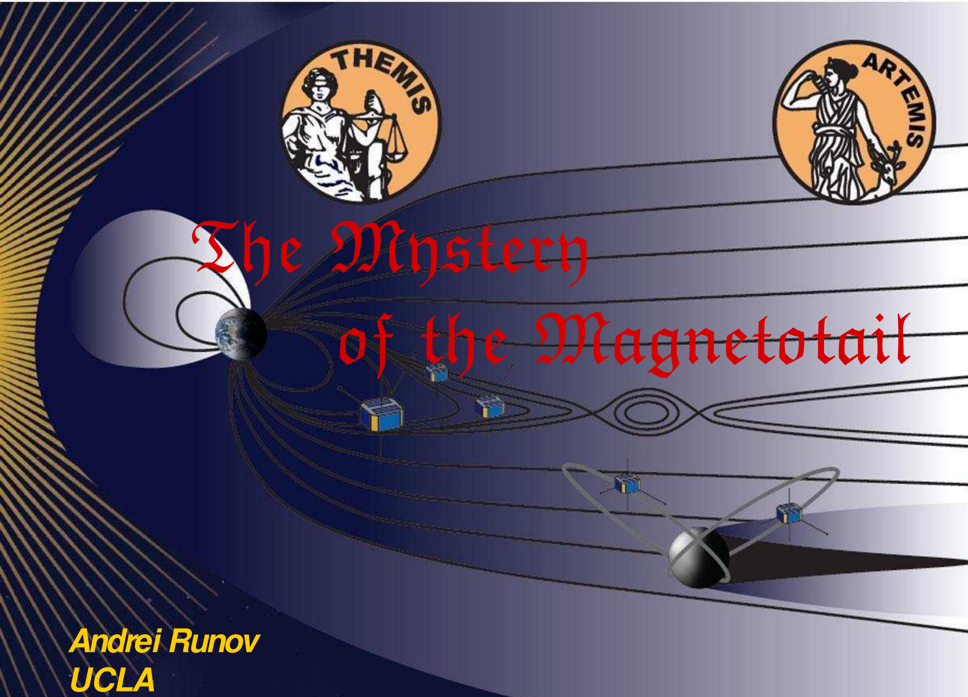
RA MPS Tutorial
Closing MPS RA FG:

- **Testing Proposed Links between Mesoscale Auroral and Polar Cap Dynamics and Substorms** (2015 - 2019; Toshi Nishimura, Kyle Murphy, Emma Spanswick, and Jian Yang; RA: MPS)
- **Tail Environment and Dynamics at Lunar Distances** (2015 - 2019; Chih-Ping Wang, Andrei Runov, David Sibeck, Viacheslav Merkin, and Yu Lin; RA: MPS, GSM, SWMI)

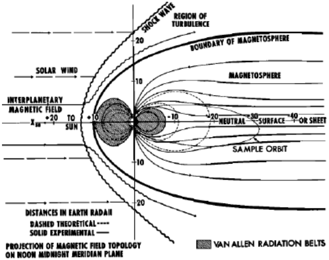
- Shall we continue? Where to go?
  Future of Tail on GEM Discussion: Friday 10:30 AM



The Mystery of the Magnetotail

Andrei Runov
UCLA

The Mystery of the Magnetotail
Outline



From *Ness et al., 1965*

- *Chapter I:*
  The Mystery of the Thin Current Sheet
- *Chapter 2:*
  The Mystery of Explosive Activity Onset
- *Chapter 3:*
  The Mystery of the Auroral Substorm

Thanks To

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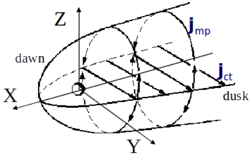
Explosive Magnetotail Activity

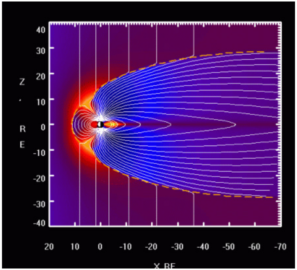
Mikhail Sitnov[1] · Joachim Birn[2] · Banafsheh Ferdousi[3] · Evgeny Gordeev[4] · Yuri Khotyaintsev[5] · Viacheslav Merkin[1] · Tetsuo Motoba[1] · Antonius Otto[6] · Evgeny Panov[7] · Philip Pritchett[8] · Fulvia Pucci[9,10] · Joachim Raeder[11] · Andrei Runov[12] · Victor Sergeev[4] · Marco Velli[3] · Xuzhi Zhou[13]

Toshi Nishimura, Kyle Murphy, Emma Spanswick, Jian Yang
Chih-Ping Wang, Yu Lin, Slava Merkin, David G. Sibeck

Vassilis Angelopoulos, Anton Artemyev, San Lu, Jiang Liu, Steven S. Xu

Chapter I: The Mystery of the Thin Current Sheet

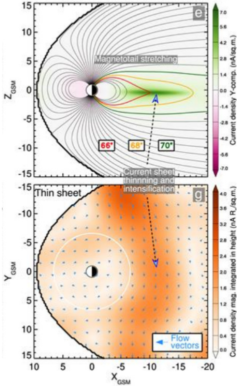




From *Tsyganenko & Andreeva, 2017*

- Typical CS thickness ∼1 - 3 R_E
- Cross-tail diamagnetic (⊥) current with density

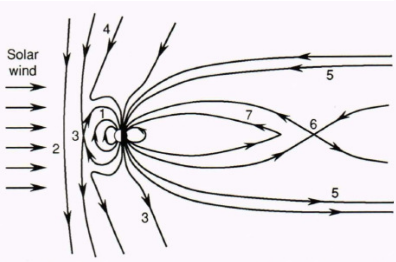
$$j_y = -\frac{c}{B_x}\frac{\partial p}{\partial z} \sim 1\,\mathrm{nA/m^2}$$

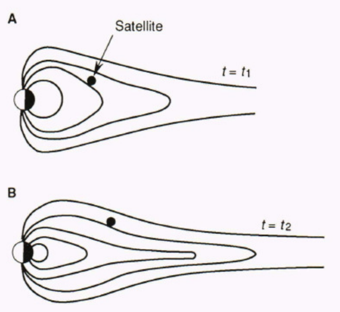


From *Stephens et al., 2019*

- CS thinning down to $\sim 10^3$ km,
- Intensification of the cross-tail current density up to $j_y \sim 10\,\mathrm{mA/m^2}$
- What are physical mechanisms of CS thinning ?

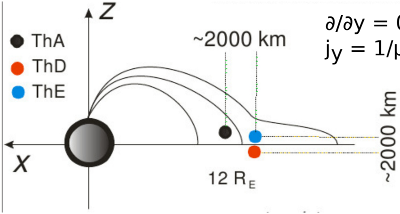
Current Sheet Thinning: The Classical Scenario





From *Lopez, 1994*

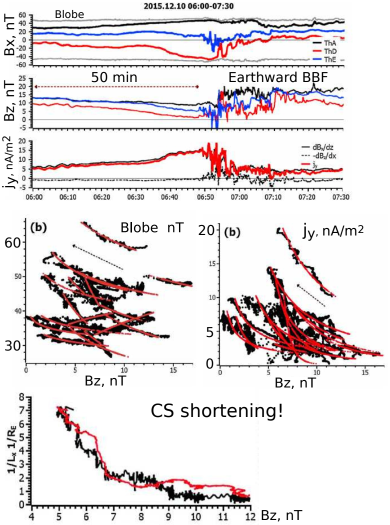
- Flux loading to lobes;
- Do *in situ* observations confirm this scenario?
- THEMIS observations of CS thinning at -12$< X <$-10 R$_E$



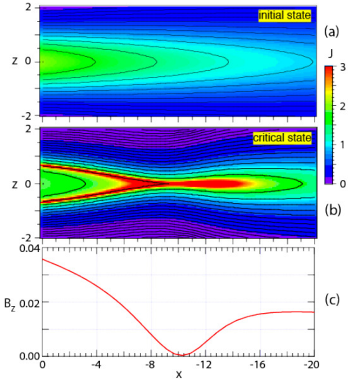
$\partial/\partial y = 0$

$j_y = 1/\mu_0(\partial Bx/\partial z - \partial Bz/\partial x)$

Current Sheet Thinning: THEMIS Observations @ $X \sim$-10 - -12 R_E



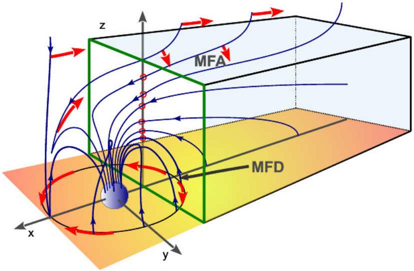
From *Artemyev et al., 2016*

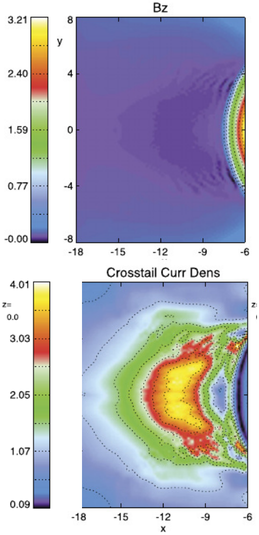


From *Sitnov et al. 2019, Birn et al., 2019*

- $j_y \propto B_z^{-\alpha}$, $\alpha \sim 1$ independent on $B_L(t)$;
- $\max(j_y)$at $X \sim$-10 - -12 R_E; dp/dx decreases;
- Inconsistent with the simple magnetic flux accumulation.

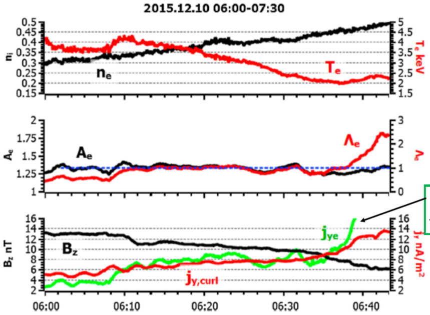
Near-Earth Magnetic Flux Depletion Mechanism: MHD Framework





From *Birn et al. 2019*, Provided by *A. Otto*;
Hsieh & Otto, 2014, *Otto, 2015*

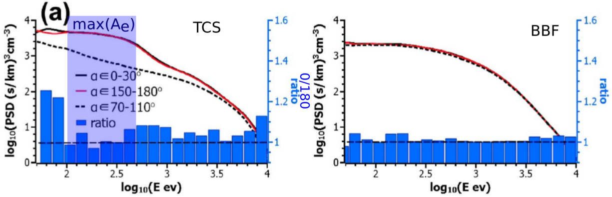
THEMIS: TCS @ X ∼-10 R$_E$ are Supported by ∼100 eV Anisotropic Electrons. From *Artemyev et al., 2016,2017*



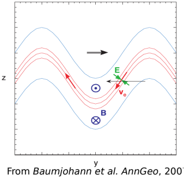
$$A_e = \frac{T_{e\parallel}}{T_{e\perp}},$$

$$\Lambda_e = \frac{4\pi p_e}{B^2}\left(A_e - 1\right)$$

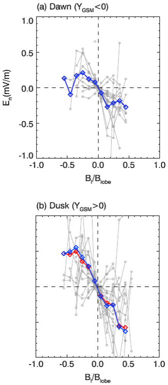
$$j_{ye,\perp} \approx \frac{c}{4\pi}\Lambda_e \frac{\left[\mathbf{B}\times(\mathbf{B}\nabla)\mathbf{B}\right]}{B^2}\mathbf{e}_y$$

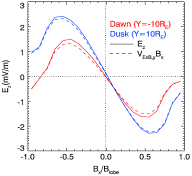


Polarized Thin Current Sheet: Models and MMS Observations



From *Baumjohann et al. AnnGeo*, 200

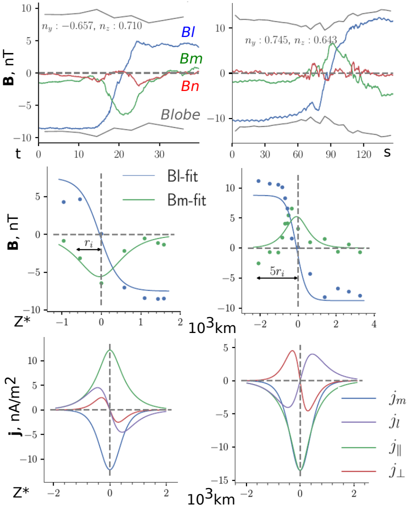




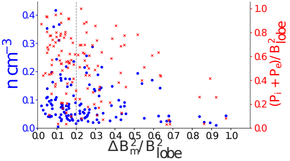
From *S. Lu et al. JGR*, 2019

- Intensive TCS are negatively charged
- Hall-type electric field normal to the TCS (E_{z*})
- Electric drifts strongly increase the electron contribution, and reduce the ion contribution to the cross-tail current density
  M.Hesse, D.Winske, and J.Birn, 1998
- Global hybrid simulations with the AuburN Global hybrId CodE in 3D (ANGIE3D): $E_{z*} \sim 1\,\mathrm{mV/m}$
- Do we observe it?
- Yes, we do. *Wygant et al., 2005*: Cluster observations at reconnection site
  S. Lu et al. 2019: MMS

What did We Lear from ARTEMIS? Thin Current Sheet Structure at Lunar Orbit:



(b)



From *S. Xu et al., 2018*

- B_y peak at $B_x \approx 0$;
- Low thermal pressure;
- Model to fit B-field data:

  $B_x = B_0 \tanh(z/\lambda)$

  $B_y = B_0 \cosh^{-1}(z/\lambda)$

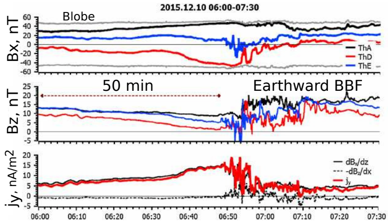
  Harrison & Neukirch, 2009
- $B_z \neq 0$: does such an equilibrium exist? What are self-consistent particle distributions?
- $\lambda \sim 10^3$ km$\sim \rho_{Li}$; $max(j_y) \sim 10$ nA/m^2 $\Rightarrow v_i \sim 300$ km/s: Newer observed!
- What is the nature of these field-aligned currents?

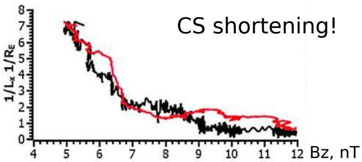
Chapter I: The Mystery of the Thin Current Sheet
Summary/ Open Questions/ Challenges

- The magnetotail current sheet thinning is non-uniform along the tail:
- Magnetic flux is evacuated from the near-tail, forming local B_z minimum where j_y maximizes.
- The magnetotail current sheet thinning is a global-scale kinetic process: the thin ($\lambda \sim \rho_{Li}$) and short ($L_x < 10\,\mathrm{R}_E$) polarized current sheet balanced by $\sim 100\,\mathrm{eV}$ anisotropic electrons is formed in the near-Earth plasma sheet;
- Current sheets with $\lambda \sim \rho_{Li}$ with partially field-aligned current at $j_y \sim 10\,\mathrm{nA/m^2}$ exist in the lunar-distant tail.

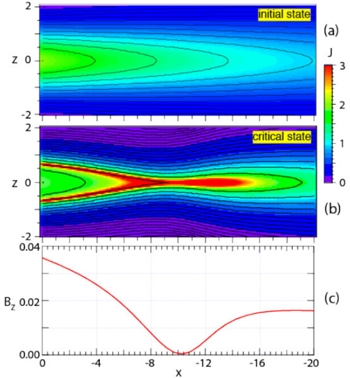
- How do the thin current sheet with increasing $\frac{\partial}{\partial x} B_z < 0$ remain stable during macroscopic time?
- What is the (kinetic) nature of intense current sheets observed far from the dipole at lunar distances?
- Non-classical (non-Grad-Shafranv) models are required.

Chapter II: The Mystery of Explosive Activity Onset





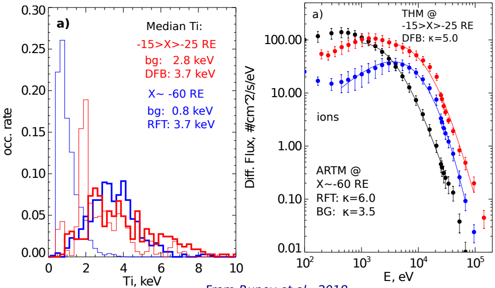
From *Artemyev et al., 2016*



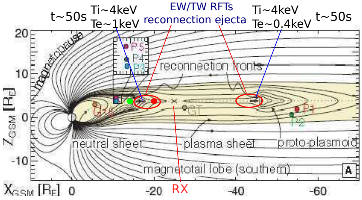
From *Sitnov et al. 2019, Birn et al., 2019*

- Is it the place where instability/reconnection occurs?
- No, likely not...

Where Does Reconnection/ Instability Occur?

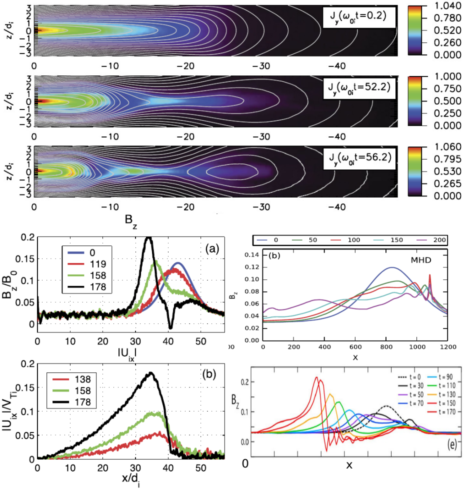


From *Runov et al., 2018*



- Geotail: RX @ $X \sim$-25 R_E *Nagai et al., 1998, 2005*
- Cluster 2001-2005 FY: 175 tail passes, 32 RX events @-20< X <-15 R_E *Eastwood et al., 2010*
- ARTEMIS: Typical RX location $\sim$ 30 R_E *Runov et al. 2018*
- If the maximum current density maximum at $X \sim$-10 --12 R_E why we do not observe RX there?

“B_z Hump” Instability

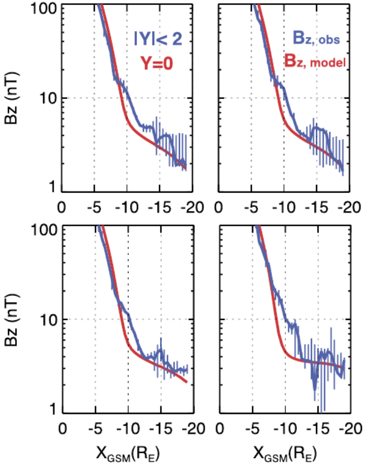


- Unstable is a configuration with local B_z maximum “B_z hump” (*Sitnov & Schindler, 2010*.
- PIC simulations:
  Sitnov et al., 2013;
  Bessho & Bhattacharjee, 2014,
  Pritchett, 2015
- MHD:
  Merkin et al., 2015; Birn et al., 2018
- Yes, the ”B_z hump“ configuration is, indeed, unstable
- Is it **the** solution?
- Did we ever observe it?

Did We Ever Observed the B_z Hump?

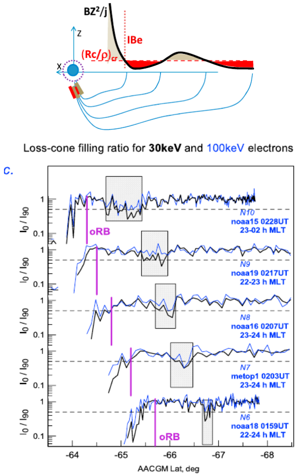
Yes, well, sorta...

- Statistics (Geotal & THEMIS)



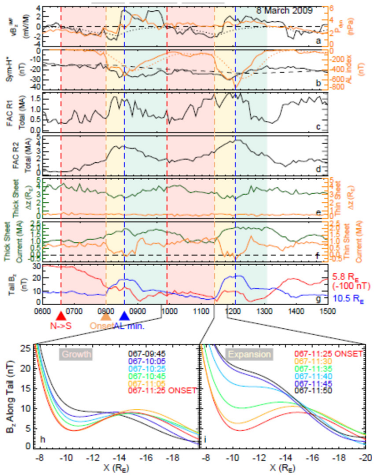
From *C. Yue et al., 2015*

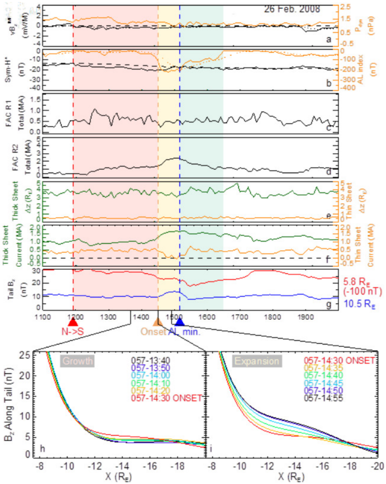
- Remote sensing w/POES



From *Sergeev et al., 2018*

Empirical Model



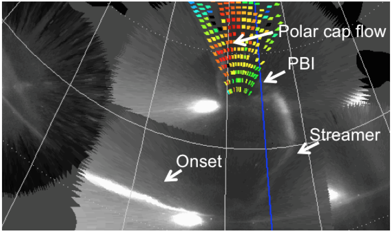


From *Stephens et al., 2019*

Chapter II: The Mystery of Explosive Onset
Summary/ Open Questions

- Apparently, the onset instability occurs tailward of the $min(B_z)$ and $max(j_j)$;
- It has been shown in simulations that the configuration with B_z "hump" is unstable;
- Observations suggest that B_z hump configuration indeed may exist.
- Is it the solution?
- How does the "hump" configuration form?

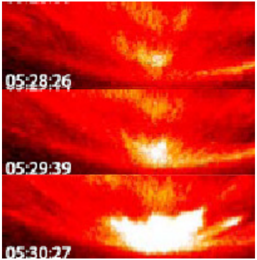
Chapter III: The Mystery of the Auroral Substorm



Courtesy *Y. Nishimura*

Detailed optical and radar observations:

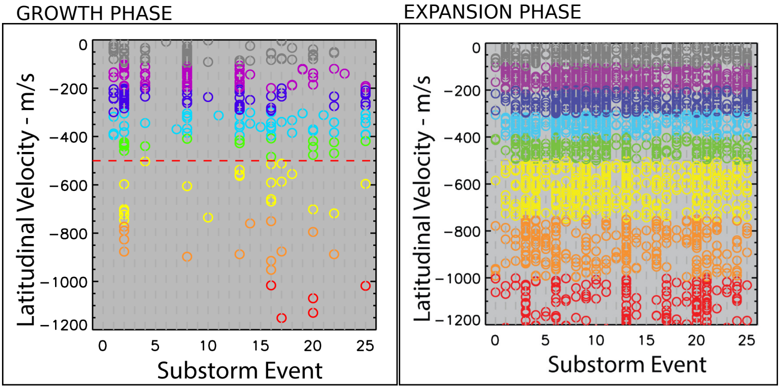
- Pre-existing stable auroral arc;
- Polar cup flows (equatorward and poleward)
- PBIs, streamers;
- Onset: brightening near the equatorward boundary of the auroral oval (*Nishimura et al., 2016*);
- Auroral streamers are often (not always) observed as precursor;



From *Kepko et al., 2009*

- Onset preceded by an equatorward patch that coincided with an earthward BBF in the near tail (*Kepko et al., 2009*);
- Streamers, patches do not correspond to the flow channels themselves but to upward FAC generated at the duskward edges of the flows (*Nakamura et al. 2001*)
- *Miyashita & Ieda (2018)*: Auroral streamers and related processes are not responsible for the initial brightening of onset arc;

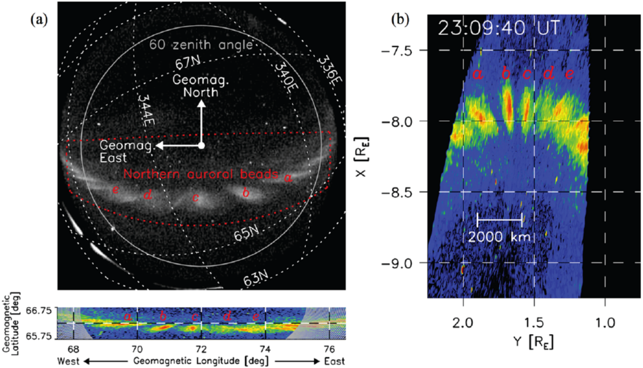
Attempts to Quantify Auroral Dynamics



Courtesy *K. Murphy*

- Analysis auroral dynamics during the growth and expansion phase of 26 substorms;
- Utilize image processing tools to track auroral forms and calculate velocities (*Grono et al., 2017*);
- Fast auroral forms, characteristic of streamers, are more likely to be observed during the expansion phase then during the growth phase of substorms

Auroral Beading



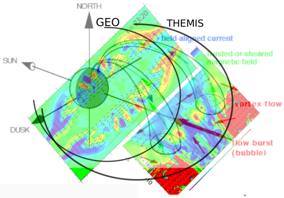
From *Motoba et al. 2012*

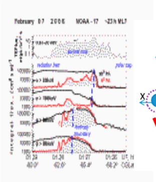
- observed most often along the east-west aligned arc minutes prior to the onset of auroral breakup (*Donovan et al. 2006; Liang et al. 2008; Sakaguchi et al. 2009; Motoba et al. 2012; Hosokawa et al. 2013; Kalmoni et al. 2015, 2017; Nishimura et al. 2016*)
- characteristic wavelength of ∼10–100 km
- likely caused by localized filamentary FAC structures
- temporal evolution suggests that they are driven by an instability in the tail
- 10 minutes before substorm onset, at a different location *Henderson et al., 2009*
- Mapping is an issue

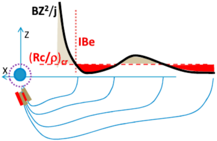
Chapter III: The Mystery of the Auroral Substorm Summary/ Open Questions

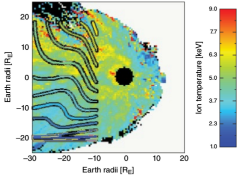
- Auroral streamers are often (but not always) observed as precursor activity prior to the initial brightening arc;
- Auroral beads/rays emerge along the arc near the auroral breakup region prior to auroral expansion onset;
- Auroral streamers and beads/rays are believed to be ionospheric manifestations of magnetotail processes, BBFs, instabilities;
- Mapping remains unsolved issue.
- What do pre-onset stable arc correspond to? What magnetotail processes lead to onset arc brightening?
- What are the relative roles of processes in the ionosphere, acceleration regions, and magnetotail plasma sheet for the formation of pre-onset auroral structures?

What do we need more: data, models, both?





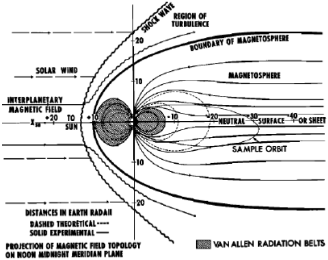




- Physics-based framework including global electrodynamics and plasma kinetics
- Data - model assimilation
- Measurements:
  - Multi-point measurements in the tail-dipole transition region
  - Remote sensing from LEO: $J_{\|}/J_{\perp}$ ratio (*Imhoff et al. 1977, Sergeev et al, 2018*). NOA A POES data were used. What's next? CubeSats (ELFIN*)
  - Imaging (TWINS ENA, *Keesee et al., 2011*)

Thank You!

The Mystery of the Magnetotail



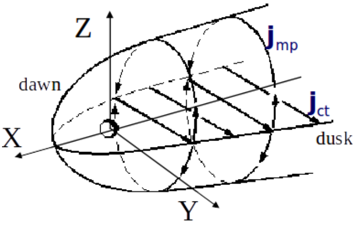
From *Ness et al., 1965*

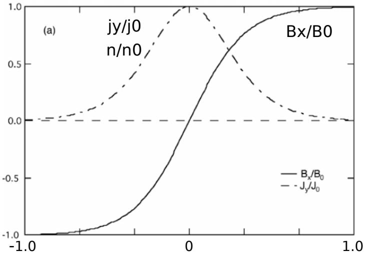
- **The Mystery of the Thin Current Sheet**
  Current sheet thinning: global-scale kinetic process. How to model it?

- **The Mystery of Explosive Onset**
  Thin current sheet with $B_z \rightarrow 0$ seems not enough for onset. Is B_z "hump" the solution?

- **The Mystery of the Auroral Substorm**
  If the ionosphere is a TV screen, who controls the channels?

the Simplest Magentotail Current Sheet Representation





- Nominal geometry: the electric current along Y_{GSM}, B_z is normal to the current sheet plane
- High-β region: $\beta > 1$

From textbooks:

- Typical CS thickness $\sim$1 - 3 R_E
- Cross-tail diamagnetic ($\perp$) current with density

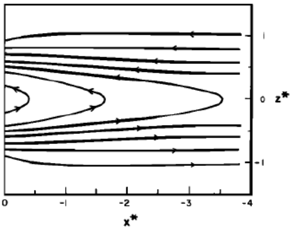
  $j_y = -\frac{c}{B_x}\frac{\partial p}{\partial z} \sim 1\,\text{nA/m}^2$
- Harris [1962] function

  $B_x = -\partial A_y/\partial z = B_0 tanh(z/\lambda)$

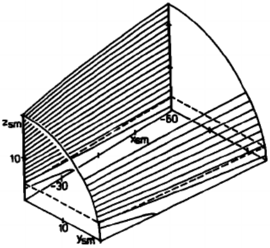
  $p = B_0^2/(8\pi) cosh^{-2}(z/\lambda)$

  scales of $\frac{\partial}{\partial z}B_x$ and $\frac{\partial}{\partial z}p$ are the same

Generalized Classical Magentotail Current Sheet Configuration



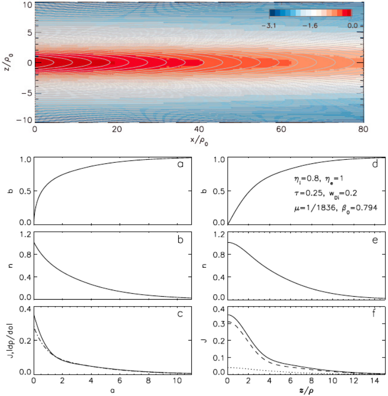
From *J.R.Kan*, 1973



From *J.Birn*, 1979

- Magnetic tension force balance:
  $B_z j_y = \sum_{\alpha=i,e} \left(\frac{\partial p_{\alpha\, xx}}{\partial x} + \frac{\partial p_{\alpha\, zz}}{\partial z} \right)$
  where $p_{\alpha\, m,n}$ is the plasma pressure tensor for the species α.
- Vector potential $\mathbf{A}$, $\nabla \times \mathbf{A} = \mathbf{B}$
- Grad-Shafranov equation:
  $\nabla^2 A_y = \frac{4\pi}{c} j_y = -c \sum_\alpha \frac{\partial P_\alpha}{\partial A_y}$
  where $p = \sum_{\alpha=i,e} \left(p_{\alpha\, xx} + p_{\alpha\, zz} \right) /2$
- p, j_y are functions of A_y and remain constant along $A_y = const$, $\nabla_{\|}$=0
- 3-D generalization *Birn, 1977, 1979*

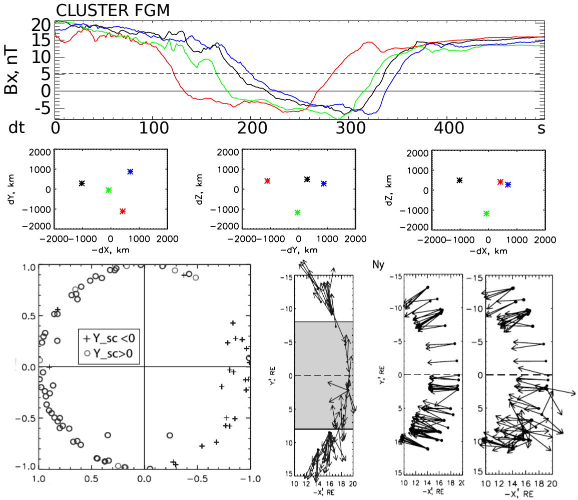
“Non-Classical” Current Sheet Models



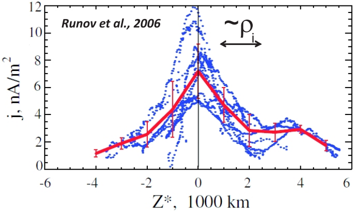
From *Sitnov and Merkin, 2016*

- Observational challenges:
  - the magnetotail CS thickness may be $\sim 1\rho_L$ (TCS)
  - TCS are embedded into thicker CS (different j and p scales)
- GS approximation is not valid: $\frac{4\pi}{c} j_y \neq \frac{\partial P_\alpha}{\partial A_y}$
- Anisotropic pressure of adiabatic electrons with $p_{e\|} \neq p_{e\perp} \Rightarrow$ curvature force $(p_{e\|} - p_{e\perp})[\mathbf{B} \times (\mathbf{B}\nabla)\mathbf{B}]/B^2$ *e.g., Egedal et al., 2013*
- Quasi-adiabatic ion motion to balance the magnetic tensions *Sitnov et al. 2000, 2003; Sitnov&Merkin, 2016*

Current Sheet Crossings due to Rapid Flapping: the Way to Scan CS Structure

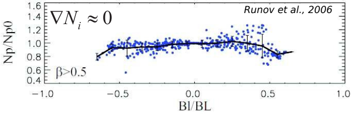


Vertical profiles of *flapping* current sheet.

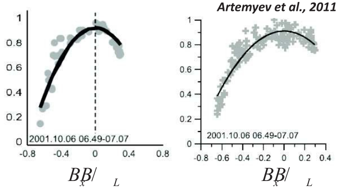


- CS is typically embedded into thicker PS;
- CS thickness is comparable to suprathermal ion gyroradius;
- Current density $j = \mu_0^{-1}|\nabla \times \mathbf{B}| \sim 5$ - 10 nA/m^2, that requires $v_D = j/n_i \sim 100$ km/s.

  Never observed!

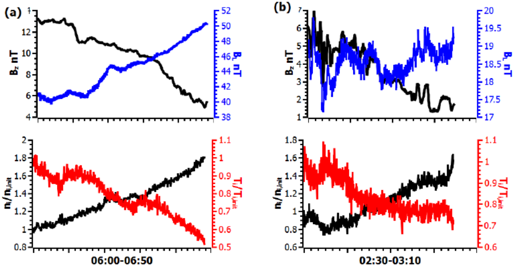


$$\nabla P_i \approx N_i \nabla T_i, \quad \nabla P_e \approx N_e \nabla T_e$$



- A weak density gradient in CS
- Stronger temperature (T_i and T_e) gradient.

Current Sheet Thinning: Temperature and Density THEMIS/ARTEMIS Observations



From *Artemyev et al., 2019*