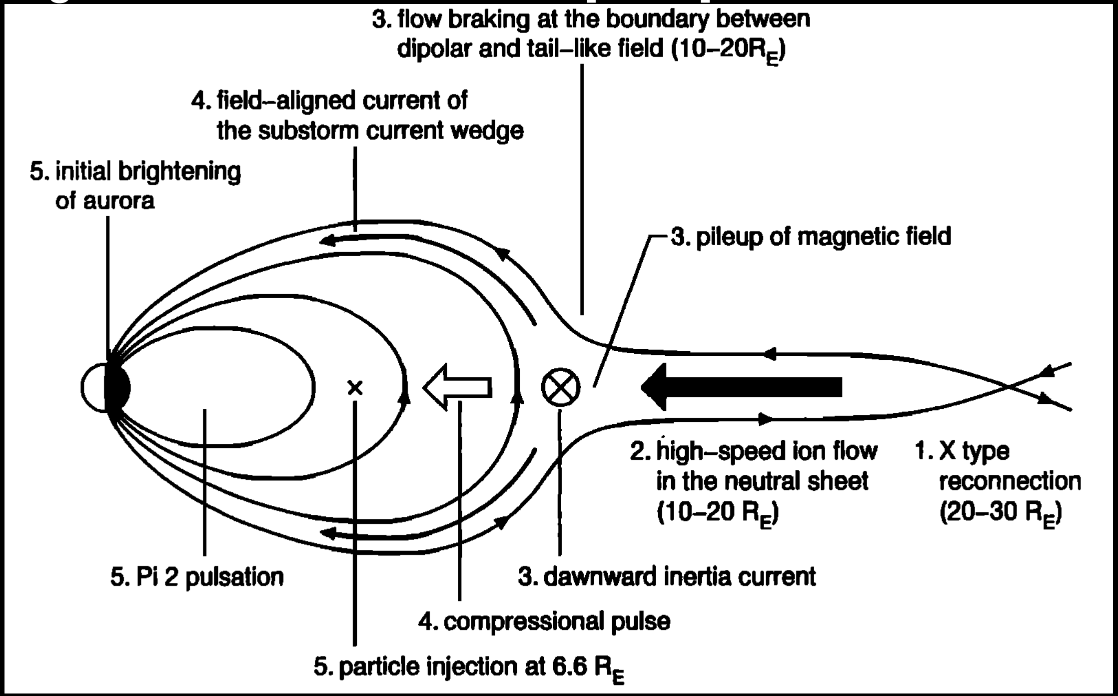
Lopez and VonRosenvinge [1993]

What drives a substorm?

The Dungey cycle for southward IMF drives convection up the tail toward Earth. This convection is adiabatic, so the pressure grows [Erikson and Wolf, 1980]. The resolution to the global instability is reconnection in the near-Earth tail. This produces the substorm phenomena.

The BBFs from the tail reconnection region produce the substorm current wedge.

Fig15 from Shiokawa et al. [1998]



$$\vec{J}_\perp = \frac{\vec{B} \times \nabla P}{B^2} + \frac{\vec{B} \times \rho \dfrac{d\vec{V}}{dt}}{B^2}$$

The ring current

Magnetic storms and the ring current

- Occasional disturbances in Earth's magnetic field were first discovered in 1724 by George Graham.
- By the early 19th century, Alexander Von Humbolt had shown that these disturbances were worldwide. He called them "magnetic storms" in his encyclopedic *Kosmos.*
- By the early 20th there was consensus that the worldwide depression in the horizontal component of Earth's magnetic field was due to a current around Earth - the ring current.
- This was an important part of the theory of magnetic storms put forward by Chapman and Ferraro in a series of papers in 1931.

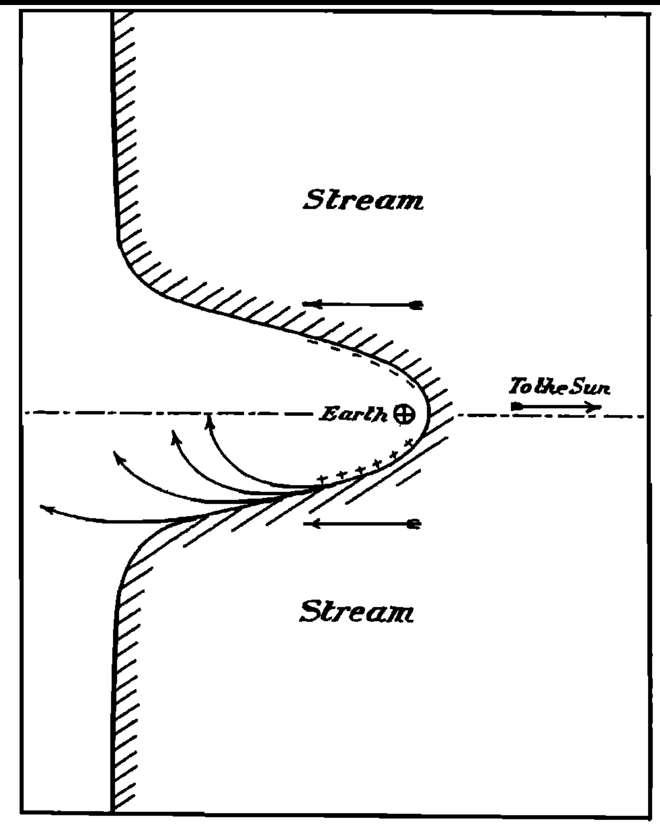
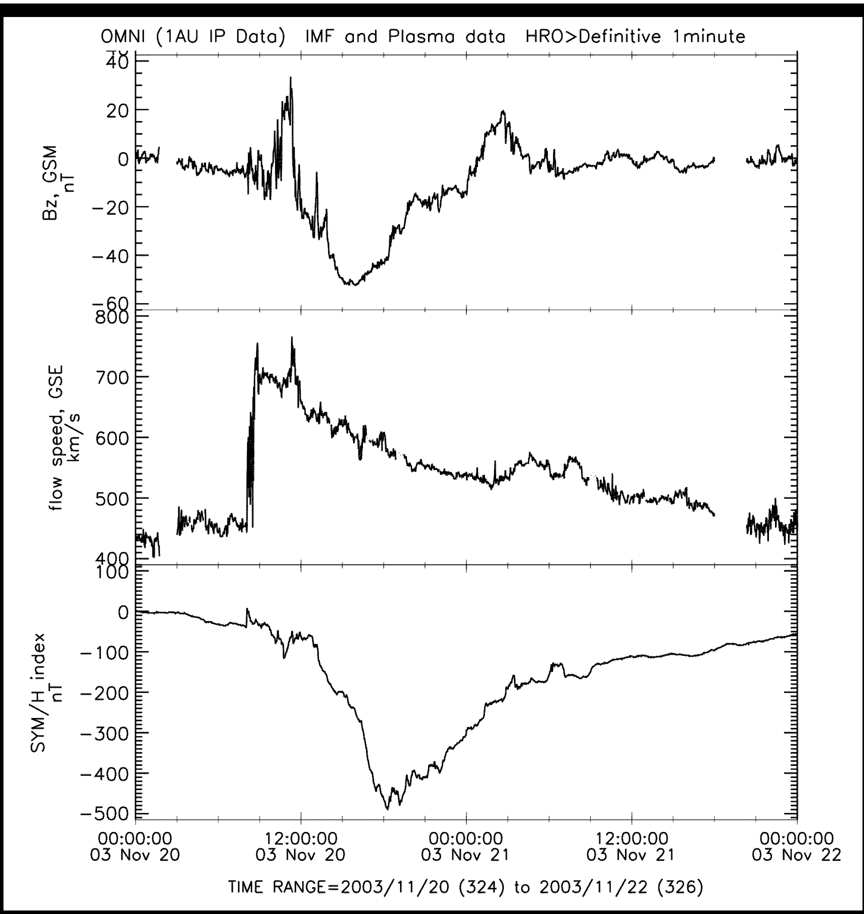


FIG. 5—Equatorial section

- Alfvén's guiding center approximation and adiabatic invariants allows us to understand the particle motions in the ring current.

Magnetic storms are defined by the development of the ring current

- Storms are driven by extended periods of strongly southward IMF [Gonzalez et al., 1994].
- The Disturbance storm-time (Dst) index was developed in 1957 to quantify the average equatorial disturbance field from the ring current.
- Dessler and Parker [1959] and Sckopke [1966] showed that Dst was proportional to the energy content of the ring current.
- The loss of ring current particles was initially thought to be only charge exchange, though Leimohn et al. [1999] showed that main phase losses were through the dayside magnetopause.
- The origin was originally thought to be enhanced convection [e.g. Burton et al., 1975]



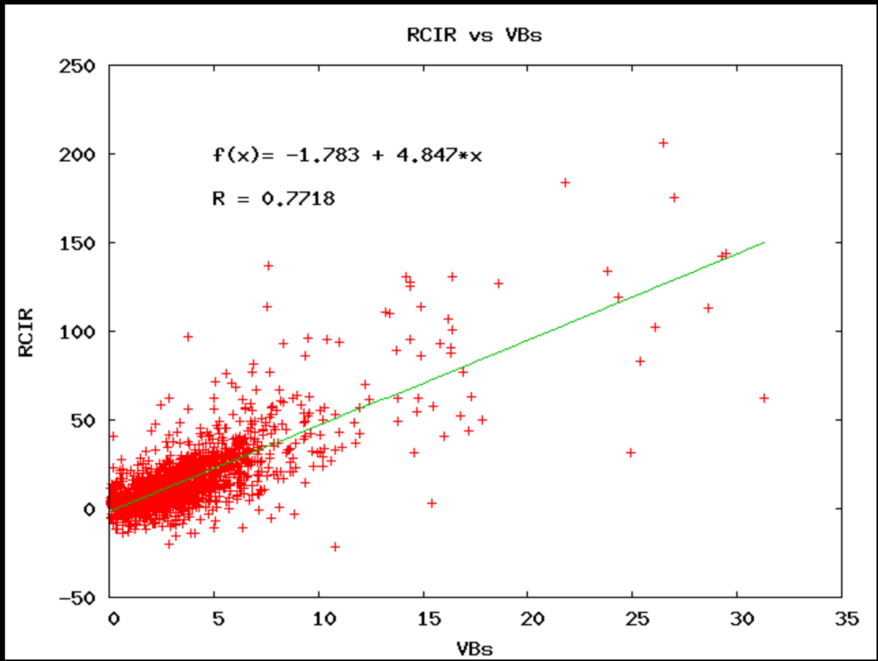
- Additional work showed that O^+ was a major component of the ring current during storms [Daglis, et al., 1999]

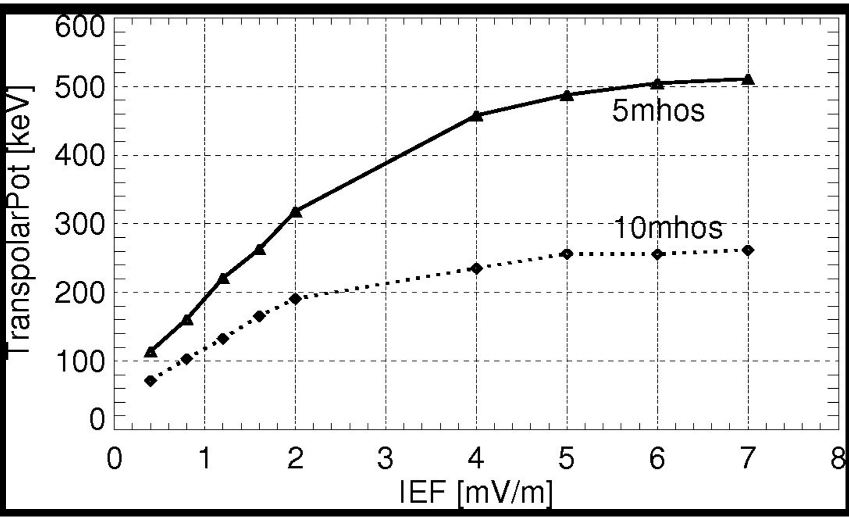
Conundrum

Burton et al. [1975]

$$\alpha VB_z = \frac{Dst}{\tau} + \frac{\partial Dst}{\partial t}$$

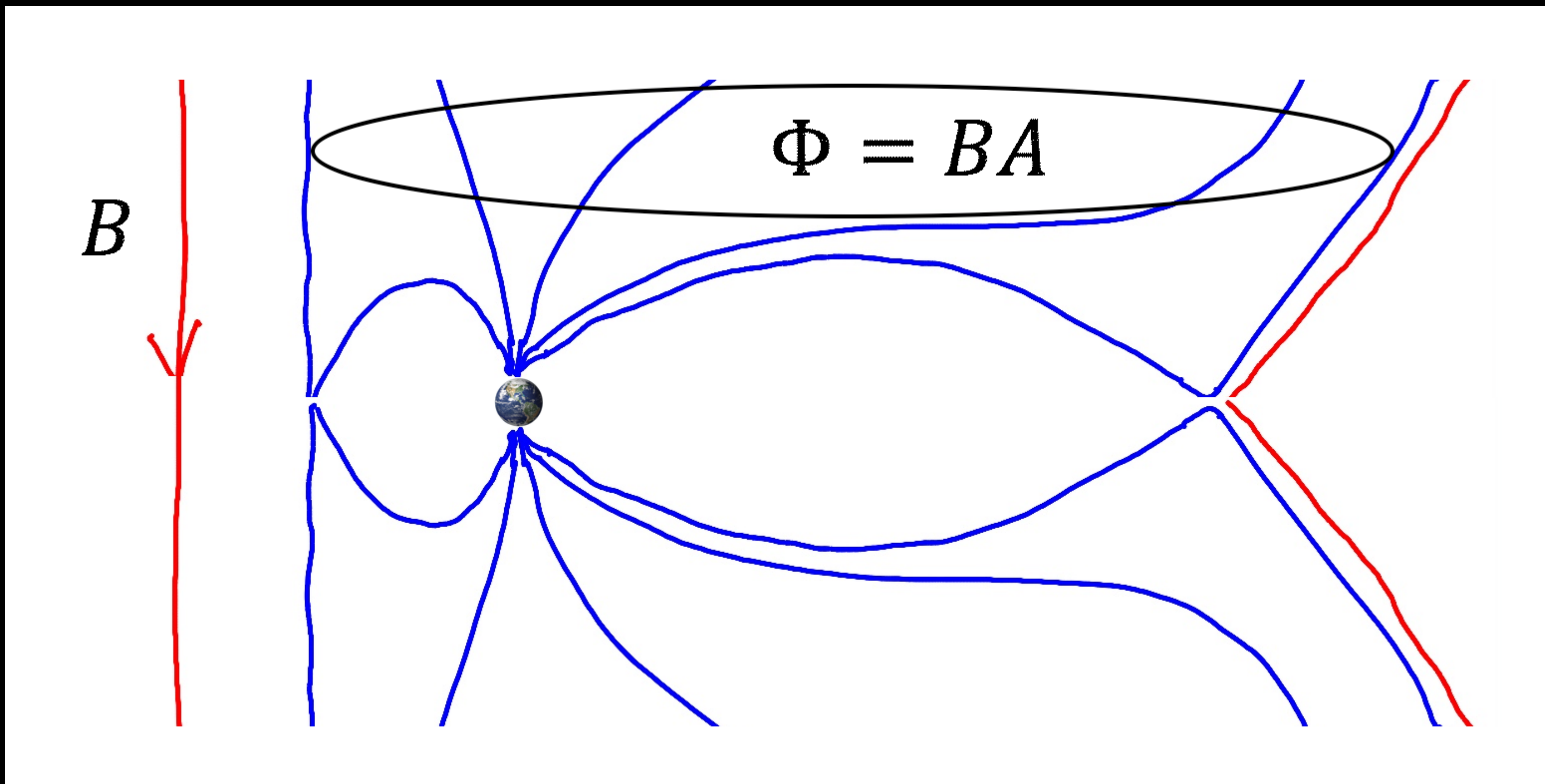
- General view was that the ring current is created by enhanced convection, which should be driven by the storm transpolar potential.
- Transpolar potential saturates with respect to VB_z, but the RCIR does not.
- The problem was noted by Russell et al. [2001] in the paper that demonstrated the phenomenon of saturation.





So what makes the ring current anyway?

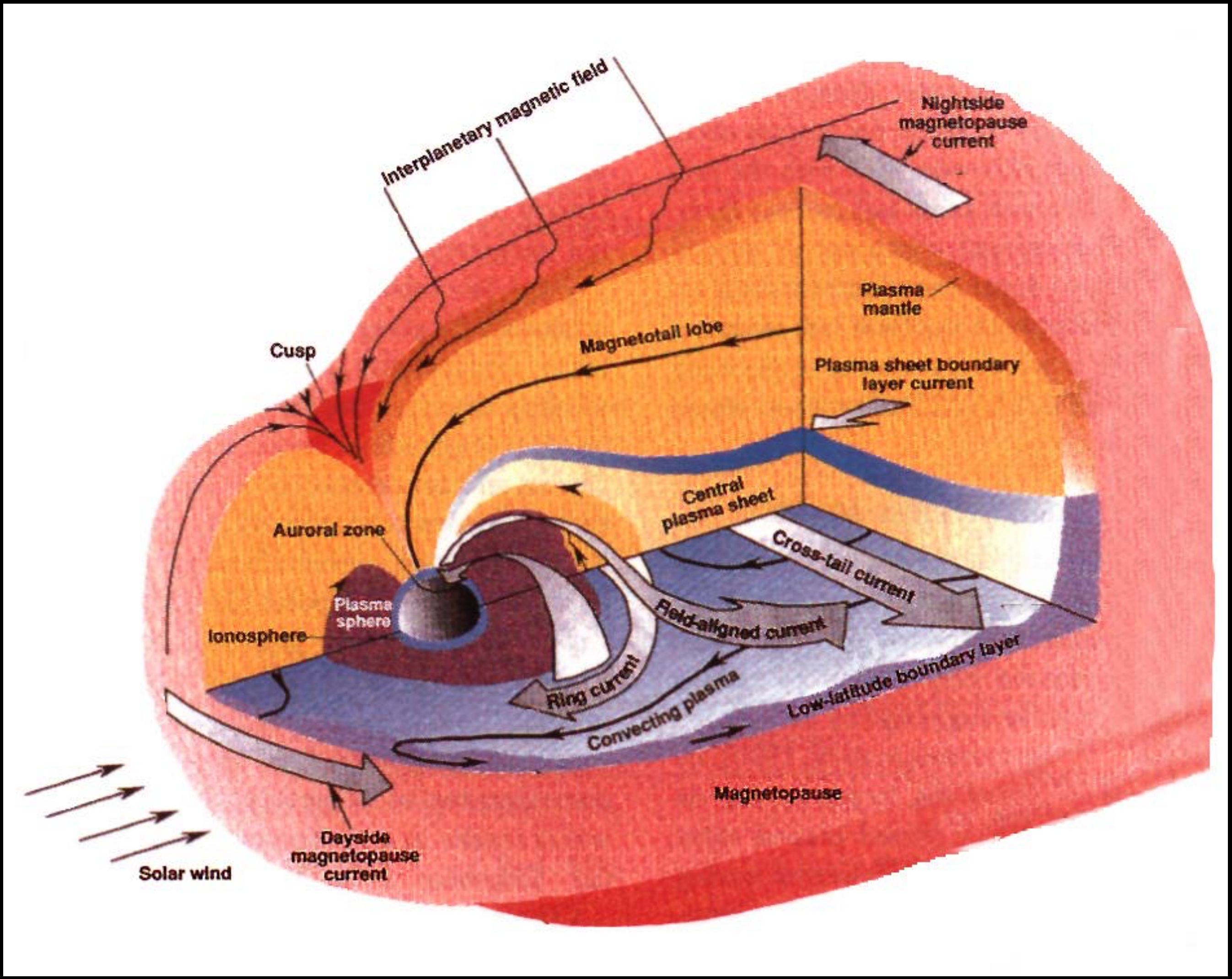
- In the Rice Convection Model, low PV^{γ} flux tubes are required
- These are interchange unstable and transport particles into inner magnetosphere
- Transported particles are adiabatically accelerated, forming ring current energy particles
- What makes low PV^{γ} flux tubes? Reconnection in the tail!



$\Phi = BA$
B

Now we have our answer

- During storms a quasi-steady reconnection region forms in the tail near the Earth.
- This reconnection region moves steadily closer to the Earth for larger values of solar wind B_z.
- As the neutral line moves closer closer to Earth it creates lower PV^{γ} flux tubes which can penetrate deeper into the inner magnetosphere and are more effective in creating a strong ring current.
- This leads to a continued dependence of the ring current injection rate on B_z even though the polar cap potential has saturated.
- Convection has little or nothing to do with the ring current injection rate.

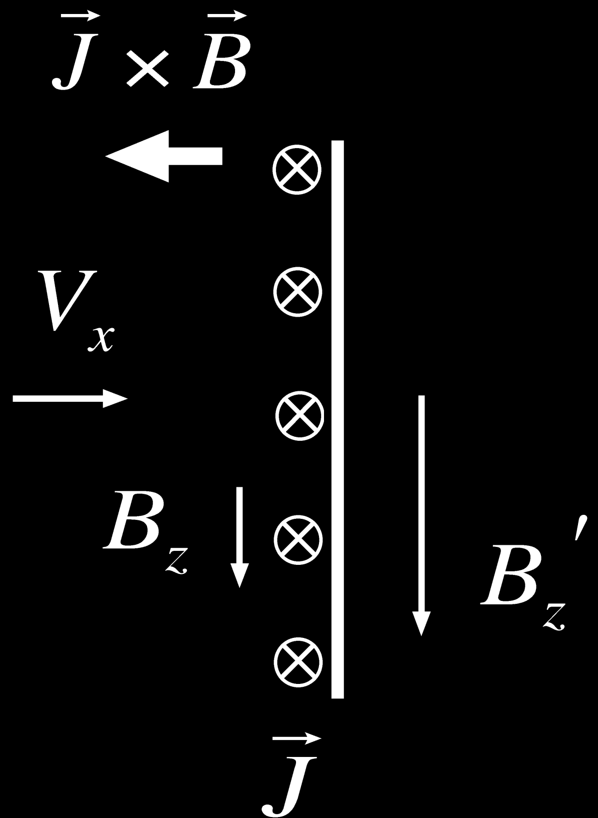


What is missing?

Fig. from Lopez [1990] JHU/APL Tech. Digest

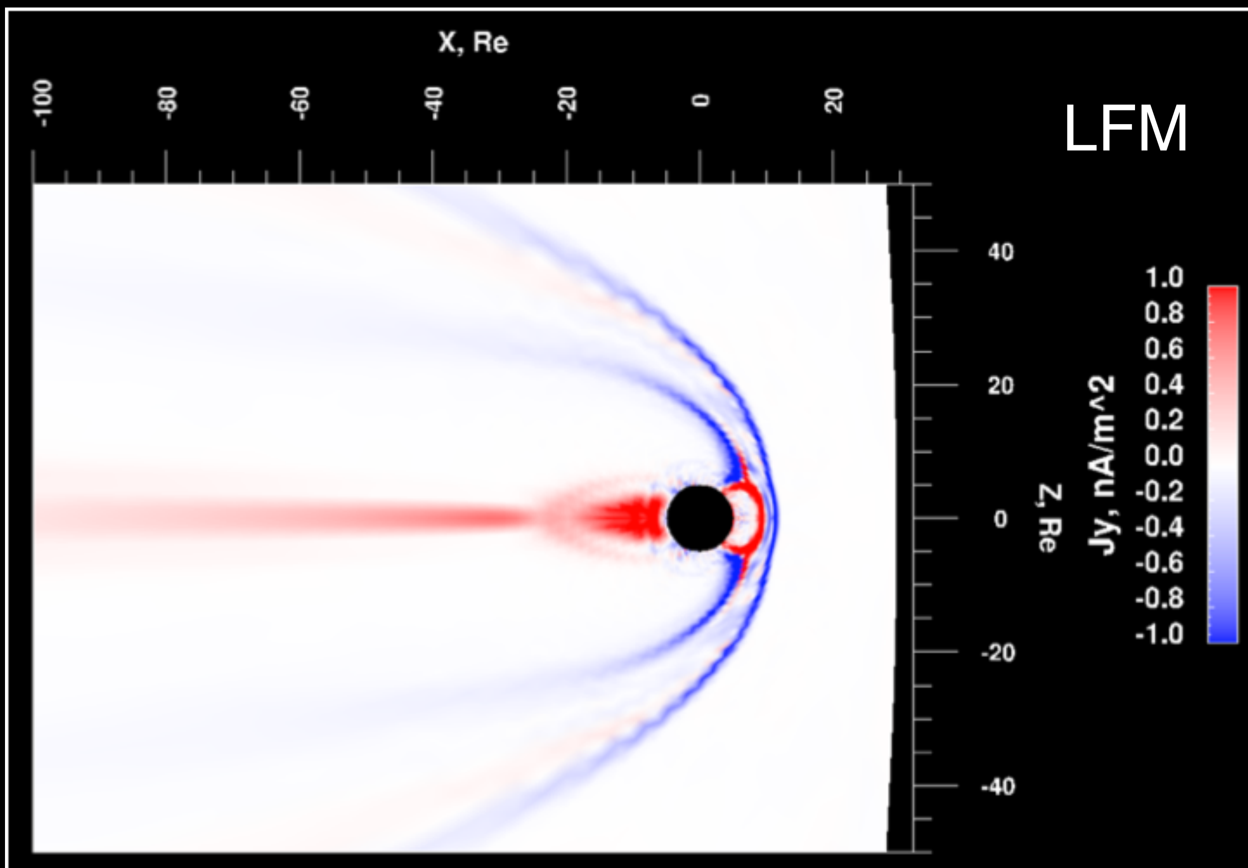
The bow shock current

The bow shock current



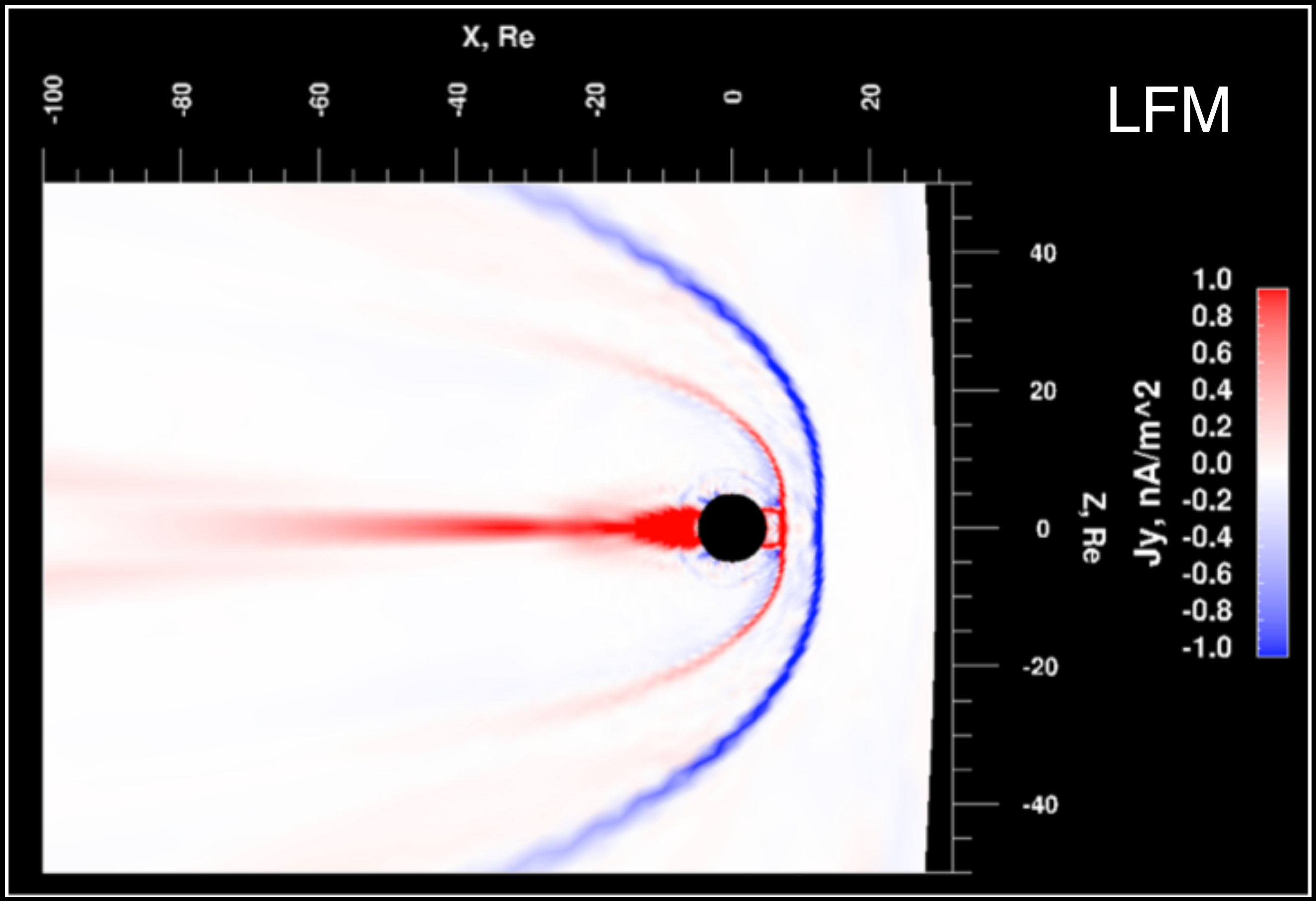
$$J_y = \frac{\Delta B_z}{\mu_0} = \frac{B_z(r-1)}{\mu_0}$$

Simulations show the standard picture, plus something else (B_z = -5 nT, V = 400 km/s, n = 5 cm^{-3})
$E_y > 0$ so $J_y > 0$ load (red) $J_y < 0$ generator (blue)

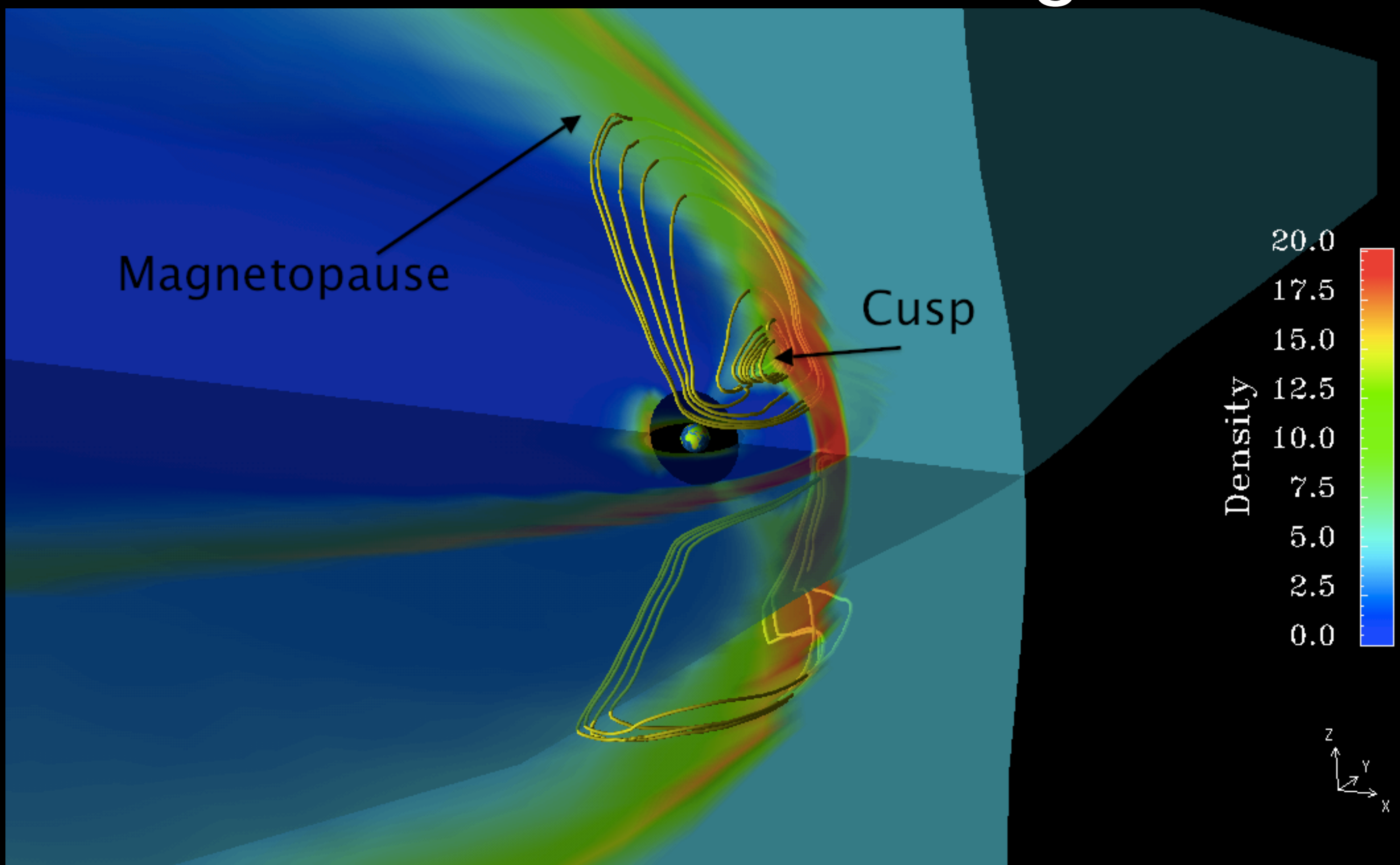


For B_z = -20 nT, the bow shock is the only generator

$E_y > 0$ so $J_y > 0$ load (red) $J_y < 0$ generator (blue)



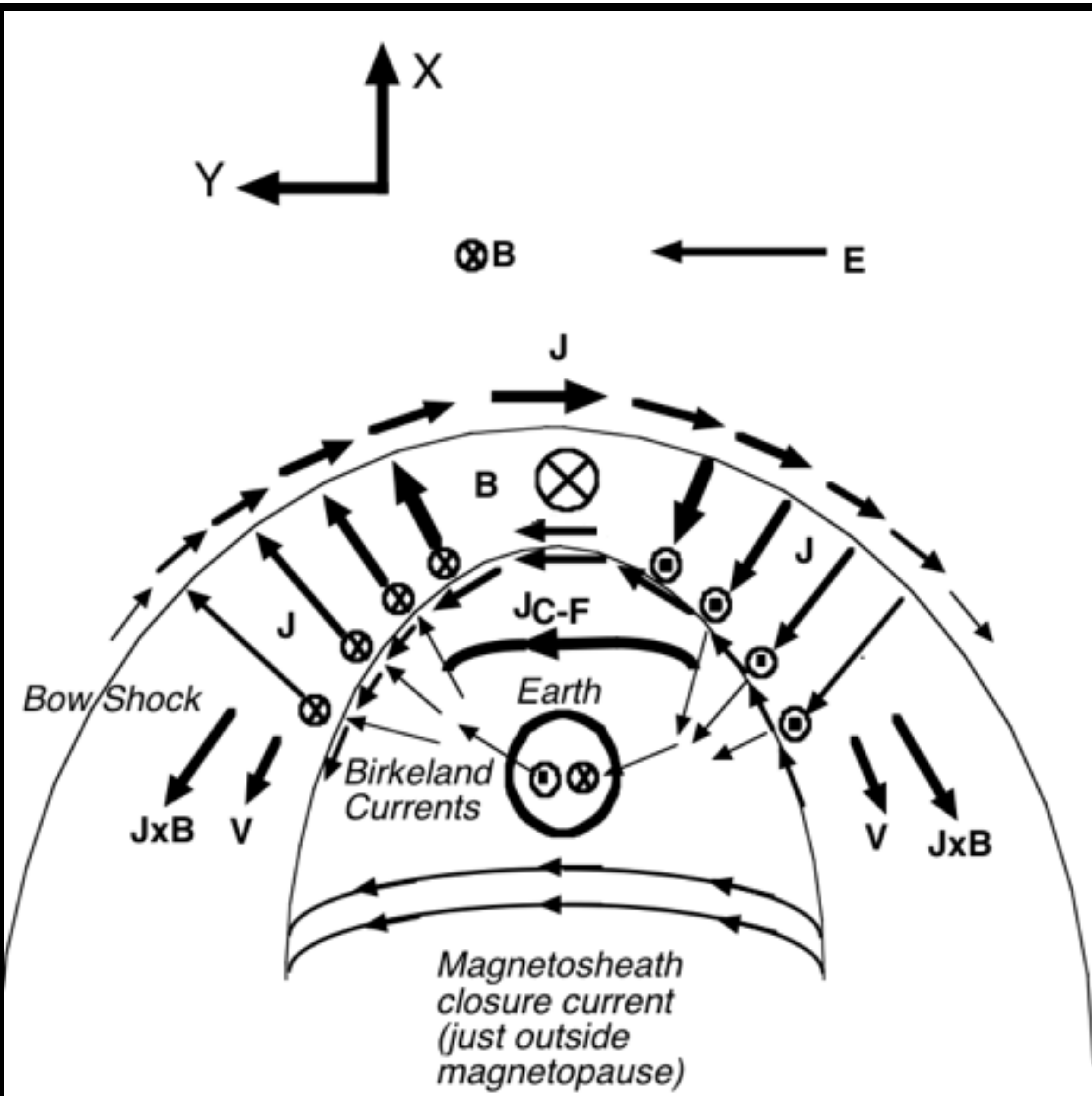
Where does this current go?



From Lopez et al. [2011]

Simulations show that the bow shock current connects in part to the C-F current and also to the Region 1 current

This has been discussed by Siebert and Siscoe [2002], Siscoe et al. [2002], Lopez et al. [2010, 2011]



The bow shock current system is integral to global dynamics, but we still don’t know all of the important details.

from Lopez [2018, in AGU monograph *Electric Currents in Geospace and Beyond*]

To sum it up

- The major current systems in the magnetosphere are driven by the interaction between Earth's magnetic field and solar wind, by which solar wind energy and momentum is transferred across the magnetopause.
- Much is known about these current systems, but there are also plenty of known unknowns, and probably some unknown unknowns.
- One known unknown in particular, the details of the bow shock current system, has received relatively little attention, but it deserves much more.