Transport From the Tail to the Inner Magnetosphere

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(Thanks to Asher Pembroke, Jian Yang, John Lyon and Frank Toffoletto for providing unpublished results)

Note: Slides 21 and 26 have been modified to correct errors that Paul Song and Misha Sitnov pointed out in the original presentation.

Transport From the Tail to the Inner Magnetosphere

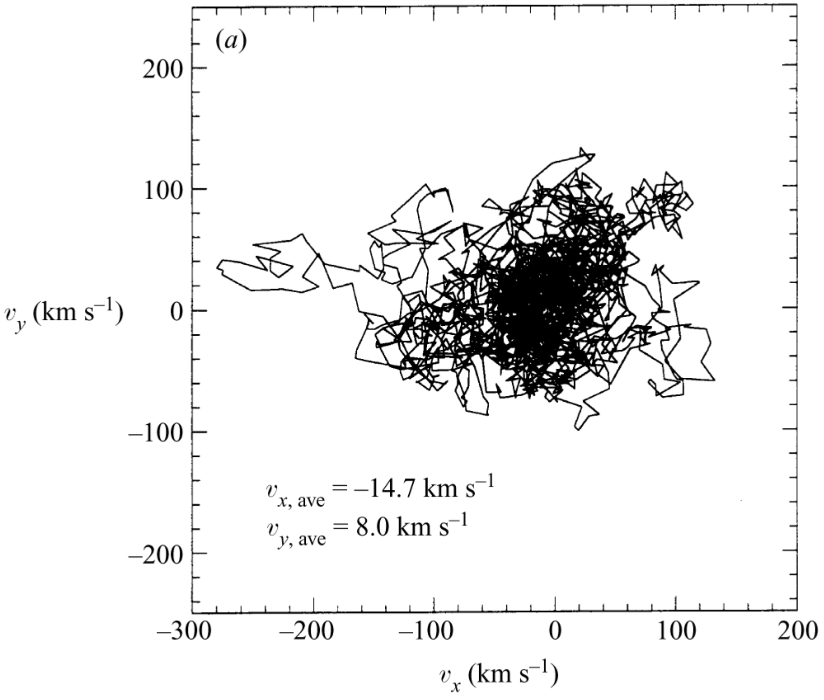
Outline

- Introduction and outline
- Radial transport in the plasma sheet: General considerations
- Plasma sheet transport with steady driving: Bursty bulk flows and bubbles
- Bubble creation mechanisms
- Radial transport through 6-10 R_E
- Summary

Radial Transport in the Plasma Sheet: General Considerations

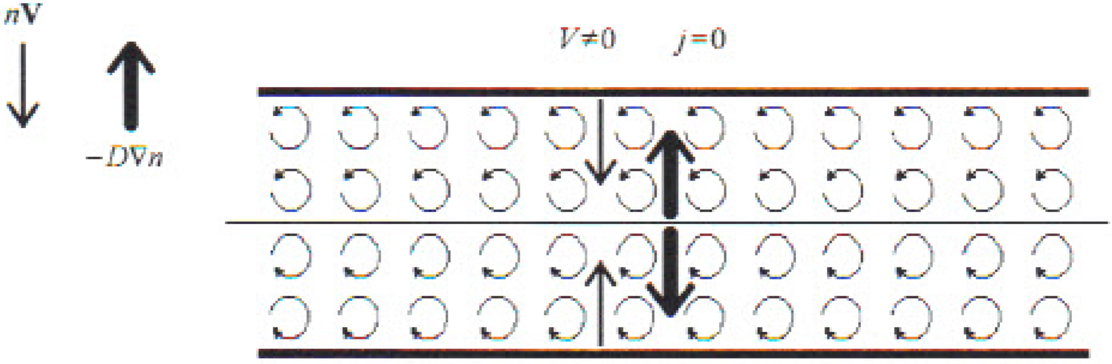
Diffusive Radial Transport in the Plasma Sheet

- Two approaches to radial transport have been very successful for inner magnetosphere: diffusion theory and time-dependent convection.
- Both approaches have been tried for the plasma sheet.
- Diffusion theory looks like a good bet for the plasma sheet, because the data look quite random.
  - For the case shown, rms velocity was ~10 times the mean.
- *Borovsky et al*.[1997] found autocorrelation times of a 2 minutes for velocities, several times longer for the magnetic field.



V_xV_y hodogram for 2-hr period in March 1979. ISEE-2 data. From *Borovsky et al*. (*J. Plasma Phys*., *57*, 1, 1997)

Diffusive Radial Transport in the Plasma Sheet



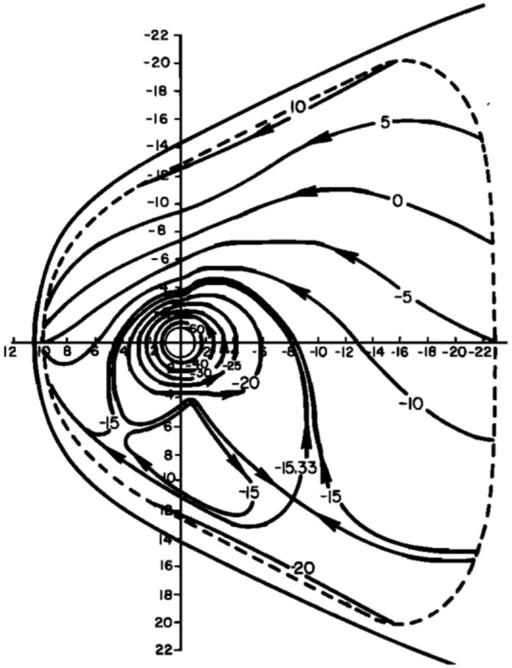
- *Antonova* [*Int. J. Geomag. Aeron.*, *3*, 117, 2002] has suggested that the structure of the plasma sheet is mainly governed by diffusion, and that mainly in the *z*-direction.
  - On closed field lines, this is equivalent to radial transport in the equatorial plane.
- There are many possible mechanisms for generating turbulence in the plasma sheet:
  - Pressure gradients, velocity shears, unstable current sheets, non-equilibrium features of distribution functions.

- Estimate of diffusion coefficient (from *Borovsky* [*JGR*, *103*, 17617, 1998])

$$D_{zz} = \frac{V_{z,rms}^2 \tau_{auto}}{2} \sim 2.6 \times 10^5 \frac{\text{km}^2}{\text{s}} \approx 0.37 \frac{R_E^2}{\text{mn}}$$

Convective Radial Transport in the Plasma Sheet

- Convective picture
  - In the early years, the plasma sheet radial transport was viewed as quasi-steady sunward convection, with some features due to conductance variations:
    - We knew that all the plasma-sheet parameters were highly variable, but we hoped that the variations were due to random variations that average out.



Early RCM-Computed Equatorial Streamlines (cold particles)

(*Jaggi and Wolf*, *JGR, 78*, 2852, 1973)

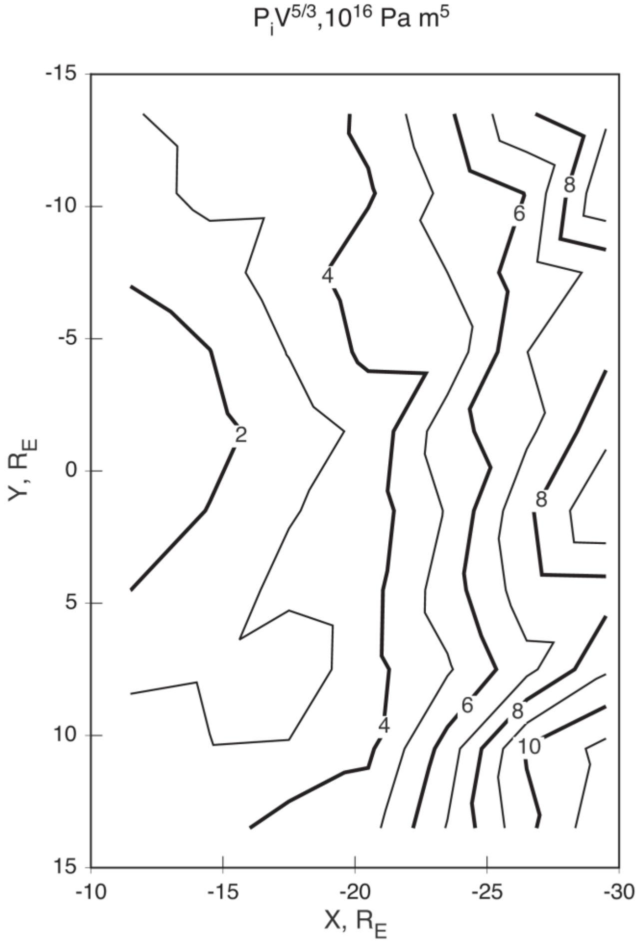
Problem for Convective Model: Pressure Balance Inconsistency

- Assuming isotropic pitch angles, the flux-tube-averaged gradient/curvature drift velocity is given by

$$\mathbf{v}_{GC} = \lambda \frac{\mathbf{B}\times\nabla V^{-2/3}}{qB^2} \qquad V = \int ds / B$$

$$\lambda = W_K V^{2/3} = \text{invariant} \qquad \eta_s = V \int_s d^3p\, f$$

$$\left[\frac{\partial}{\partial t} + \left(\mathbf{v}_{E\times B} + \mathbf{v}_{GC,s}\right)\cdot\nabla\right]\eta_s = s - L \qquad S^{5/3} = PV^{5/3} = \frac{2}{3}\sum_s \eta_s \lambda_s$$

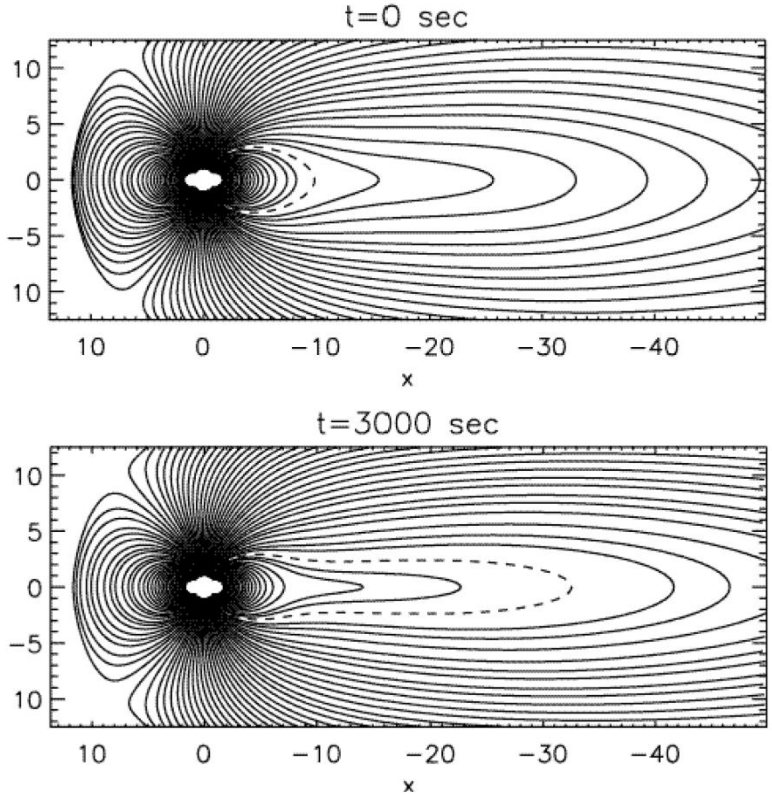


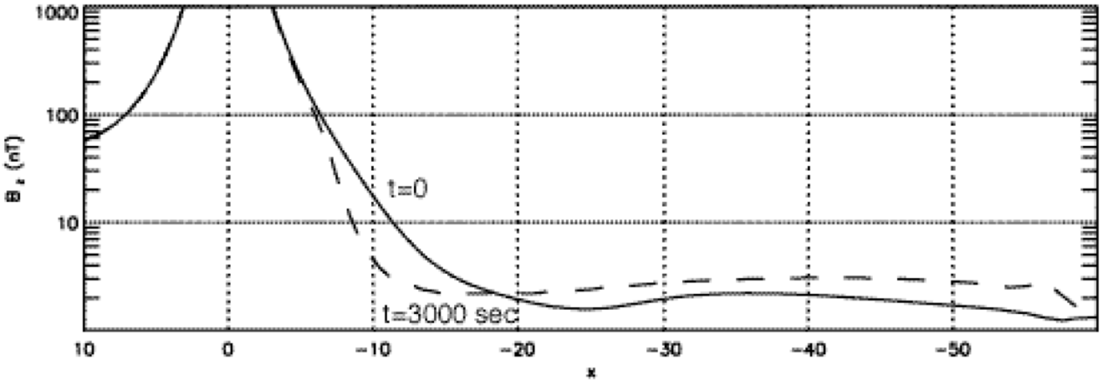
- If the distribution function is approximately uniform on the inflow part of the boundary, then we would expect $S^{5/3}$ to be approximately uniform tailward of the inner edge of the plasma sheet, but it isn't.
- For typical solar-wind conditions, $PV^{5/3}$ at 30 R_E is ~5 times as large as at 12 R_E.
- Called "pressure balance inconsistency" or "pressure crisis".
  - "Entropy crisis" might have been a better name.

(*Kaufmann et al*., *JGR, 109*, A08204, 2004)

Result of Forcing Strong Adiabatic Convection

- If you force adiabatic convection to the inner plasma sheet from the distant plasma sheet and require force balance, what does the solution look like?
- Steady convection solutions exist, and they aren't ridiculous, but their B-fields are more stretched than statistical B-field models.
  - Resemble the substorm growth phase.

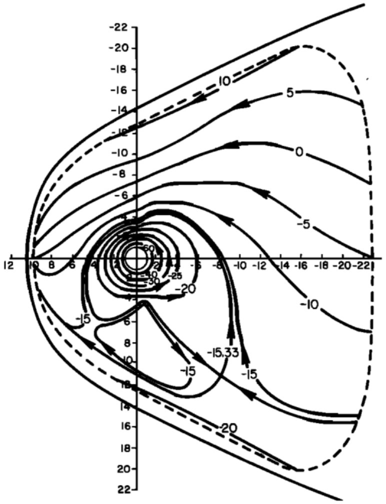




(*Toffoletto et al*., space weather book, 2001)

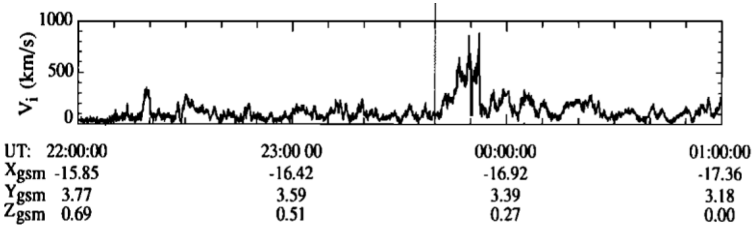
Mechanisms That Don’t Resolve Pressure-Balance Inconsistency

- Precipitation loss:
  - Electrons don’t carry much of the plasma sheet pressure
  - Ion precipitation isn’t strong enough, even with strong pitch angle scattering.
- Ions are in chaotic motion, so adiabatic drift conditions don’t apply.
  - The flux-tube-average drift equation for isotropic pressure is valid even if some ions are chaotic or execute Speiser orbits [*Usadi et al*., *JGR*, *101*, 15491, 1996].
- Inner plasma sheet ions gradient/curvature drift west, perhaps coming from the low latitude boundary layer, not from the distant plasma sheet [*Tsyganenko*, *Planet. Space Sci*., *30*, 1007, 1982; *Spence and Kivelson*, *JGR*, *98*, 15487, 1993; *Wang et al*., *JGR*, *108*(A2), 2003].
  - In times of weak convection, this could be important.
  - But in times of strong convection, the average plasma-sheet ion energy is much less than half the potential drop, at least beyond ~10 R_E.
  - In steady convection, if an ion has drifted half way across the tail, it must have picked up about half the cross-tail potential drop.

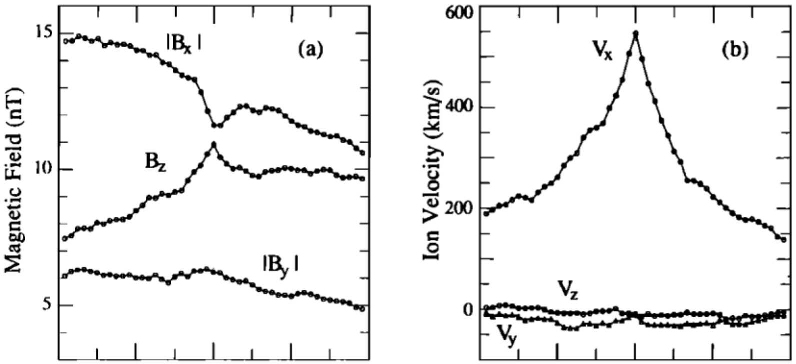


Plasma Sheet Radial Transport with Steady Driving: Variable Phenomena

Observed Mesoscale Phenomenon: Bursty Bulk Flows



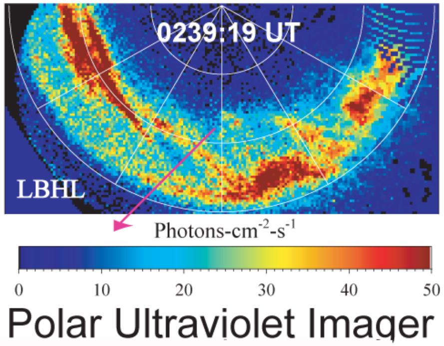
(*Angelopoulos et al*., 1992)

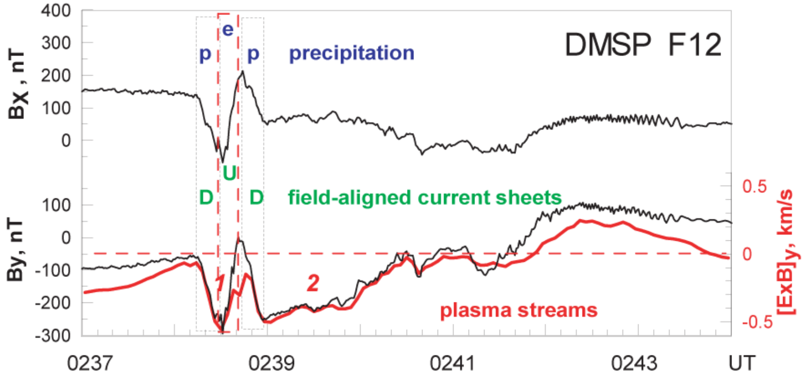


(1 minute tic marks)

- It was discovered in the early 1990's [*Baumjohann et al*., *JGR*, *95*, 3801, 1990; *Angelopoulos et al*., *JGR*, *97*, 4027, 1992] that, though the average earthward flow velocity was only a few km/s, **a large fraction of the earthward flow came in brief flow bursts with velocities of 100s of km/s, which occurred in periods called "bursty bulk flows".**
- Flow bursts tend to have enhanced B_z and decreased $|B_x|$. Field lines more dipolar.
- Earthward of about 20 R_E, bursty bulk flows are almost entirely earthward.
- Cluster measurements suggest that flow bursts have dawn-dusk dimension ~ 2-3 R_E [*Nakamura et al*., *GRL*, *31*, L09804, 2004].

Auroral Streamers



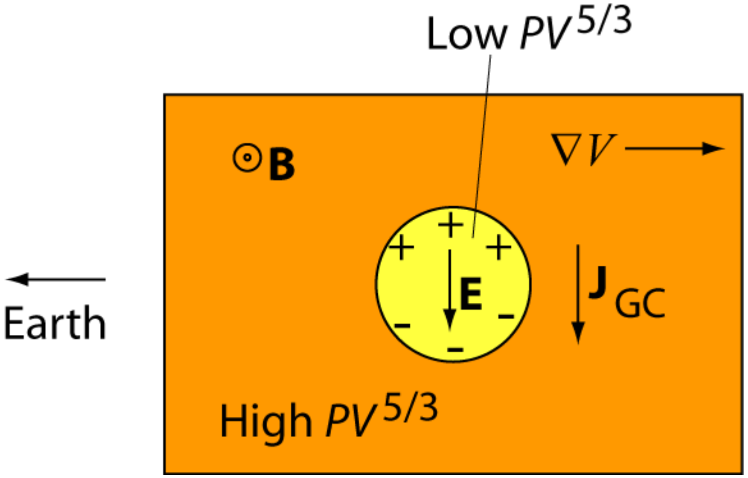


Adapted from *Sergeev et al*. [*AG, 22*, 537, 2004]

- Auroral streamers appear on the west edge of regions of strong, partly equatorward flow.
  - Correspond to region of strong upward Birkeland current.
- Auroral streamers in the ionosphere seem to be associated with BBFs in the plasma sheet (e.g., *Zesta et al*. [*JGR*, *111*, A05201, 2006]).
- The mesoscale BBF/auroral-streamer phenomenon (time scale of minutes, a few R_E width) doesn't fit comfortably within the picture of quasi-steady earthward convection.
- It also doesn't fit comfortably within the diffusion picture.
  - Distance scale is somewhat larger than a typical gyroradius, particularly away from the center of the current sheet, where $B \approx B_z$.
  - Time scale (a few minutes) is long compared to an ion gyroperiod, particularly away from the center of the current sheet.

Plasma Sheet Bubbles

- *Pontius and Wolf* [*GRL*, *17*, 49, 1990] pointed out that “bubbles” (underpopulated flux tubes) would move earthward relative to background.
  - The westward tail current is weaker inside the bubble.
  - Charge builds up on the sides, creating a dawn-dusk electric field in the bubble.
  - To maintain quasi-neutrality, currents flow down to the ionosphere on the dawn (upper) side of the bubble, up from the ionosphere on the dusk (lower) side.



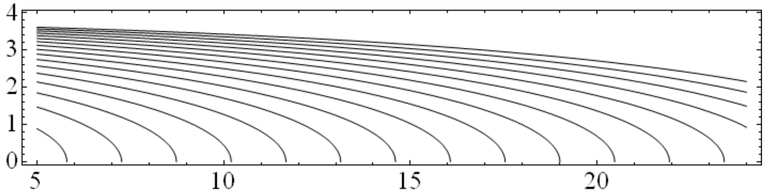
  - There tends to be a strong dawn-dusk electric field inside the bubble, both near the equatorial plane and at the ionospheric footprint.
- *Chen and Wolf* [*JGR*, *98*, 21409, 1993] interpreted earthward BBFs in terms of “bubbles” in the plasma sheet.
- The bubble is defined by its value of $S=\int P^{3/5}ds/B = \int(P^{3/5}/\rho)\,(\rho\, ds/B)$
  - S should be conserved in ideal MHD.
  - A flux tube is called a “bubble” if its S is smaller than its neighbors.

Buoyant Force on a Bubble

- Consider a bubble that takes the form of a thin filament with lower pressure than the background, but same total pressure.
- The background is in force balance.
- In ideal MHD, the force per unit volume is given by

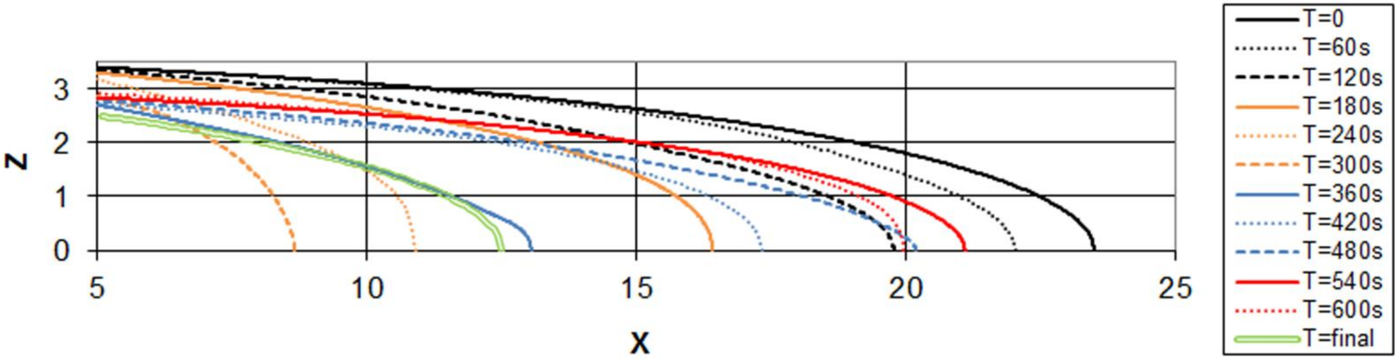
$$\mathbf{F} = -\nabla\left(P + \frac{B^2}{2\mu_o}\right) + \frac{(\mathbf{B}\cdot\nabla)\mathbf{B}}{\mu_o}$$

- Inside the filament, the first term, which is the gradient of total pressure, is the same as in the background medium.
- The magnetic field is stronger in the filament, so the tension force in the filament (2nd term) is stronger than in the background.
- But since the total-pressure gradient and tension terms balance in the background, the earthward tension force on the filament is stronger, and the filament (bubble) will accelerate earthward.



Thin-Filament MHD Simulation of the Life History of a Bubble

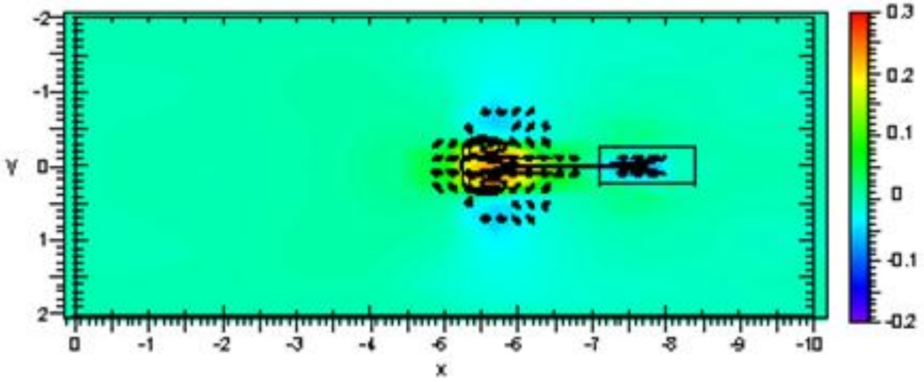
(*Wolf et al.*, *JGR*, *117*, A02215, 2012)



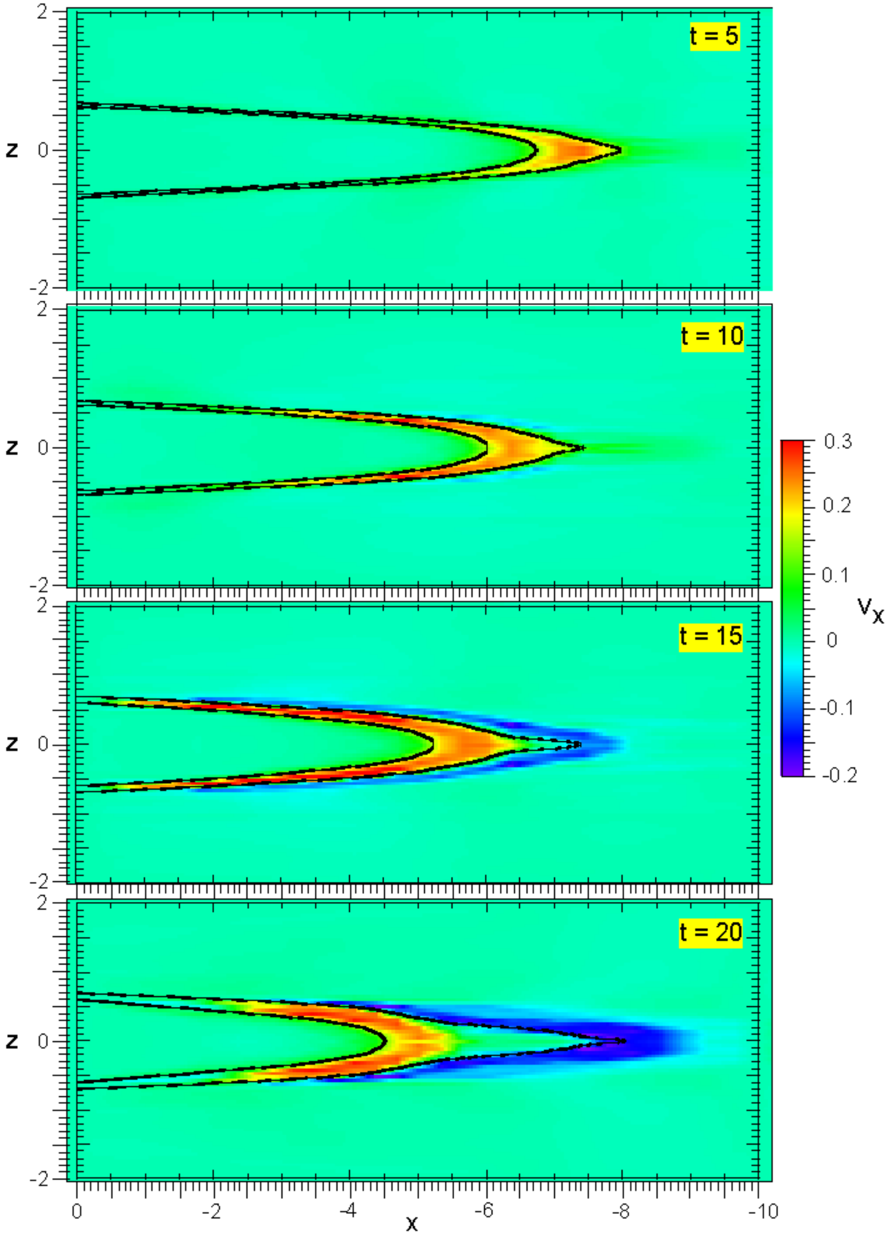
- Background $PV^{5/3}$ increases tailward, as in real plasma sheet.
- Left boundary has ionosphere-like conductance.
- Diagram shows evolution of a bubble filament that initially stretched to 23 R_E but with *S* equal to 80% of background.
- Dawn-dusk **E** field at left end moves that end down, after initial Alfven wave reaches that end.
  - Motion depends on “ionospheric” conductance.
- Filament rushes earthward, overshoots, oscillates.
- Filament reaches final equilibrium when its *S* value matches its neighbors (double-green curve).

3D Tail-MHD Bubble Simulation

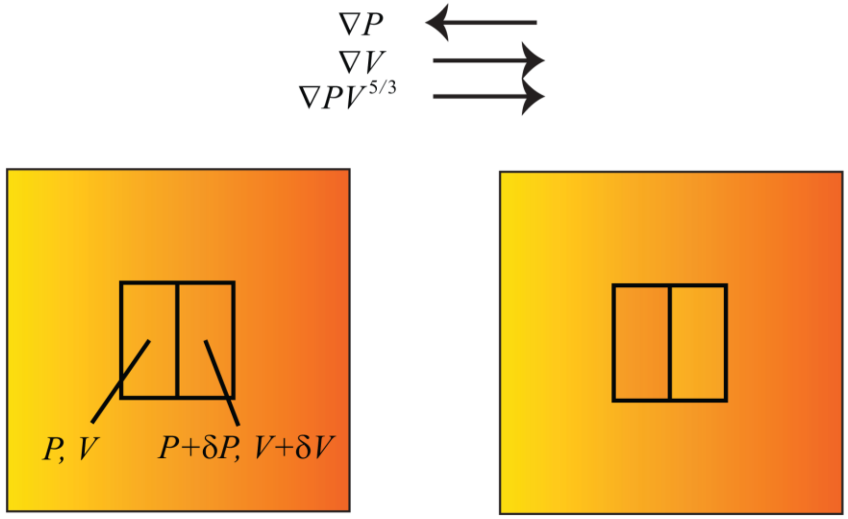
- *Birn et al*. (*Ann.Geophys*., *22*, 1773, 2004) did a full 3D MHD simulation of a bubble.
- In the plot, colors show sunward velocities V_x.
- Black lines are magnetic field lines.
- These calculations have a perfectly conducting earthward boundary.



- More examples: *Birn et al.* [*JGR*, *114*, A00d03, 2009; *JGR*, *116*, A01210, 2011]



Interchange Stability and Implications for Diffusive Transfer

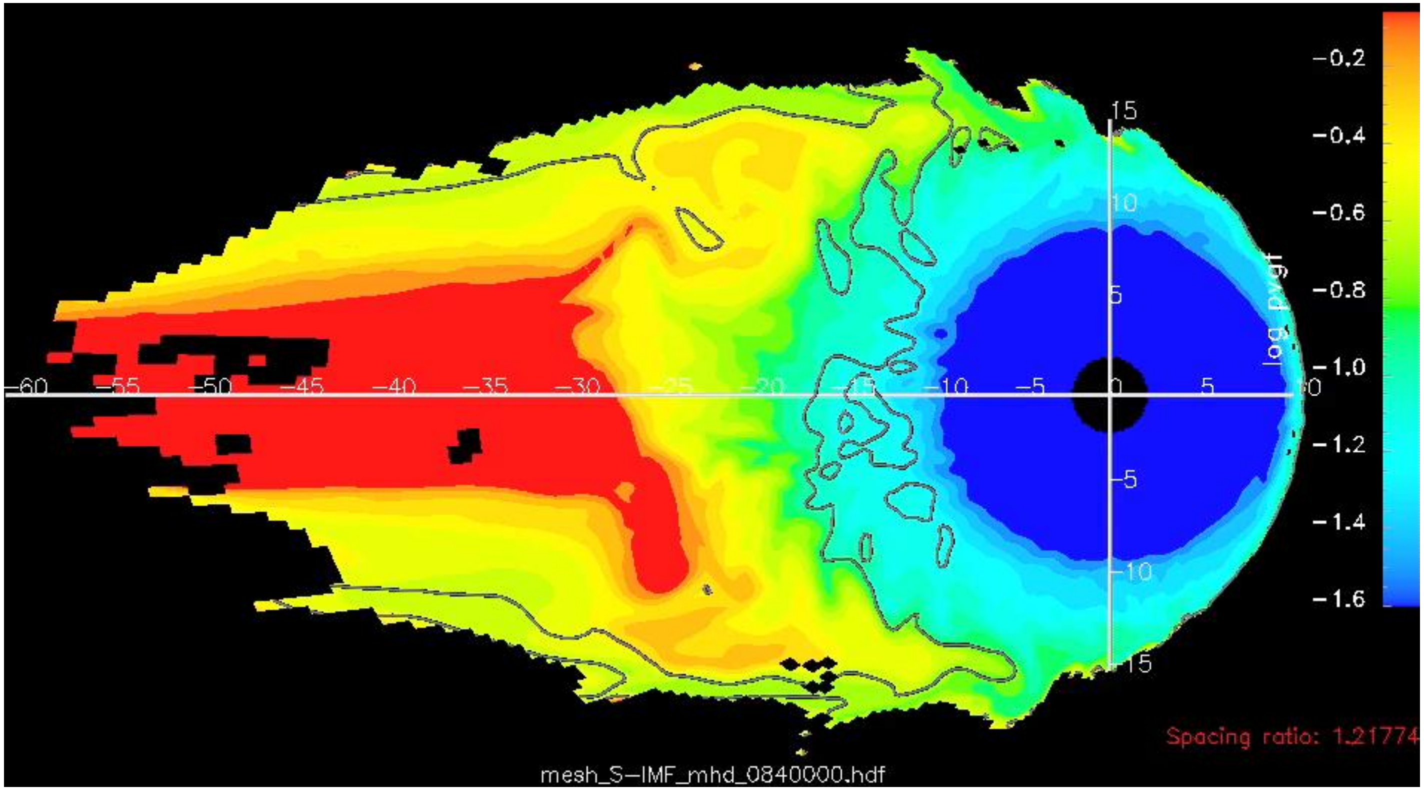


- Classical ideal-MHD energy-principle analysis:
  - Interchange two adjacent fluid elements, assuming adiabatic changes with frozen-in flux
  - Change in potential energy is

$$\delta W = K\left[\delta V - \mu_o \delta P \int \frac{ds}{B^3}\right]\delta\left(PV^{5/3}\right)$$

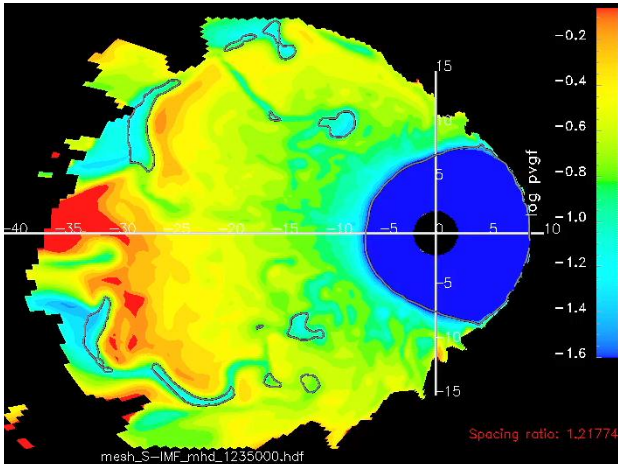
  - With gradients as shown (normal for statistical plasma sheet), $\delta W>0$ →interchange stable.
- Consequence for diffusion picture:
  - If turbulence is ideal MHD, and it moves a flux tube earthward and an adjacent one tailward, thus accomplishing tailward motion of a low-$PV^{5/3}$ flux tube, there will be a restoring force that pushes that low-$PV^{5/3}$ flux tube back earthward.
  - In an environment like the normal plasma sheet that is interchange stable, ideal-MHD radial diffusion will be inhibited.
  - Is there a diffusion theory that takes this into account?
  - *Wang et al.* [*JGR*, *115*, A06210, 2010] found it necessary to add diffusion to explain how effects of a change in IMF reach the plasma sheet near the *y*-axis.

$S^{5/3}$ Movie

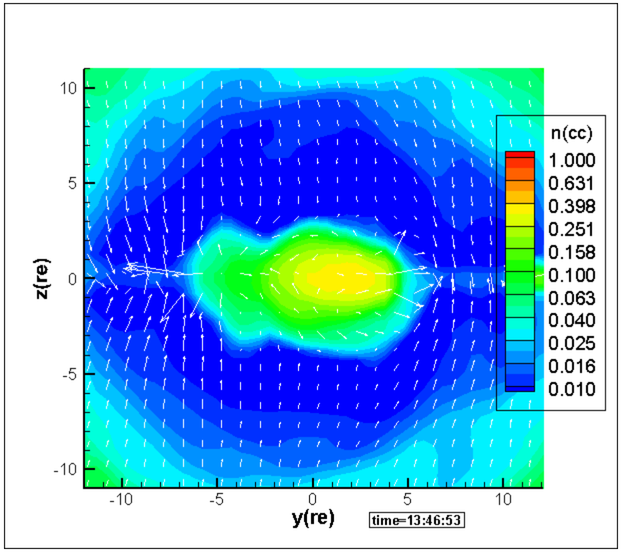


- Colors show $\log_{10}(S^{5/3})$
  - Red=0.8 nPa(RE/nT)$^{5/3}$, Blue=0.025, Black=at least one end not connected to Earth
- Hi-res LFM run by John Lyon, movie by Asher Pembroke.
- IMF B_z= -5, n=5, V=400 km/s.
- S=conserved in ideal MHD. You will see green and blue bubbles move Earthward.

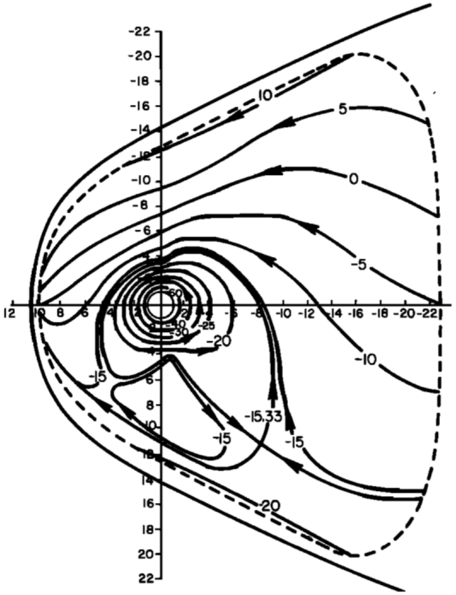
Comments on *$PV^{5/3}$* Movie



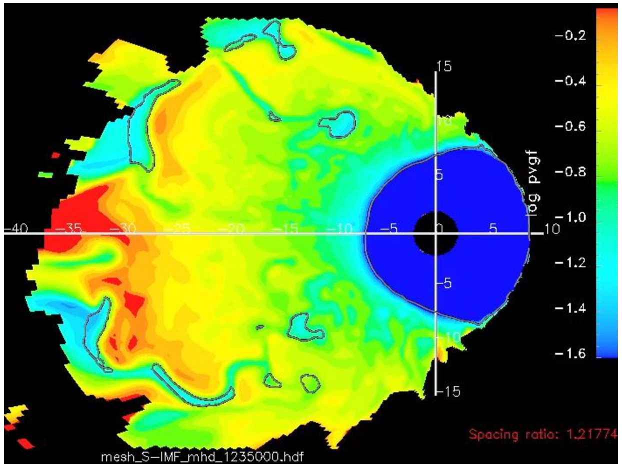
- Red and yellow regions (blobs) are roughly stationary.
- Blue bubbles clearly move systematically Earthward.
  - Typical velocity of a few hundred km/s – look like BBFs.
  - The bubbles don't random walk.
    - Motion is irregular but not diffusive.
  - There are often channels of depleted flux tubes moving earthward, similar to suggestion by *Sergeev and Lennartsson* [*PSS*, *36*, 353, 1988].
- Bubble channels seem to begin in low $S^{5/3}$ regions along the open-closed boundary.
- Tail lobe flow is concentrated toward those regions.
  - Maybe high-$PV^{5/3}$ regions of plasma sheet create back pressure, shutting off reconnective flow into those regions.
  - Seems consistent with *Zesta et al.* [2006] picture in which streamers begin in poleward boundary intensifications.



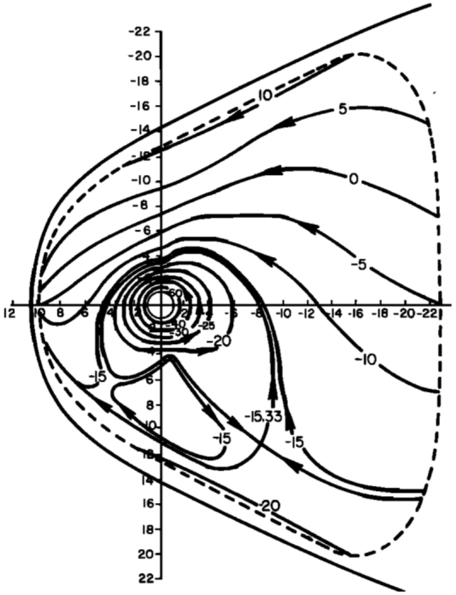
Comments on Movie



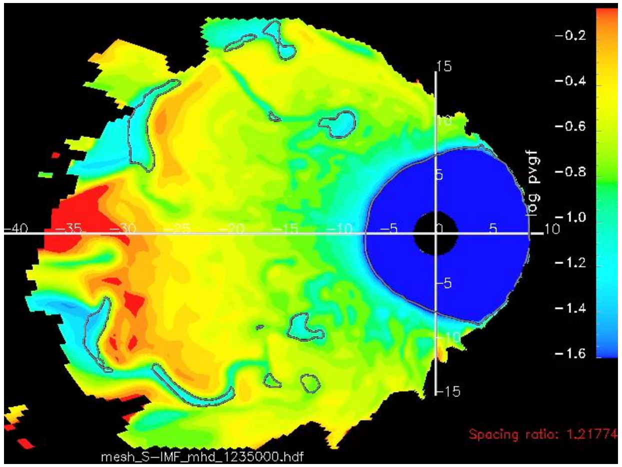
- The two diagrams at the right indicate how my vision of the plasma sheet have changed over the last 40 years.
- The lower diagram shows how I think we should picture the plasma sheet in a time of steady southward IMF.
  - Low-*S* flux tubes moving through a roughly stationary background of higher-*S* flux tubes



Irony of Nomenclature

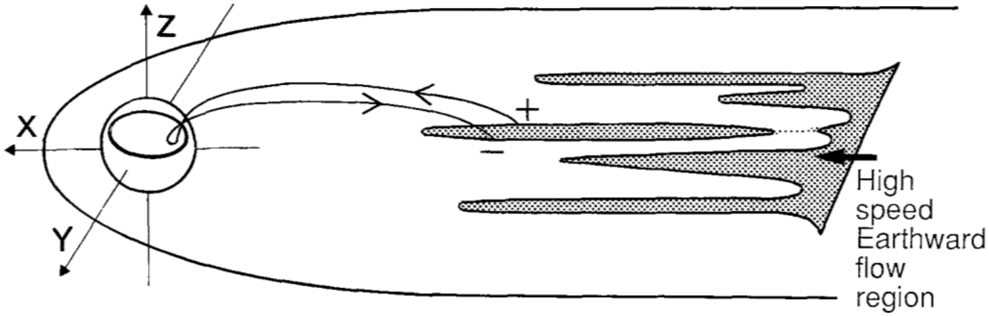


- Axford and Hines used the term “convection” to describe the systematic circulation of magnetospheric plasma, with boundary layers moving antisunward and the interior moving sunward.
- “Convection” seemed to me an imperfect word for this.
- Natural heat convection is a process that depends on buoyancy in a gravitational field and often exhibits a complex, turbulent pattern.
  - Magnetospheric convection has nothing to do with gravity and seemed pretty organized, with the boundary layers always flowing antisunward, interior sunward.
- But now it turns out that the plasma sheet exhibits a non-gravitational buoyancy causes low-*S* bubbles to move Earthward through a background of high-*S* flux tubes.
  - Flow patterns are very complex and variable.
- I think Ian Axford would be happy with how this has turned out.

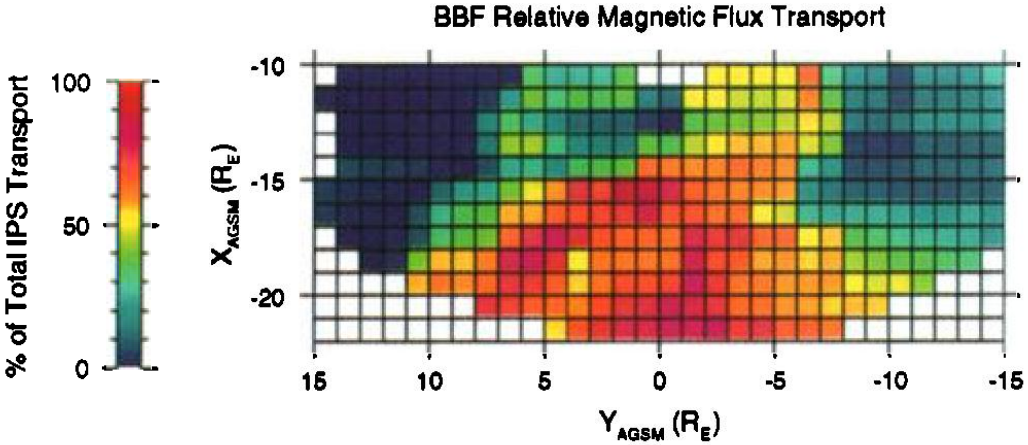


Observations of Fast Flows in SMC Events

- Bursty bulk flows seem to be particularly common in steady magnetospheric convection (SMC) events.
- Estimates of the fraction of total Earthward transport $\int V_x B_z dt$ with $V_x>0$ in fast flows vary:
  - Fraction depends a lot on where the spacecraft is, definition of BBF, etc.
- Estimates of overall fraction of SMC transport in high-velocity events ranges from ~20% to ~80% [*Sergeev et al*., *SSR*, *75*, 551,1996; *Kissinger et al*., *JGR*, *117*, A05206, 2012].



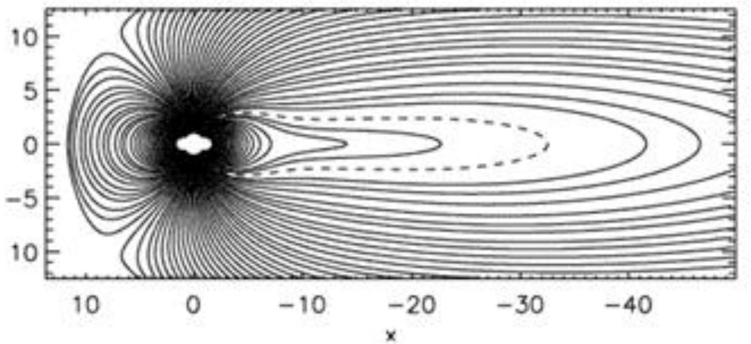
(Adapted from *Sergeev et al*., 1996)



Fraction of BBF transport in all ISEE events. [*Angelopoulos et al*., *JGR*, *99*, 21257, 1994]

Evidence for the Role of Bubbles in Substorm Particle Injections

- It is well known that some growth-phase stretched field lines dipolarize in a sector near local midnight, in the expansion phase of a substorm.
- This can only happen if the dipolarizing flux tubes have their $PV^{5/3}$ reduced.

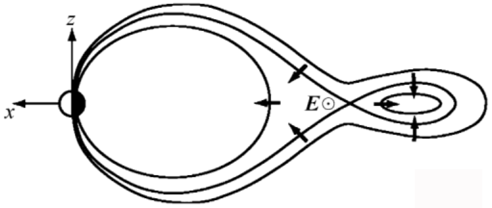


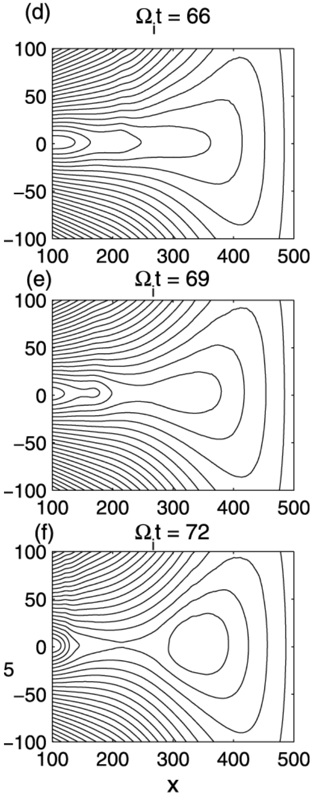
- In a simulation with self-consistently calculated magnetic fields, enforcing steady convection from the distant tail produces stretching in the inner plasma sheet.
    - Dipolarizing a set of flux tubes substantially reduces their V, and there is nothing to balance that.
- *Nishimura et al*. [*JGR*, *115*, A07222, 2010] have shown that many substorm expansions seem to be triggered by streamers that start from a poleward boundary intensification and propagate equatorward. The expansion onset seems to occur when the streamer hits the onset arc.
- Sharp dipolarization fronts [*Runov et al*., *116*, A05216, 2011] form where the head of an earthward-moving bubble contacts the high-S ambient medium. Intense current sheet forms with interesting kinetic effects.
- See *Sergeev et al*. [*GRL*, *39*, L05101, 2012] for excellent compact review of this topic.

Bubble Creation Mechanisms

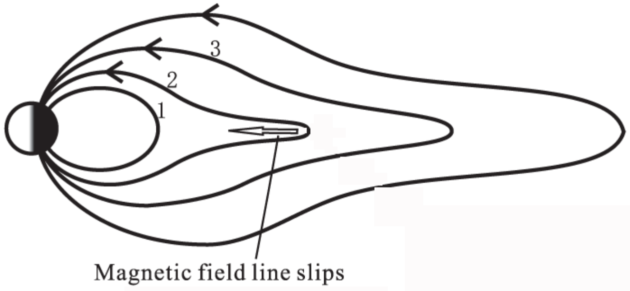
Processes that Create Bubbles Within the Plasma Sheet

- Inhomogeneities in reconnection rates at far-tail X-line.
  - Exemplified by LFM run shown in movie.
- Patch of reconnection on closed plasma-sheet field lines.
  - *Birn et al*.[*JGR*, *114*, A00d03, 2009] showed that $S=\int P^{3/5}ds/B$ is nearly conserved in reconnection.
  - Some of the *S* goes into plasmoid, so *S* on closed flux tube is reduced from initial value.
- Interchange-ballooning-reconnection combinations
  - *Pritchett and Coroniti* [*GRL*, *38*, L10102, 2011] started a PIC simulation from a configuration that had a region where *S* had a strong earthward gradient and was thus strongly MHD interchange unstable
    - Earthward propagating interchange fingers triggered reconnection closer to Earth (seems consistent with *Nishimura et al*. [*JGR*, *115*, A07222, 2010] suggestion).

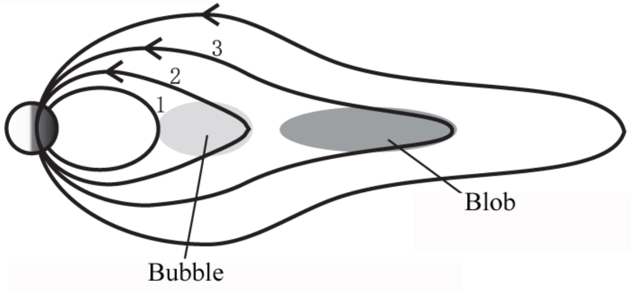




More Processes that Create Bubbles



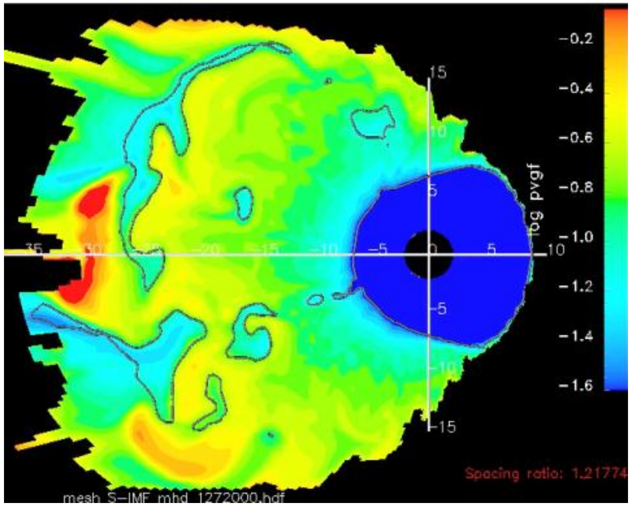
- Another interchange-ballooning-reconnection combinations:
  - *Yang et al*.[*GRL*, *38*, L01107, 2011] and *Hu et al*. [*JGR*, *11* A06223, 2011] used RCM-E and the OpenGGCM global MHD code to study a process in which
    - In a highly stretched region of inner plasma sheet where *PV*$^{5/3}$ is high and roughly uniform, and current density is high, field lines slip Earthward on the plasma.
    - Creates a bubble (1-2) earthward of a blob (2-3).
    - Bubble moved Earthward, blob moved tailward, creating highly stretched region in between and reconnection.
    - "Tearing" or "slipping"?



- *Sitnov and Swisdak* [*JGR*, *116*, A12216, 2011] used a full-particle code to find that a dipolarization front sometimes formed before the kind of topological change that is usually associated with reconnection.
  - They found that the steep gradient in the dipolarization front caused an instability similar to an ion tearing mode on closed field lines.
    - Caused closed field lines to slip on plasma
    - Eventually resulted in a secondary X-line and topological reconnection.
    - In 3D, that would create a bubble.

Radial Transport Events, with Emphasis on 6-10 R_E

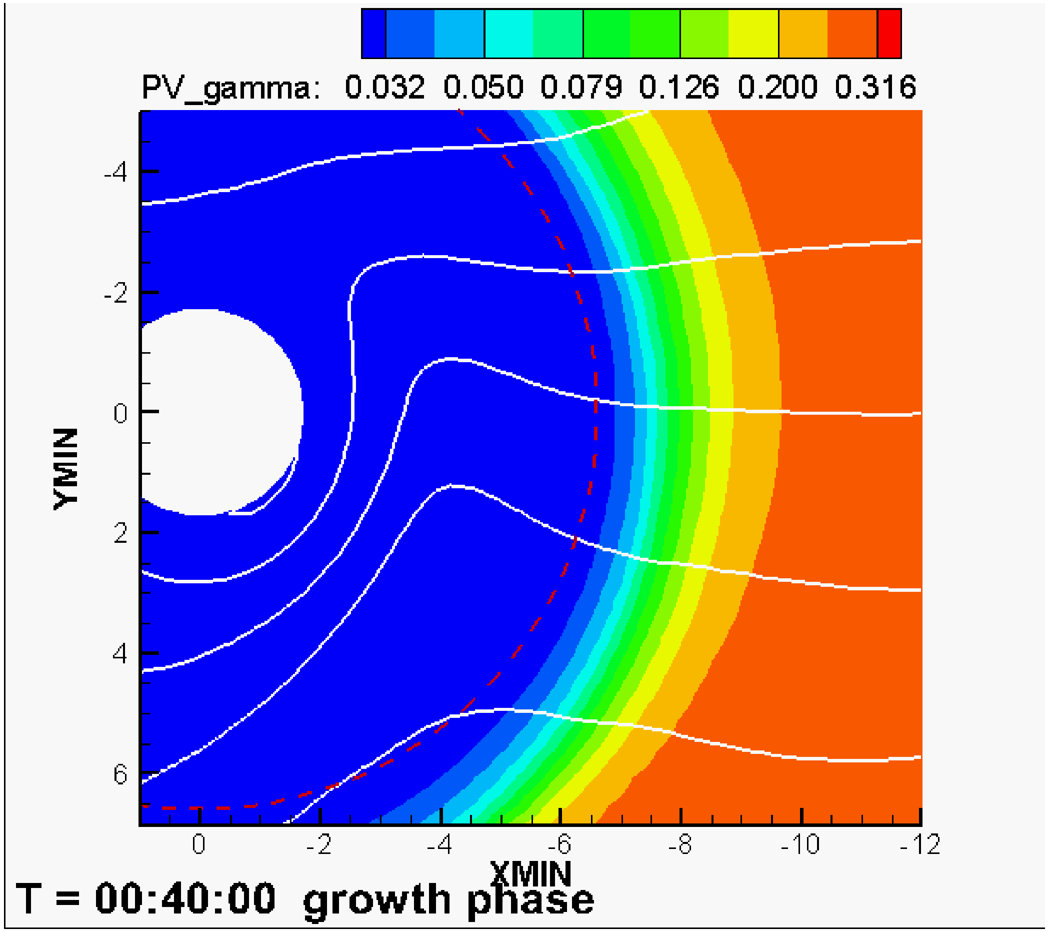
Theoretical Difficulties With Treating Transport in the 6-10 R_E Region



- LFM movies showed bubbles entering inner magnetosphere
  - Gradient/curvature drift plays a major role in transport near geo, so ideal MHD is inadequate.
- RCM-E includes gradient/curvature drift with 3D magnetic field model maintaining approximate force balance.
  - But it neglects inertia
  - Valid only for time scales >> Alfvén wave travel time.
  - Tests [*Wolf et al.*, *JGR*, *112*, A02216, 2012] suggest that this causes RCM-E to underestimate bubble travel times and overestimate electric field strengths, though net motion and $\int E_y\, dt$ should be ok.
- We still don't have a large-scale computational model that includes both inertia and gradient/curvature transport along with ionosphere-magnetosphere coupling.

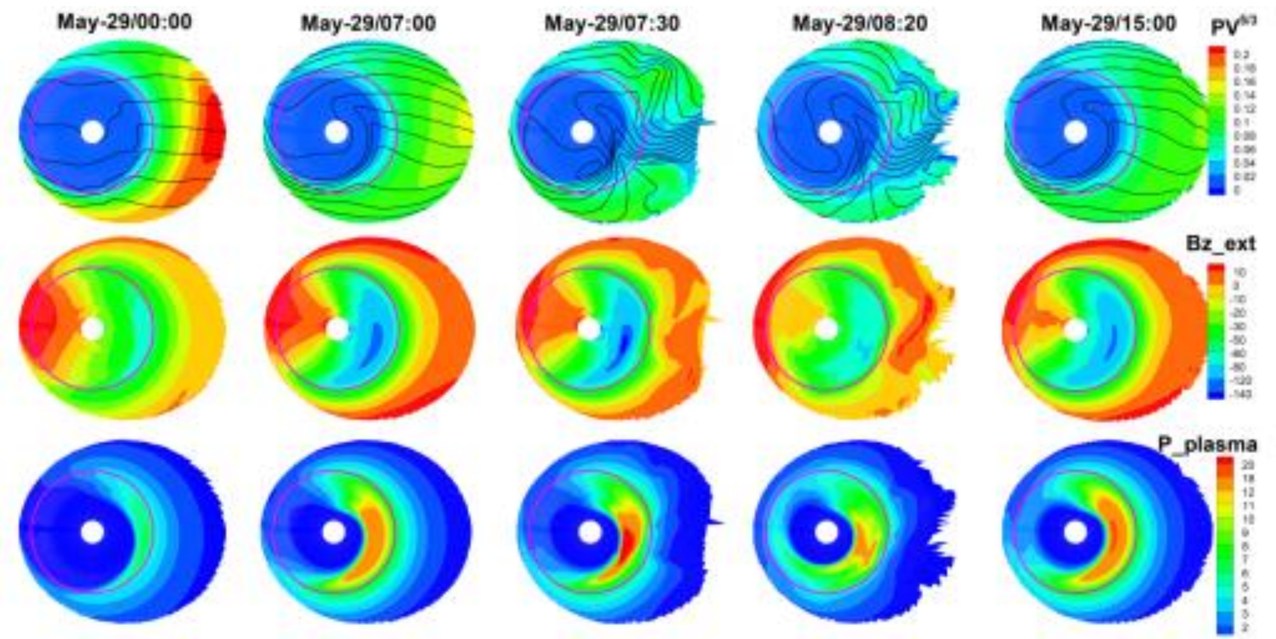
RCM-E Simulation of an Idealized Substorm

- Jian Yang has performed RCM/RCM-E simulations of different kinds of injections.
- Movie shows equatorial plane for the last 15 minutes of the growth phase, first 10 minutes of expansion.
- Color is $S^{5/3}=PV^{5/3}$
- Lines are equipotentials
- Plasma sheet inner edge moves slowly until bubble (green) is imposed at RCM-E boundary.
- Bubble moves rapidly earthward
  - Strong westward potential field inside bubble.



- Rapid earthward motion stops when it reaches region of matching *S* (green)
  - Bubble then spreads out east-west, partly due to ExB and gradient/curvature drift

RCM-E Simulation of Moderate Storm

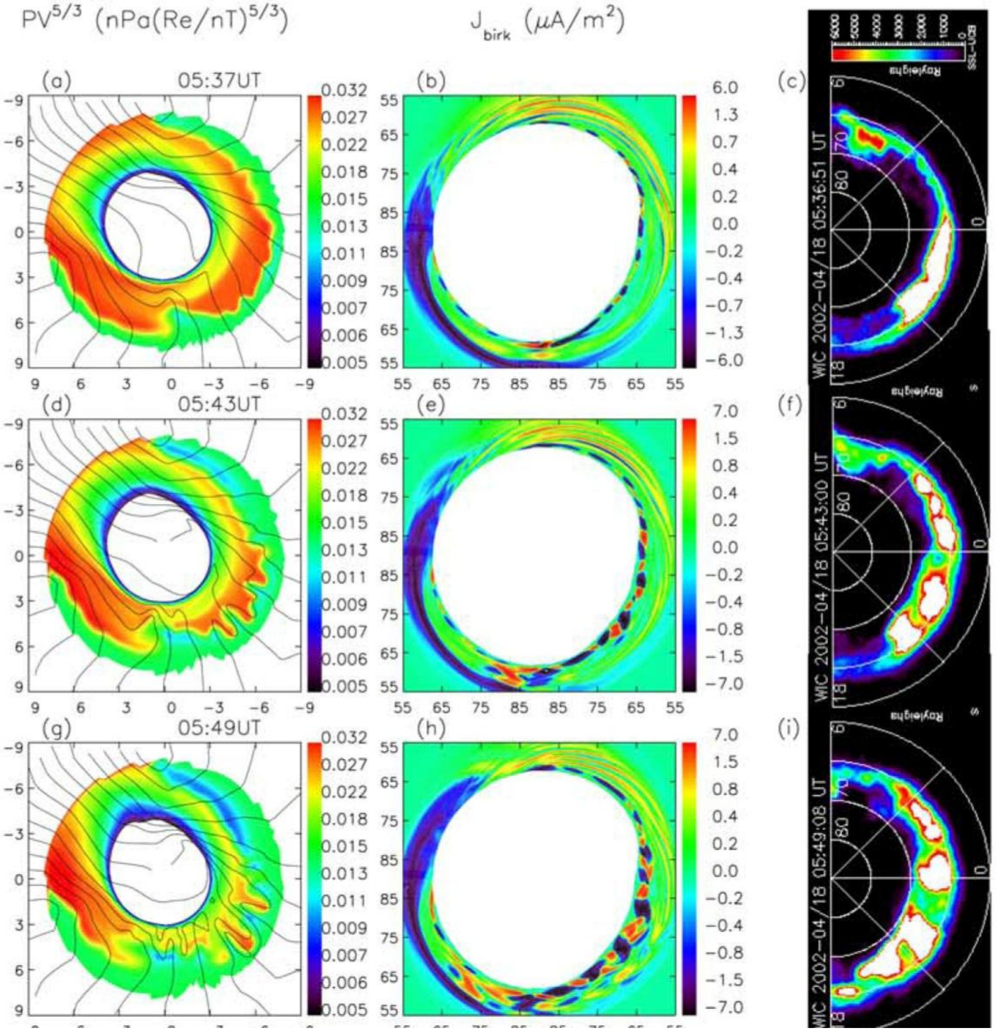


(Courtesy J. Yang)

- Figure shows equatorial plane, with Sun to the left, for the main phase of a moderate storm that occurred May 28-31, 2010.
- Top row shows $S=PV^{5/3}$, second row B_z, third row P.
- The bubbles were introduced only as indicated by dipolarizations seen by THEMIS and/or GOES. A major injection occurred before the first modeled substorm.
- Note pressure increase in ring current, centered pre-midnight and depression of B_z.
- Note bifurcated ring current after second substorm.

RCM Simulation of a Sawtooth Event

- Sun to the left.
- RCM outer boundary was at geosynchronous orbit.
- Left column shows *S* in equatorial plane
- Middle column shows Birkeland currents, viewed from above north pole.
- Red and yellow indicate downward current (mostly on the sides of the fingers). Blue means upward current.
- Right column shows the aurora viewed by the IMAGE FUV WIC camera.
- We suggest that the north-south auroral forms are due to currents on the sides of the interchange fingers.

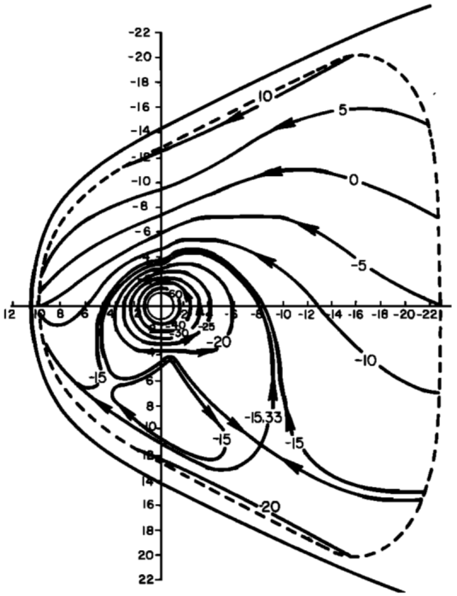


(*Yang et al*., *JGR*, *113*, A11214, 2008)

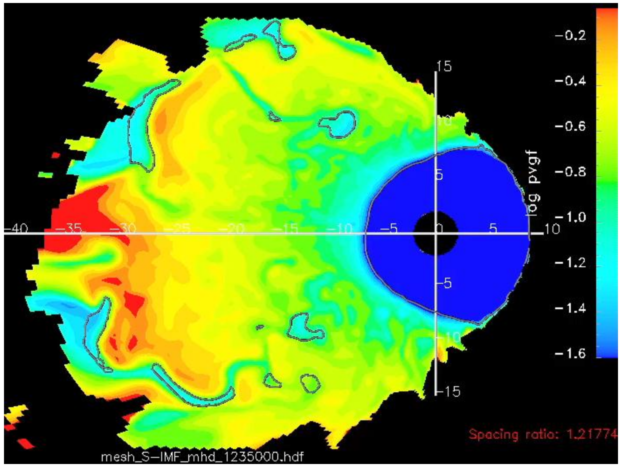
(See also *Sazykin et al*. [*GRL*, *29*(10), 2002])

Summary

Summary Concerning Radial Transport



- There are two classical ways of theoretically treating radial transport in the magnetosphere: diffusion and time-dependent large-scale flow (convection).
- Neither really describes radial transport in the plasma sheet.
- A mesoscale phenomenon (bursty-bulk-flows/streamers/bubbles) plays an important role in plasma sheet radial transport.
- Modelers are struggling to cope:
  - No large-scale model includes inertia, g/c drift transport, and i-m coupling.
  - Small scale processes, which require particle or hybrid codes, obviously play an essential role.
  - We are making clear progress toward understanding, using insights from rich spacecraft and ground-based data, MHD and RCM-type large-scale codes, and particle and hybrid codes.
  - Results are beginning to represent the complexities of the real world.



Key Issues Remaining to be Resolved

- Where do the major violations of adiabatic convection (E×B and bounce-averaged gradient/curvature drift) occur around the time of substorm onset? Do violations occur inside 10 R_E in substorm expansion?
- What causes flows to be concentrated in limited regions of the nightside open/closed boundary?
- How well can expansion-phase physics at $L<10$ be represented in convection models that include bubbles?
- What violations of adiabatic convection are involved in a typical magnetic storm?
  - Series of substorm bubbles? Continuous stream? Low $PV^{5/3}$ in entire plasma sheet?
- Does accurate ring-current modeling require consideration of bubbles, specifically variation of $PV^{5/3}$ along the outer boundary of the ring-current calculation?