Field Line Resonance in "Tuna Half" Dimensions

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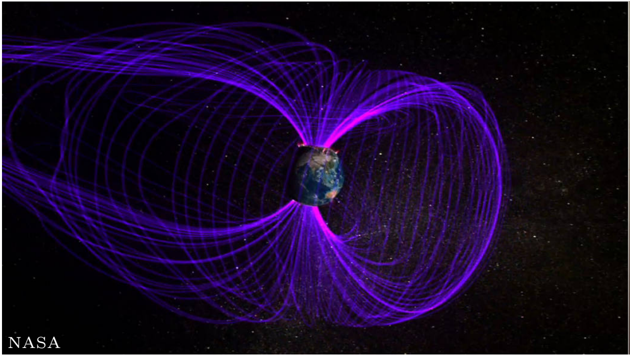
Summary

- Field line resonances (FLRs) have been shown to exhibit a mishmash of as-yet unrelated properties.
- Tuna is a new two-and-a-half-dimensional simulation created with FLRs in mind.
- Numerical results from Tuna suggest novel connections between several FLR properties.
- A survey of Van Allen Probes data shows good agreement with numerical results.

Earth's Magnetic Field

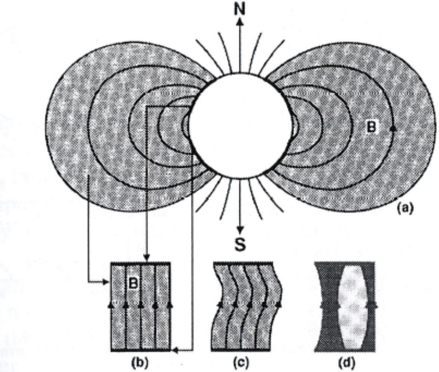
When shaken by the solar wind, etc, Earth's magnetic field lines rattle.


NASA


Flóra Borsi

Alfvén Waves

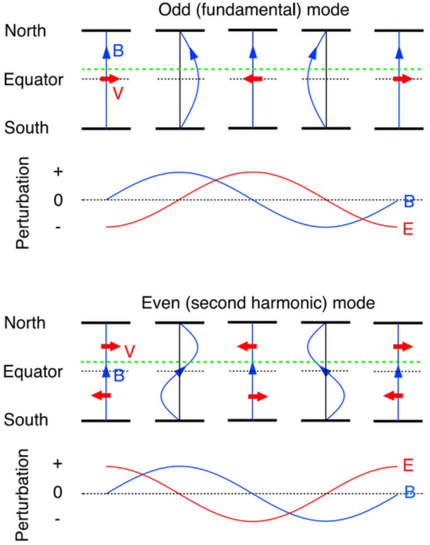
- Shear Alfvén waves carry energy along magnetic field lines.
- Compressional Alfvén waves can carry energy across field lines.
- A field line resonance (FLR) is a shear Alfvén wave with a frequency that matches the Alfvén bounce frequency.



Kivelson and Russell

First and Second Harmonics

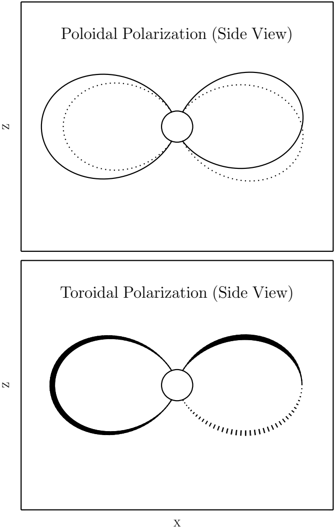
- First harmonic — the entire magnetic field line moves together.
- Second harmonic — the northern and southern halves of the magnetic field line move opposite one another.
- A changing magnetic field creates an electric field.



Adapted from Takahashi et al, 2011

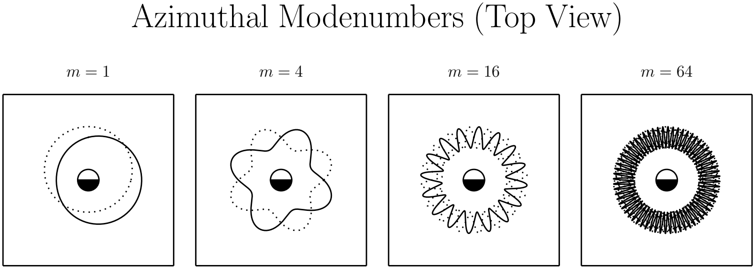
Poloidal and Toroidal Polarizations

- Poloidal wave — the magnetic field line pulses in and out.
- Toroidal wave — the magnetic field line twists in the azimuthal direction.
- Corresponding electric fields are flipped.



Azimuthal Modenumber

- Small azimuthal modenumber means the wave extends broadly around the equator.
- Large modenumber means the wave could fit many times around the equator.
- Small-m and large-m waves behave differently.



Pc4s and Giant Pulsations

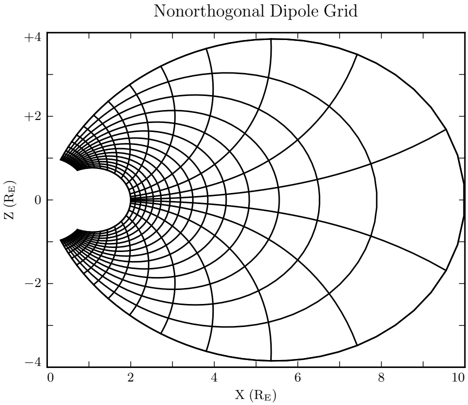
- Pc4 pulsations (7 mHz to 22 mHz) resonate at auroral latitudes.
- They interact with trapped energetic particles.
- Giant pulsations are a small, distinctive subset of Pc4s.

IAGA Frequency Bands [Jacobs, 1964]

	Pc1	Pc2	Pc3	Pc4	Pc5
Period (s)	0.2–5	5–10	10–45	45–150	150–600
Frequency (mHz)	200–5000	100–200	22–100	7–22	2–7

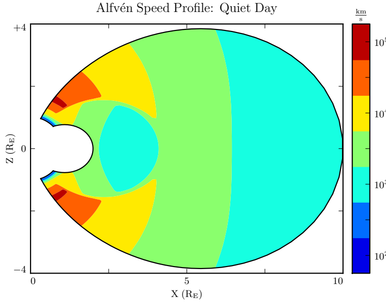
"Tuna Half" Dimensional Model

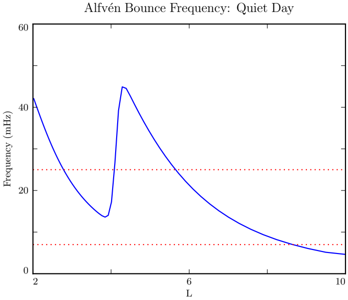
- Near Earth, at high m, 3D is too expensive.
- Simplifying assumption: 2D grid, fields go as $\exp(im\phi)$.
- Then $\frac{\partial}{\partial\phi} \rightarrow im$ allows 3D fields and 3D derivatives.



Physical Parameter Profiles

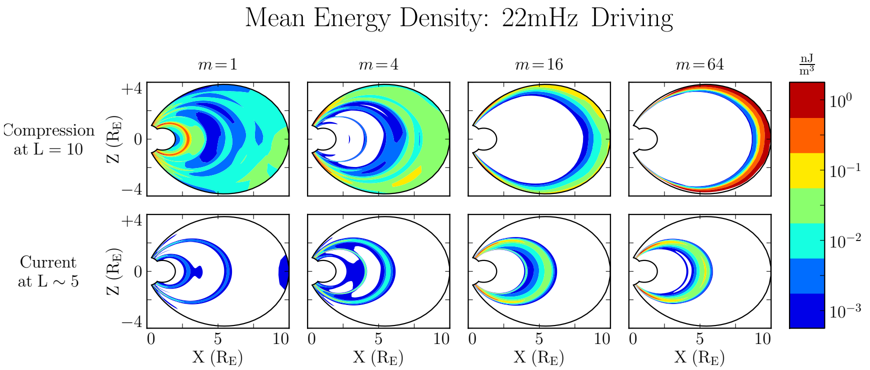
- Height-resolved conductivity from Kelley, modified by Lysak.
- Plasma density, including the plasmasphere.
- Alfvén speed from dipole field and density: $v_A \equiv \frac{B}{\sqrt{\mu_0 \rho}}$
- Four profiles: active day, quiet day, active night, quiet night.





Driving — Compression or Current?

- At high m, driving at the outer boundary doesn't work.
- Tuna drives by perturbing the ring current instead.



Maxwell's Equations

Electric fields are updated using Ampère's law and Ohm's law:

$$\underline{\underline{\epsilon}} \cdot \frac{\partial}{\partial t}\underline{E} = \frac{1}{\mu_0}\nabla \times \underline{B} - \underline{J} - \underline{\underline{\sigma}} \cdot \underline{E}$$

Let $\quad \underline{\underline{V}}^2 \equiv \frac{1}{\mu_0}\underline{\underline{\epsilon}}^{-1} \quad$ and $\quad \underline{\underline{\Omega}} \equiv \underline{\underline{\epsilon}}^{-1} \cdot \underline{\underline{\sigma}} \quad$ so

$$\left(\underline{\underline{\Omega}} + \underline{\underline{\mathbb{I}}}\frac{\partial}{\partial t}\right) \cdot \underline{E} = \underline{\underline{V}}^2 \cdot \left(\nabla \times \underline{B} - \mu_0 \underline{J}\right)$$

Which can be solved with an integrating factor:

$$\boxed{\underline{E} \leftarrow \exp\left(-\underline{\underline{\Omega}}\,\delta t\right) \cdot \underline{E} + \delta t\, \exp\left(-\underline{\underline{\Omega}}\,\frac{\delta t}{2}\right) \cdot \underline{\underline{V}}^2 \cdot \left(\nabla \times \underline{B} - \mu_0 \underline{J}\right)}$$

Magnetic fields are updated using Faraday's law:

$$\frac{\partial}{\partial t}\underline{B} = -\nabla \times \underline{E} \qquad \text{so} \qquad \boxed{\underline{B} \leftarrow \underline{B} - \delta t\, \nabla \times \underline{E}}$$

Coupling to the Atmosphere

- Assume a perfectly-insulating atmosphere: $\nabla \times \underline{B} = 0$.
- From Maxwell's equations, $\nabla \cdot \underline{B} = 0$.
- Then $\nabla^2 \Psi = 0$ where $\nabla \Psi = \underline{B}$.
- Solution at the top of the atmosphere is a boundary condition:

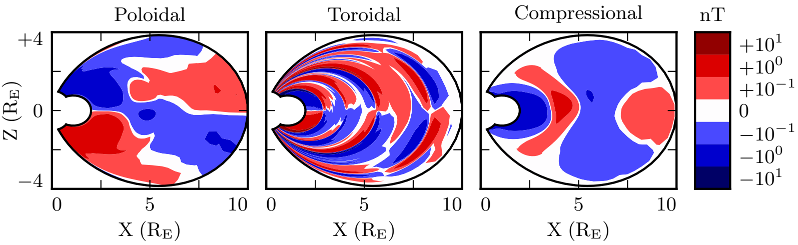
$$\underline{\underline{\Sigma}} \cdot \underline{E} = \frac{1}{\mu_0} \lim_{\delta r \to 0} \left[\hat{r} \times \underline{B} \right|_{R_I - \delta r}^{R_I + \delta r}$$

- Solution at the bottom of the atmosphere gives ground signatures.

Snapshots of a Low-m Simulation

- Poloidal and compressional waves are blobby.
- Toroidal waves are sharply defined.
- All components are similar in magnitude.

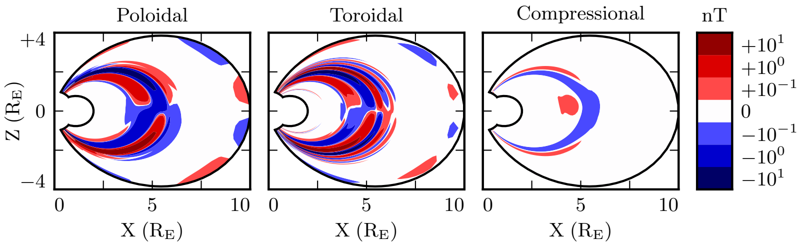
Magnetic Field Snapshots at 300s: Quiet Day , 22mHz Current, $m = 2$



Snapshots of a High-m Simulation

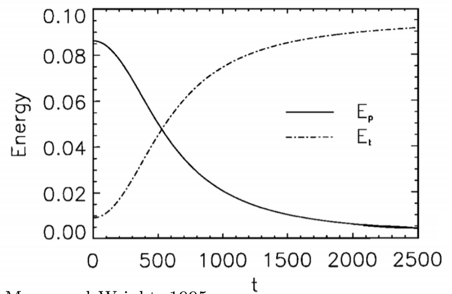
- Waves are barely compressional.
- Little energy crosses field lines.
- Poloidal waves are less smeared than at $m = 2$, but still not as sharp as toroidal waves.

Magnetic Field Snapshots at 300s: Quiet Day , 22mHz Current, $m = 32$

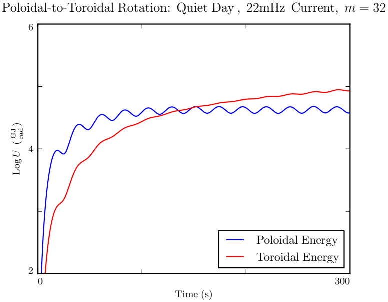


Poloidal-to-Toroidal Rotation

- Polarization rotates over time from poloidal to toroidal.
- The rotation is slower at large m.

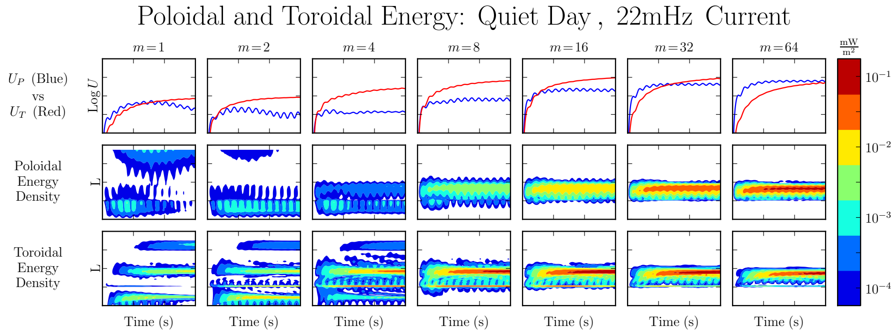


Mann and Wright, 1995



Resonance and Rotation on the Dayside

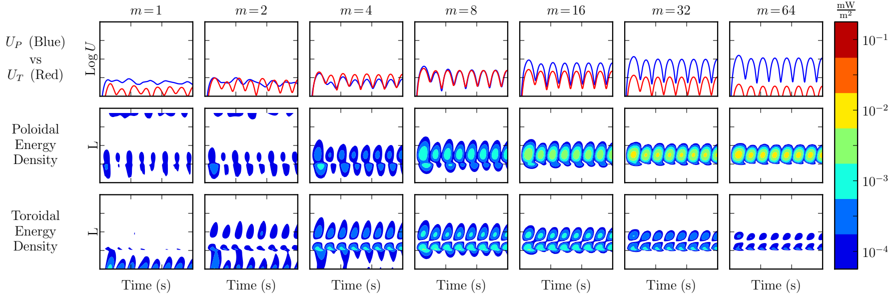
- Poloidal-to-toroidal rotation is fast compared to dissipation.
- Toroidal energy accumulates only where resonant.
- At small m, energy escapes to the outer boundary.



Resonance and Rotation on the Nightside

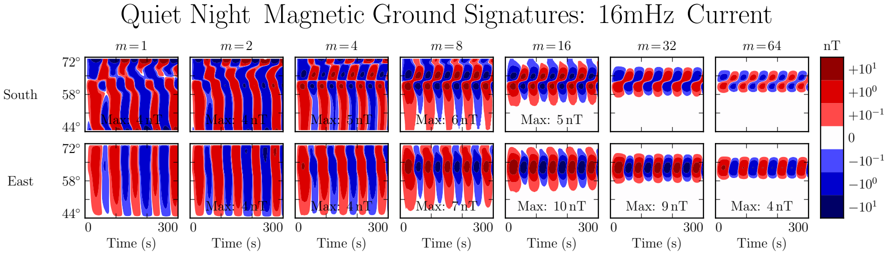
- The nightside ionosphere is much less conductive than the dayside ionosphere.
- No accumulation of energy over multiple drive periods.
- At high m, dissipation is faster than poloidal-to-toroidal rotation.

Poloidal and Toroidal Energy: Quiet Night , 13mHz Current



Ground Signatures and Giant Pulsations

- Peak at $m = 16$ to 32, near 65° latitude.
- Counterclockwise at low latitude, clockwise at high latitude.
- It seems these properties are not unique to giant pulsations!



Results from the Numerical Model

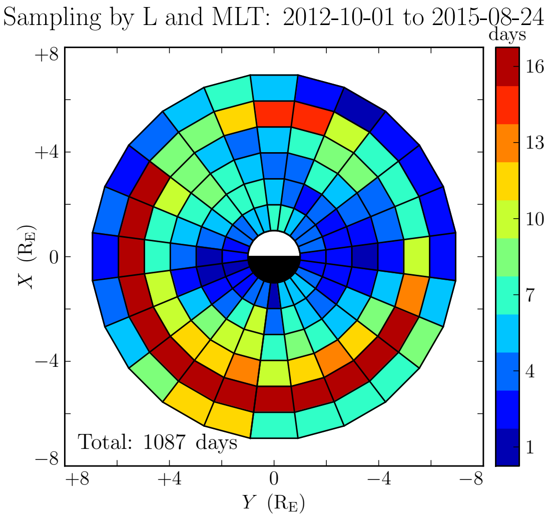
- Toroidal frequencies depend sharply on L because toroidal FLRs are sharp in L — unlike poloidal FLRs, which are smeared.
- At least in terms of m, latitude, and chirality, giant pulsations are not as distinctive as they are made out to be.
- Poloidal-to-toroidal rotation is fast — the poloidal mode is a significant source for same-harmonic toroidal waves.
- Resonance on the nightside is significantly impeded by Joule dissipation in the ionosphere.

Comparison to Observational Data?

- How does the spatial distribution of giant pulsations compare to that of odd poloidal Pc4s overall?
- How does the distribution of odd toroidal Pc4s compare to that of odd poloidal Pc4s?
- How about even toroidal and even poloidal Pc4s?
- We can address these questions with the Van Allen Probes.

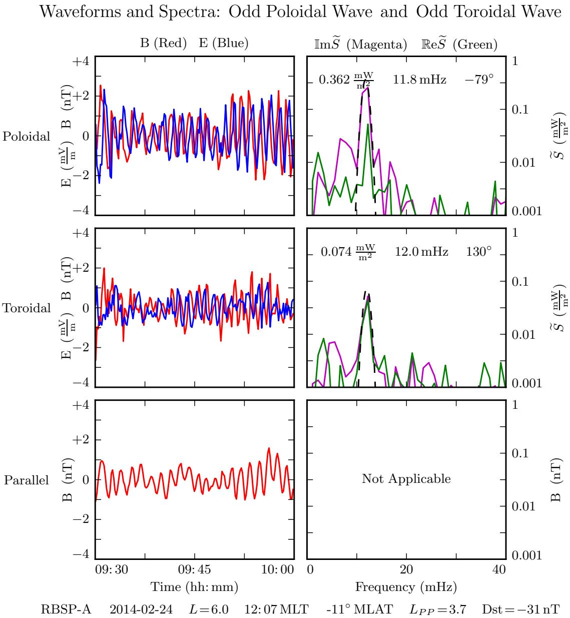
Distribution of Usable Data

- Data spans October 2012 to August 2015.
- Nightside has been sampled twice at apogee.
- Full 3D fields computed per $\underline{E} \cdot \underline{B} = 0$, about half the data gets tossed.



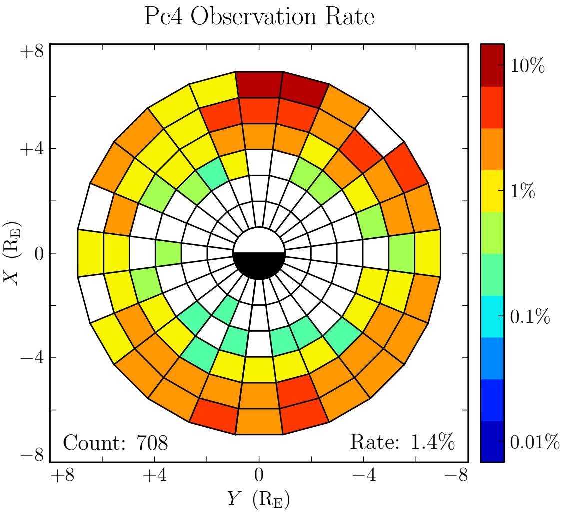
Event Selection

- Split data into half-hour events.
- Compute Poynting flux spectrum.
- Threshold on frequency, magnitude, etc.
- Classify events by polarization and harmonic.



Pc4 Observation Rate

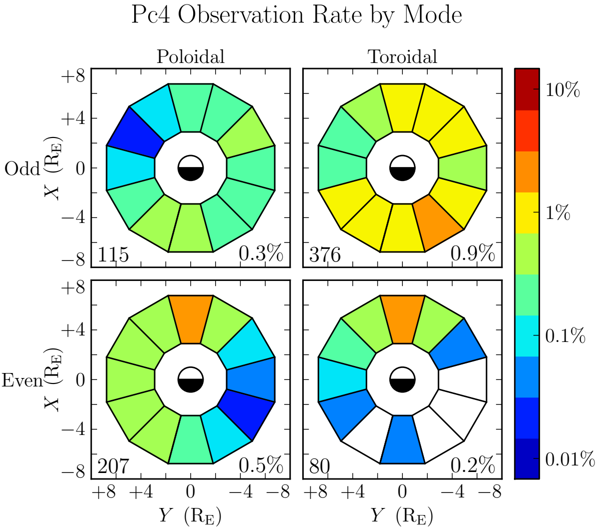
- Peak observation rate at noon.
- Fewest events at dusk.
- Stragglers near midnight.
- Generally consistent with previous surveys of Pc4 events.



Pc4 Observation Rate by Mode

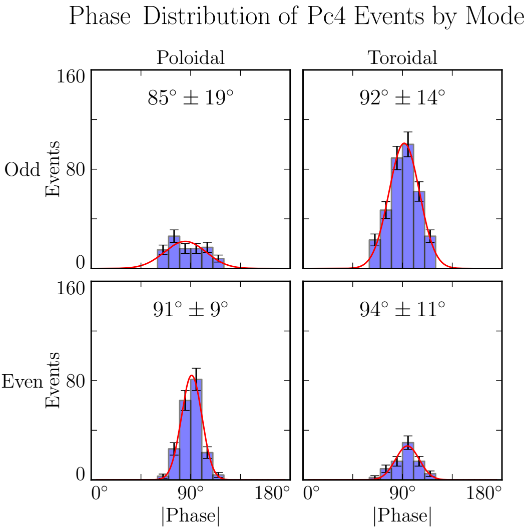
Questions from before:

- Where are odd poloidal Pc4s compared to giant pulsations?
- Where are odd toroidal Pc4s compared to odd poloidal Pc4s?
- How about even toroidal and even poloidal Pc4s?



Phase Distribution of Pc4 Events

- Perfect standing waves have a phase of $\pm 90°$.
- The further from $\pm 90°$, the shorter the wave lifetime.
- Direct phase measurements are new and exciting!



Summary

- Pc4s and giant pulsations have been shown to exhibit a mishmash of heretofore-unrelated properties.
- Tuna is a new two-and-a-half-dimensional simulation created with these waves in mind.
- Numerical results from Tuna suggest novel connections between several FLR properties.
- A survey of Van Allen Probes data shows good agreement with numerical results.

Thanks!

Committee:

- Bob Lysak (Advisor)
- Cindy Cattell (Chair)
- Tom Jones
- Lindsay Glesener

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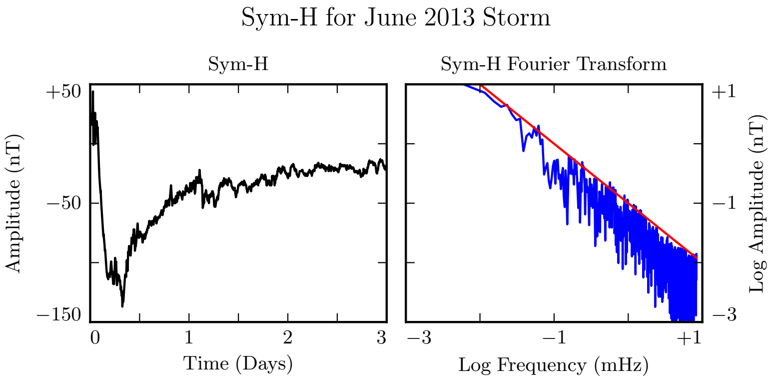
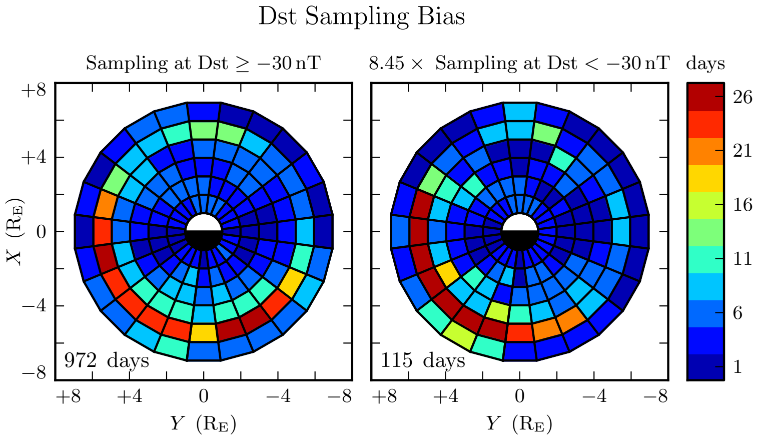
Collaborators:

- John Wygant
- Dai Lei
- Ian Mann
- Aaron Breneman
- Scott Thaller
- Sheng Tian

Estimating Current from Sym-H



Van Allen Probe Sampling by Dst



Dawn-Dusk Asymmetry