# Impact of High-Speed Stream Structures on Thermospheric Response: Solstitial and Equinoctial Events

Ryan M. McGranaghan* and Delores J. Knipp*†
*Colorado Center for Astrodynamics Research
University of Colorado at Boulder

†High Altitude Observatory
National Center for Atmospheric Research

Robert L. McPherron
Department of Earth, Planetary, and Space Sciences
University of California Los Angeles

Linda A. Hunt
Space Systems and Applications, Inc.

McGranaghan, R. et al. (2014), Impact of equinoctial high-speed stream structures on thermospheric responses, Space Weather, 12, 277-297, doi: 10.1002/2014SW001045

Acknowledgement:
Research supported by NSF Graduate Research Fellowship

# Background

Colorado Center for Astrodynamics Research

University of Colorado
Boulder, Colorado

Solar wind Alfvénic fluctuations appear to dominate magnetospheric response to high speed streams (HSSs)

We show other factors modulate thermospheric neutral density response to HSSs

- These factors are rooted, not in HSSs, but in streamer structures
- Consider the flow regimes surrounding CIRs and the stream interface - will use 'CIR-HSS' to describe overall disturbance in the flow

We characterize the response from:

- Specific structures at the sun and their extension into solar wind
- Geomagnetically-sensitive observations

Analyze 66 solstice CIR-HSS events spanning 2002-2008

Validate with 211 equinox CIR-HSSs in the same interval

# Corotating Interaction Regions

Colorado Center for Astrodynamics Research

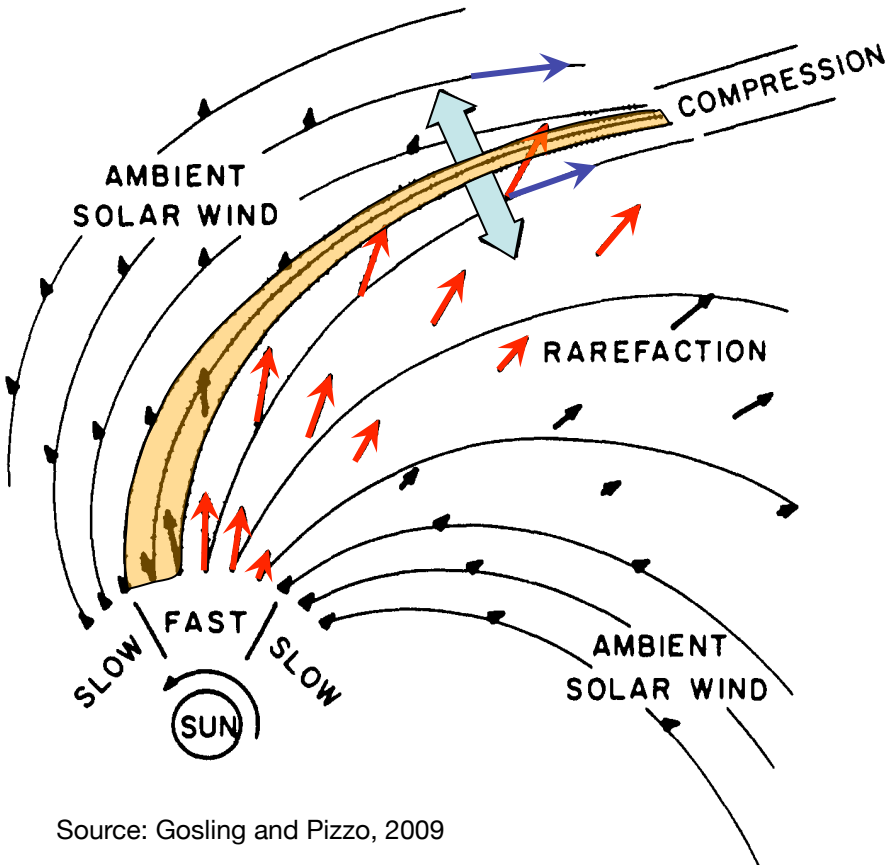
University of Colorado
Boulder, Colorado

High speed stream (HSS) emanates from coronal hole

Overtakes ambient slow speed and forms compression region corotating with sun (corotating interaction region - CIR)

Flow regimes surrounding CIR + CIR itself = CIR-HSS

Sharp, but usually moderate, geomagnetic activity enhancement




Source: Gosling and Pizzo, 2009

# Corotating Interaction Regions

Colorado Center for Astrodynamics Research

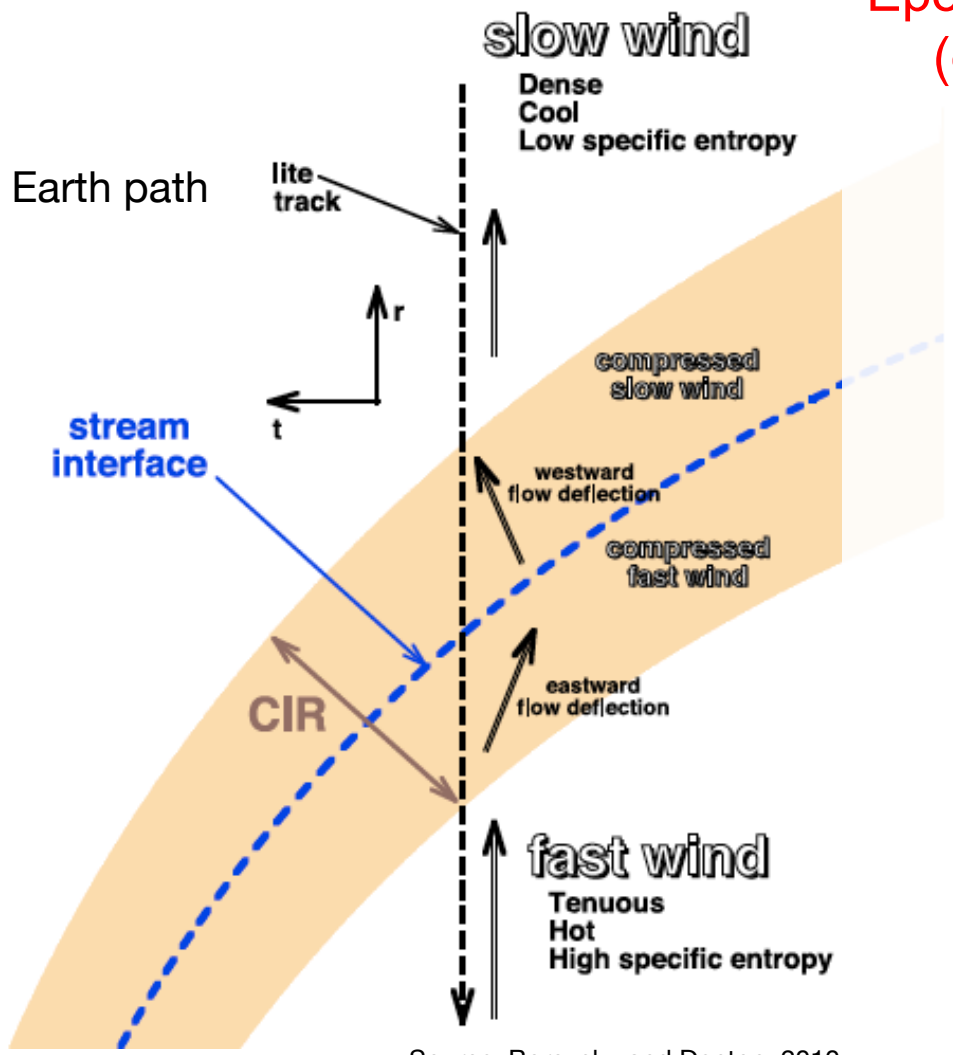
University of Colorado
Boulder, Colorado

Use Superposed Epoch Analysis (SEA)

- Keyed to stream interface crossing at Earth
- Zero epoch is zero-crossing of azimuthal flow angle

Ensemble Array

[time steps x num events]
[ 1728 x num events]




Source: Borovsky and Denton, 2010

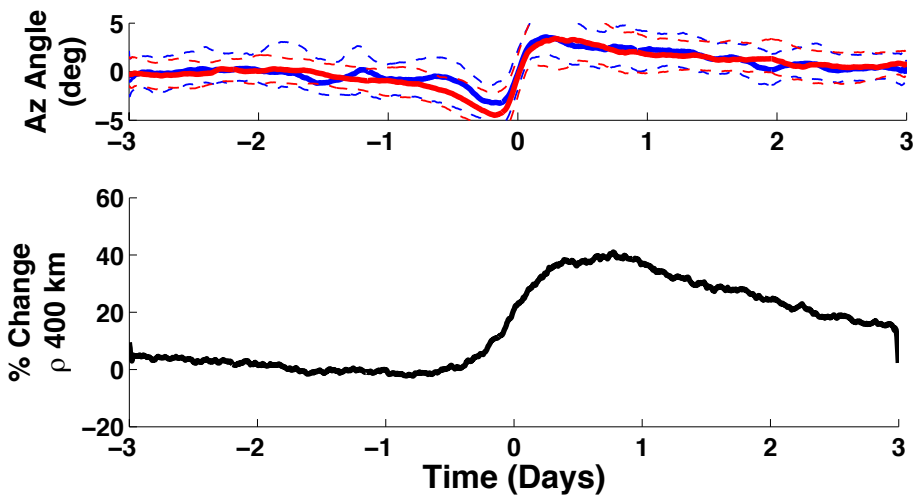
# Corotating Interaction Regions

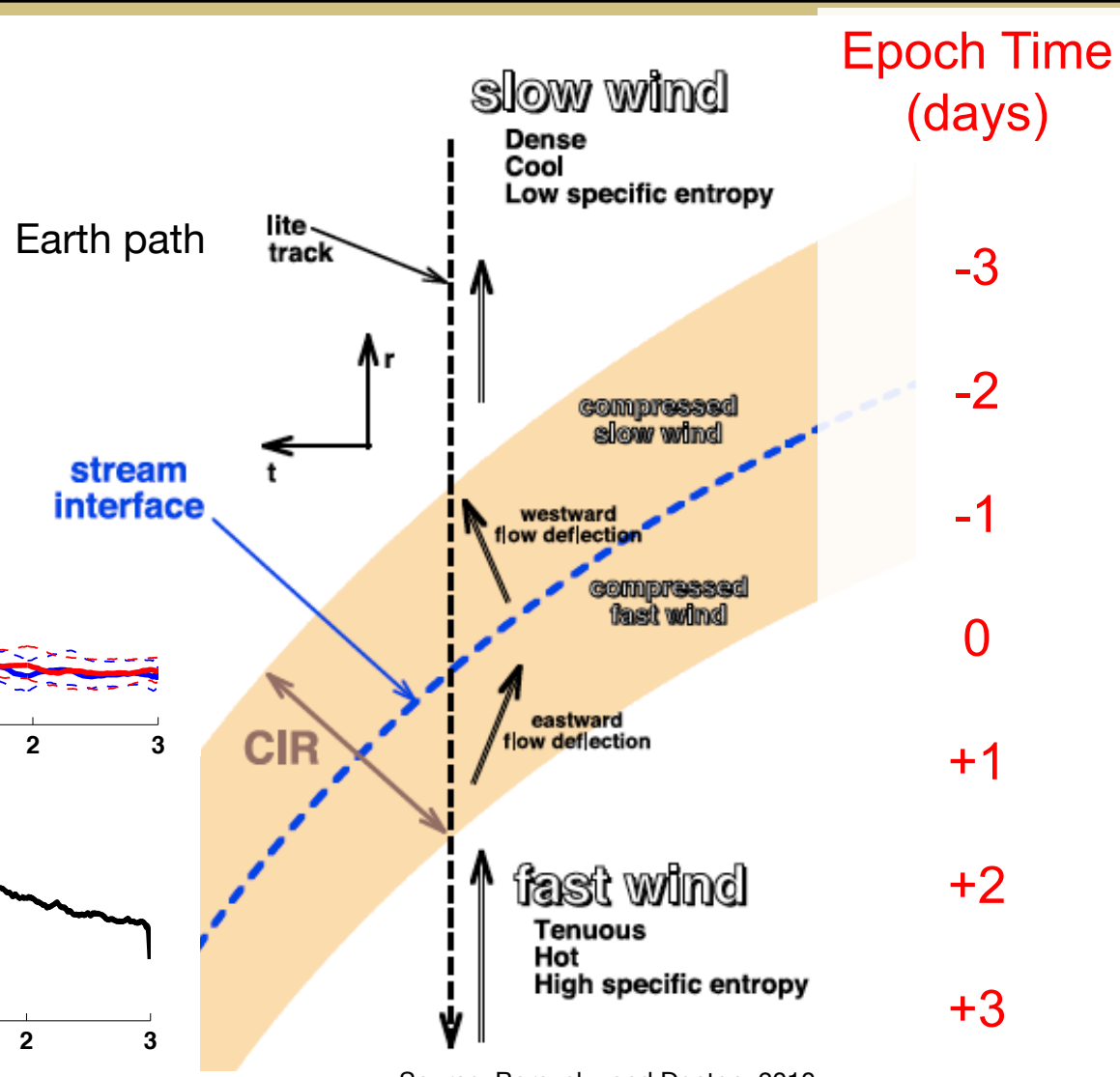
Colorado Center for Astrodynamics Research

University of Colorado
Boulder, Colorado

Use Superposed Epoch Analysis (SEA)

- Keyed to stream interface crossing at Earth
- Zero epoch is zero-crossing of azimuthal flow angle




Source: Borovsky and Denton, 2010

# Corotating Interaction Regions

Colorado Center for Astrodynamics Research

University of Colorado
Boulder, Colorado

Recurrent HSSs ➔ seasonal variation in neutral density

- Internal to thermosphere
- External to thermosphere

Analyze SC 23 decline/minimum

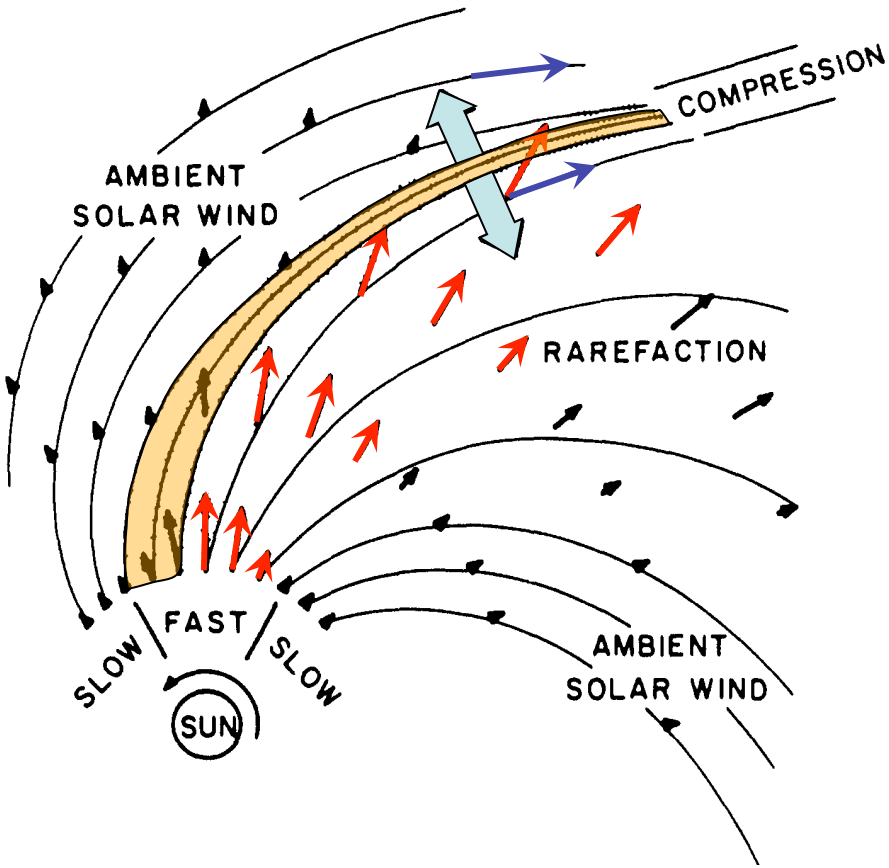
Classify CIR-HSS according to:

- Coronal/solar wind structuring and Russell-McPherron effect

Trace the activity

- from specific solar structures,
- into the solar wind,
- through geomagnetically-sensitive observations

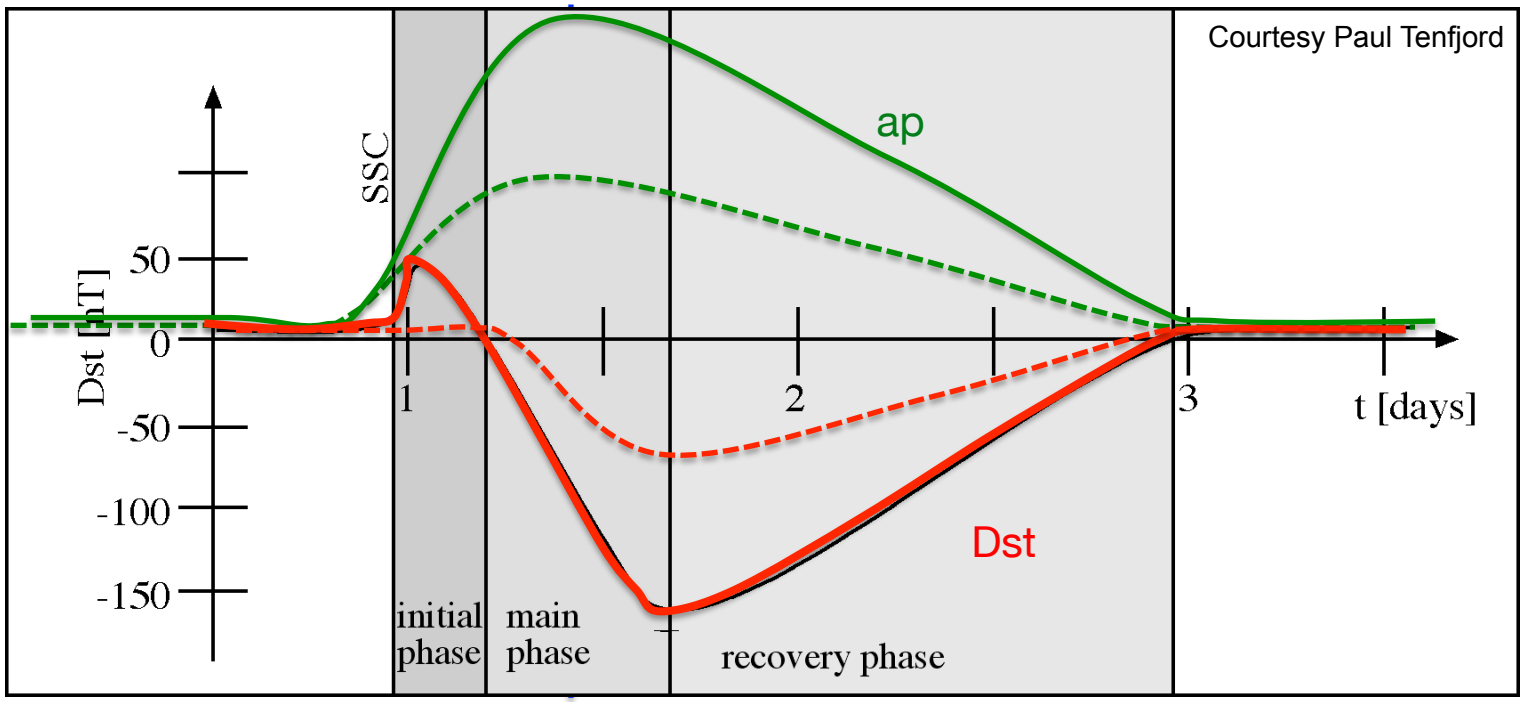
Propose neutral density effects of CIR-HSSs can be anticipated days in advance of Earth arrival

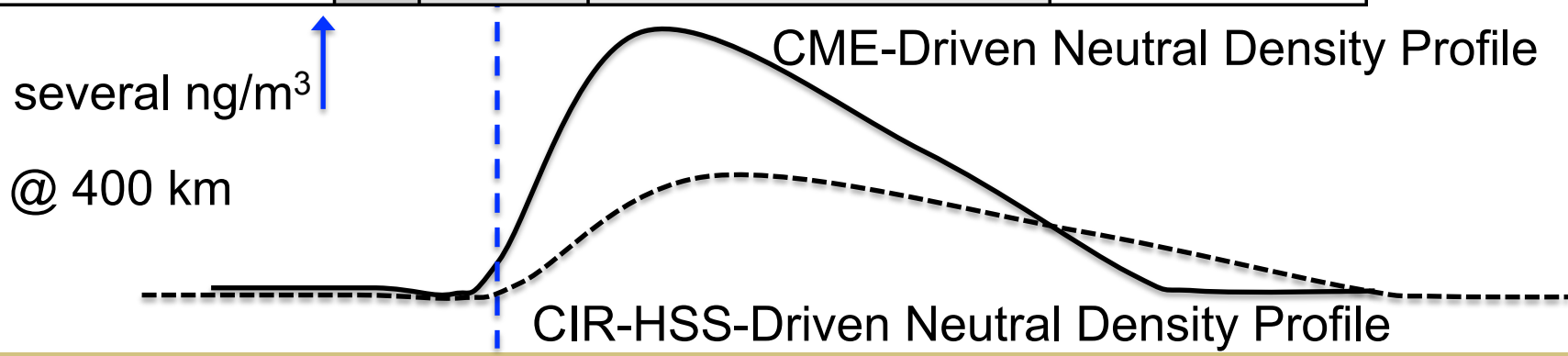


# Indice and Neutral Density Response to CIRs and High Speed Streams

Colorado Center for Astrodynamics Research

University of Colorado
Boulder, Colorado



# Solstice: One Level of Effect

Colorado Center for Astrodynamics Research

University of Colorado
Boulder, Colorado

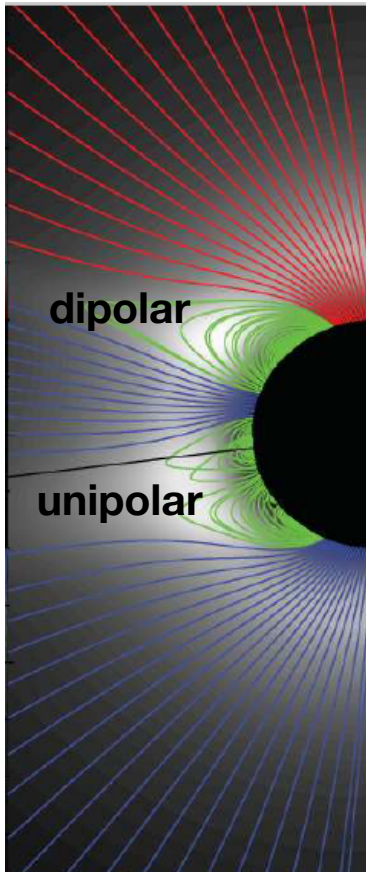
**Season:** Solstice - Equinox

**Helmet Streamers**

- Separate opposite-polarity coronal holes
- 'Smooth' structure causes heliospheric current sheet (HCS) crossing

**Pseudo-Streamers**

- Separate like-polarity coronal holes
- More structured; no HCS
- Smaller-scale 'web-like' structures of slow flow
  - More interaction with previous stream?



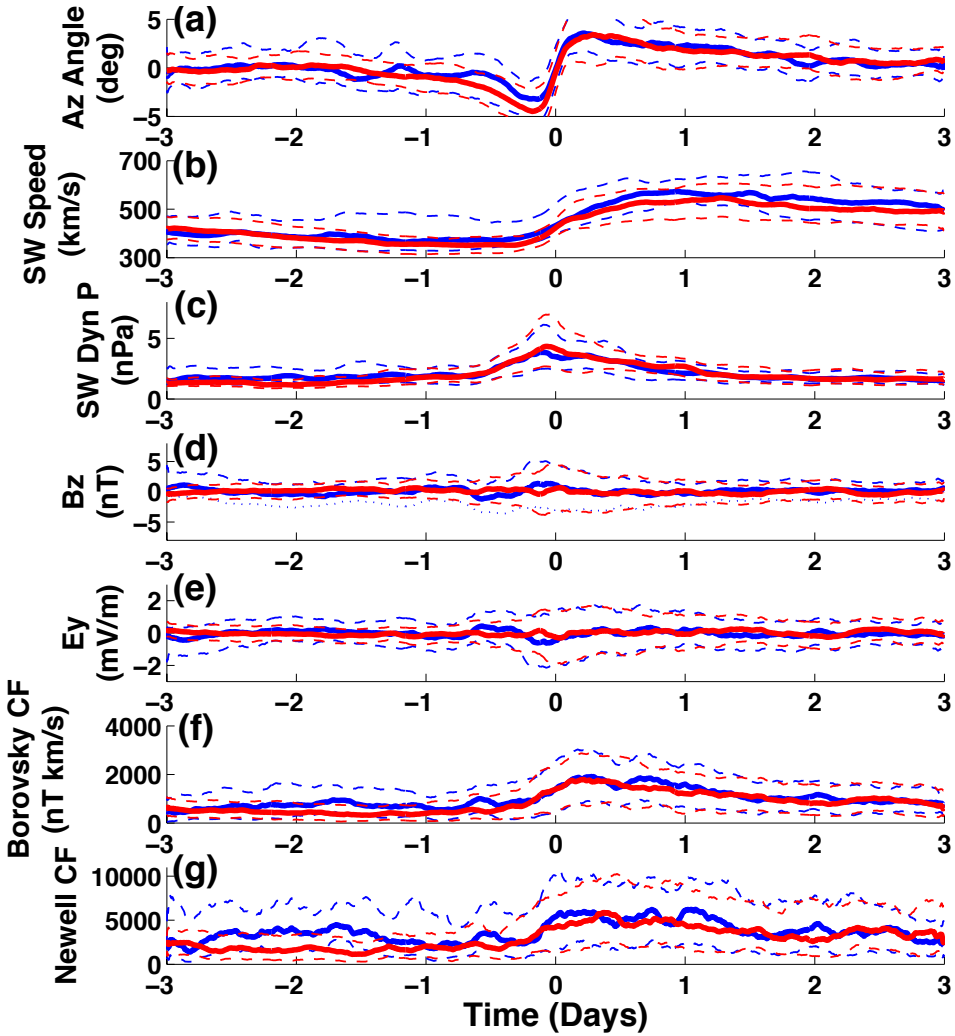

Source: Riley and Luhmann, 2012

# Helmet and Pseudo-Streamers: Solstice

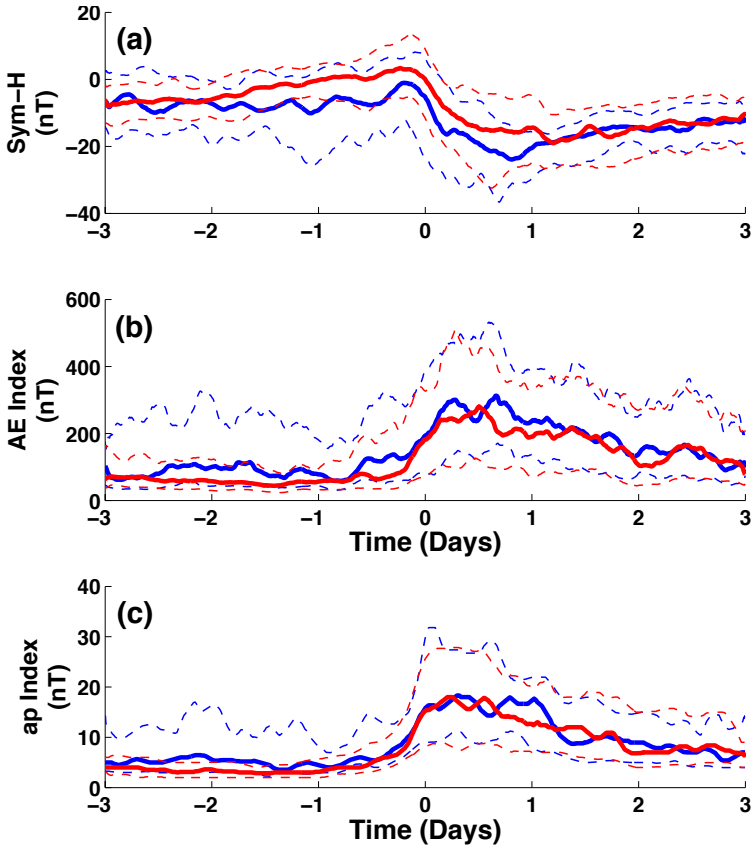
Colorado Center for Astrodynamics Research

University of Colorado
Boulder, Colorado

## Solar Wind Data: HS-solstice, PS-solstice




## Solar/GEO Indices: HS, PS



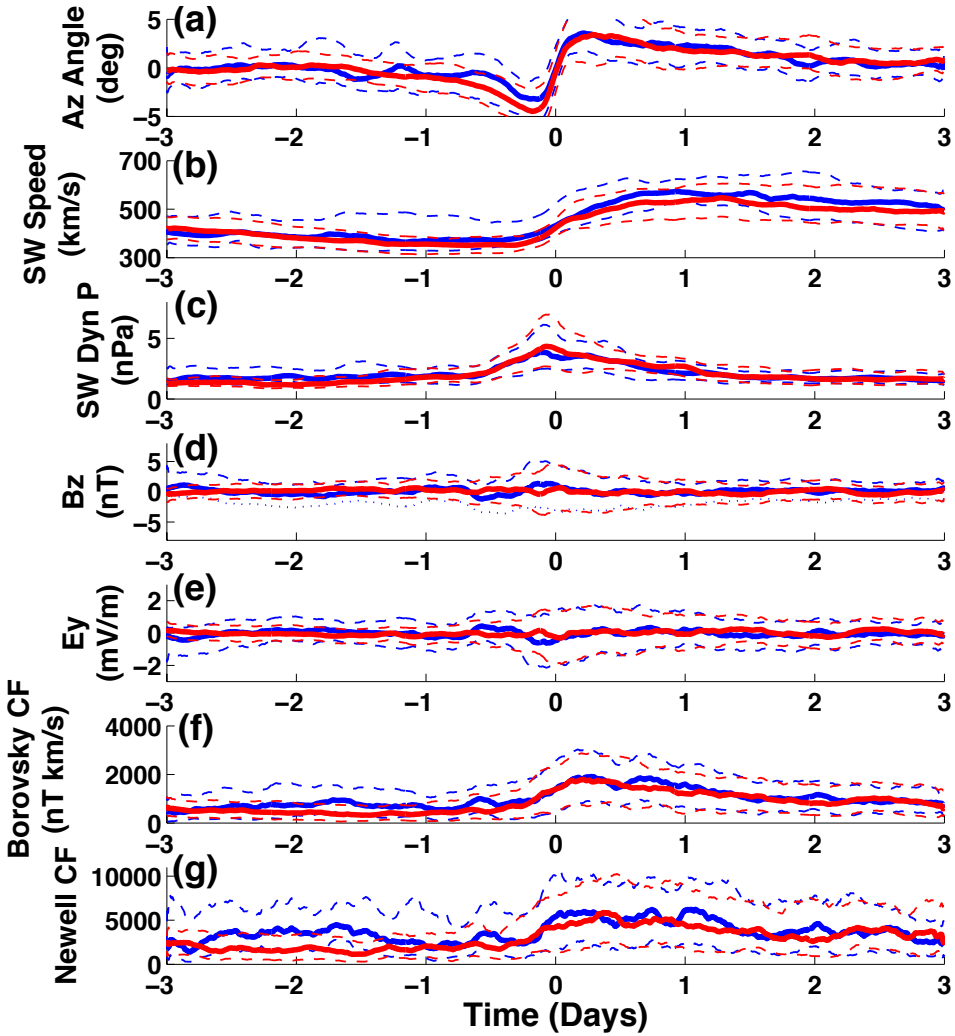

66 solstice CIR-HSSs
43 HS, 23 PS

# Helmet and Pseudo-Streamers: Solstice

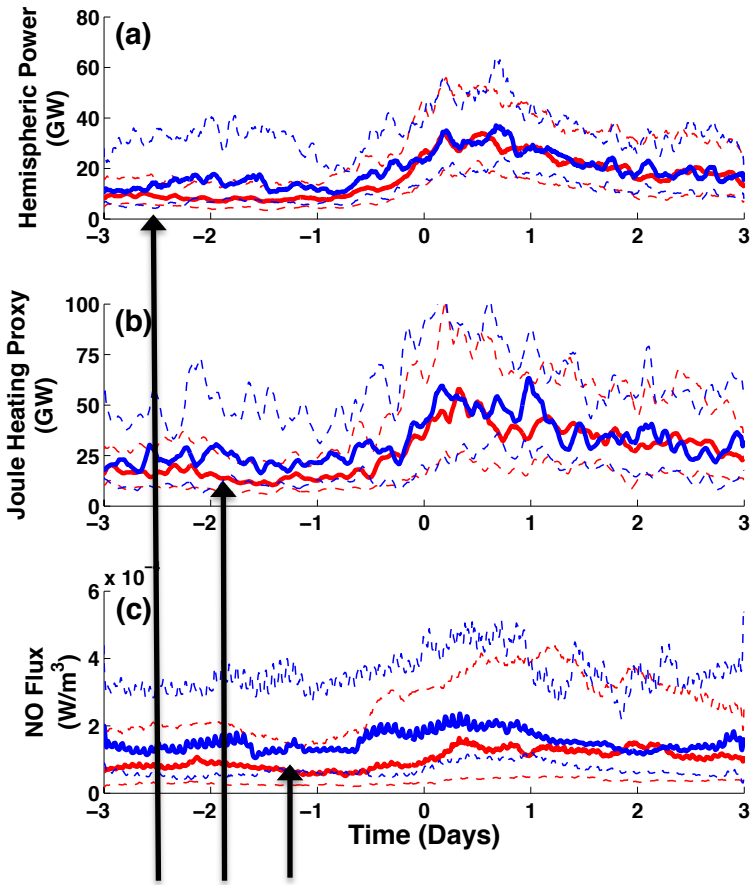
Colorado Center for Astrodynamics Research

University of Colorado
Boulder, Colorado

## Solar Wind Data: HS-solstice, PS-solstice




## HP, JHP, and NO Flux: HS, PS



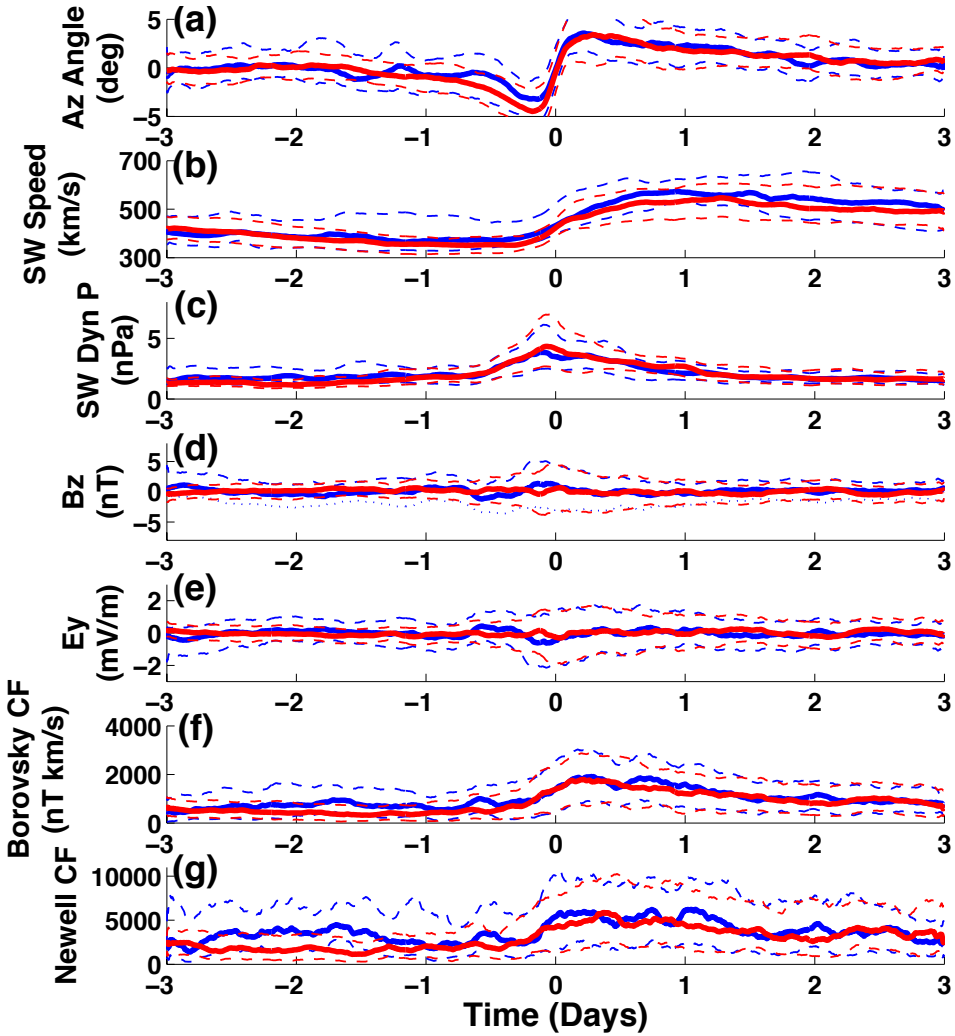

More intense Alvénic fluctuations for pseudo-streamers causing more perturbed preconditioning of iono/thermosphere

# Helmet and Pseudo-Streamers: Solstice

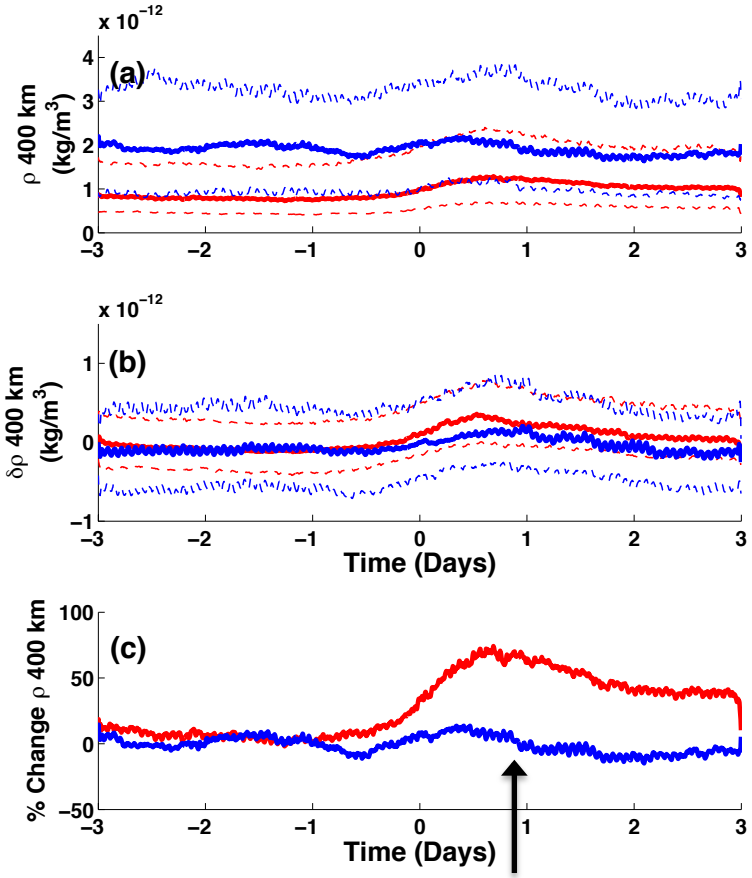
Colorado Center for Astrodynamics Research

University of Colorado
Boulder, Colorado

## Solar Wind Data: HS-solstice, PS-solstice




## Neutral Density: HS, PS



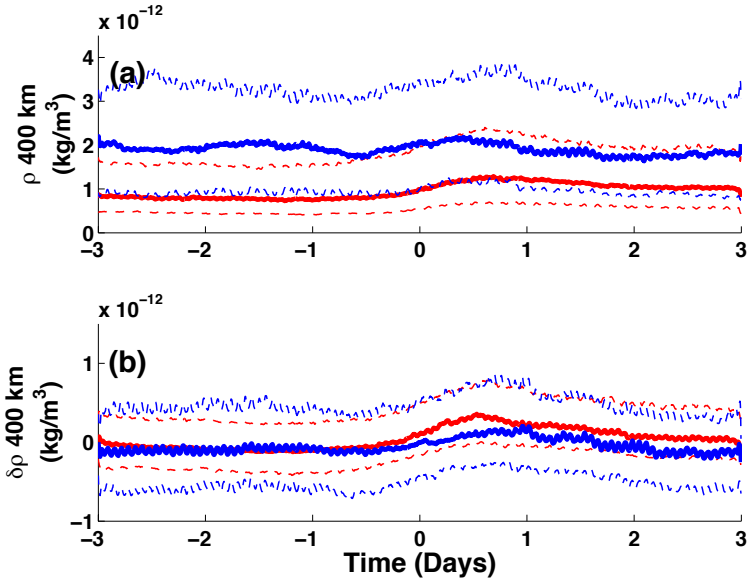

Despite early enhanced energy deposition the pseudo-streamer density response is damped

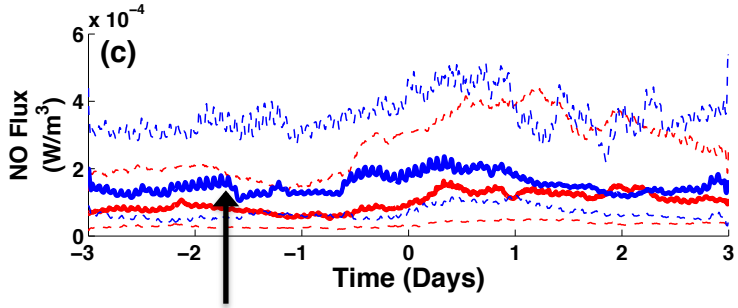
# Helmet and Pseudo-Streamers: Solstice

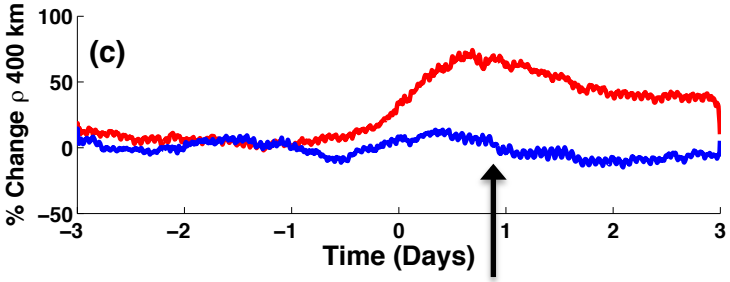
Colorado Center for Astrodynamics Research

University of Colorado
Boulder, Colorado

## Neutral Density: HS, PS




Strong evidence that NO is damping driver ➔ Mlynczak 'thermostat effect' in SABER data

Despite early enhanced energy deposition the pseudo-streamer density response is damped

# Equinox: Two Levels of Effect

Colorado Center for
Astrodynamics Research

University of Colorado
Boulder, Colorado



Two organizing aspects:

1. Coronal Streamer Structures (helmet and pseudo)
2. Russell-McPherron Effect (R-M Effect)

# Equinox: Two Levels of Effect

Colorado Center for Astrodynamics Research

University of Colorado
Boulder, Colorado

**Season:** Solstice - Equinox

## Further evidence of the counterintuitive result in much larger data base

Coronal Streamer Structure Effect (HS vs PS) is amplified by Russell-McPherron Effect

Spring
GSEQ By- projects into GSM coordinates with a negative Bz causing magnetic reconnection

Fall
GSEQ By+ projects into GSM coordinates with a negative Bz causing magnetic reconnection

General rule: 'Spring-toward, Fall-away'




Source: McPherrron et al., 2009

# Equinox: Two Levels of Effect

Colorado Center for Astrodynamics Research

University of Colorado
Boulder, Colorado

**Season:** Solstice - Equinox

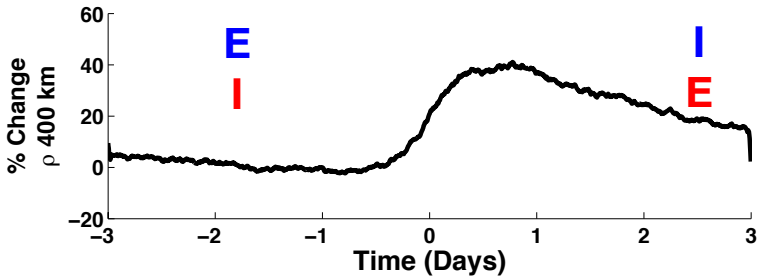
## Russell-McPherron Effect
## IMF $B_y$ projects onto GSM as $-B_Z$

| | | Slow Flow | SI | Fast Flow |
|---|---|---|---|---|
| Spring | E - I | Toward (E) | \| | Away (I) |
| | I - E | Away (I) | \| | Toward (E) |
| Fall | E - I | Away (E) | \| | Toward (I) |
| | I - E | Toward (I) | \| | Away (E) |

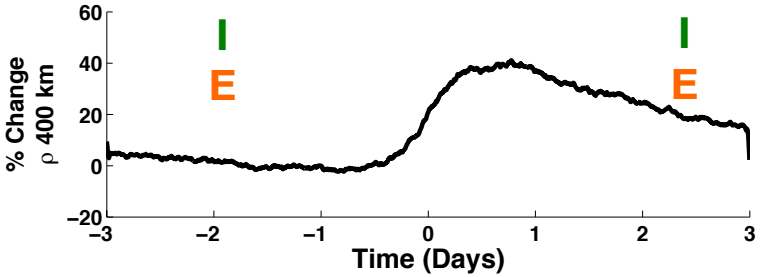
| | | Slow Flow | SI | Fast Flow |
|---|---|---|---|---|
| Spring | E - E | Toward (E) | \| | Toward (E) |
| | I - I | Away (I) | \| | Away (I) |
| Fall | E - E | Away (E) | \| | Away (E) |
| | I - I | Toward (I) | \| | Toward (I) |

## Coronal Streamer Structures

### Coronal helmet streamers




### Coronal pseudo-streamers



# Equinox: Two Levels of Effect

Colorado Center for Astrodynamics Research

University of Colorado
Boulder, Colorado

**Season:** Solstice - Equinox

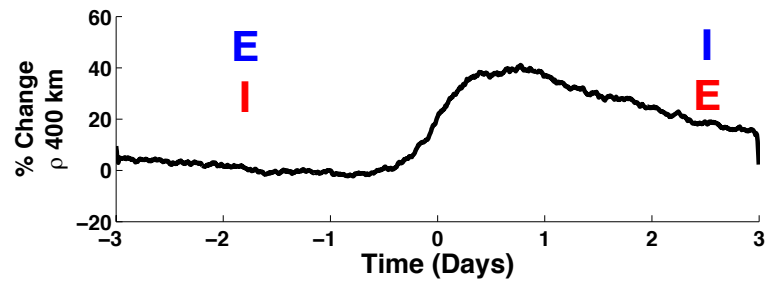
## Russell-McPherron Effect
## IMF $B_y$ projects onto GSM as $-B_Z$

| | | Slow Flow | SI | Fast Flow |
|---|---|---|---|---|
| Spring | E - I | Toward (E) | \| | Away (I) |
| | I - E | Away (I) | \| | Toward (E) |
| Fall | E - I | Away (E) | \| | Toward (I) |
| | I - E | Toward (I) | \| | Away (E) |

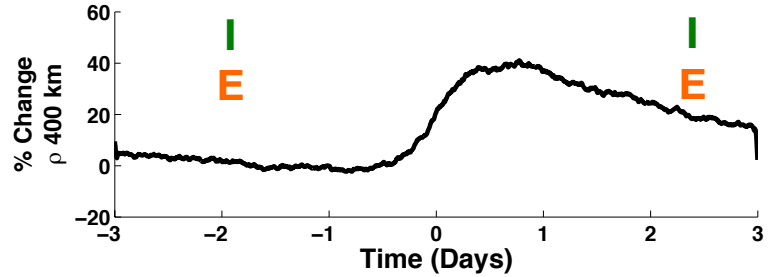
| | | Slow Flow | SI | Fast Flow |
|---|---|---|---|---|
| Spring | E - E | Toward (E) | \| | Toward (E) |
| | I - I | Away (I) | \| | Away (I) |
| Fall | E - E | Away (E) | \| | Away (E) |
| | I - I | Toward (I) | \| | Toward (I) |

## Coronal Streamer Structures

### Coronal helmet streamers




### Coronal pseudo-streamers



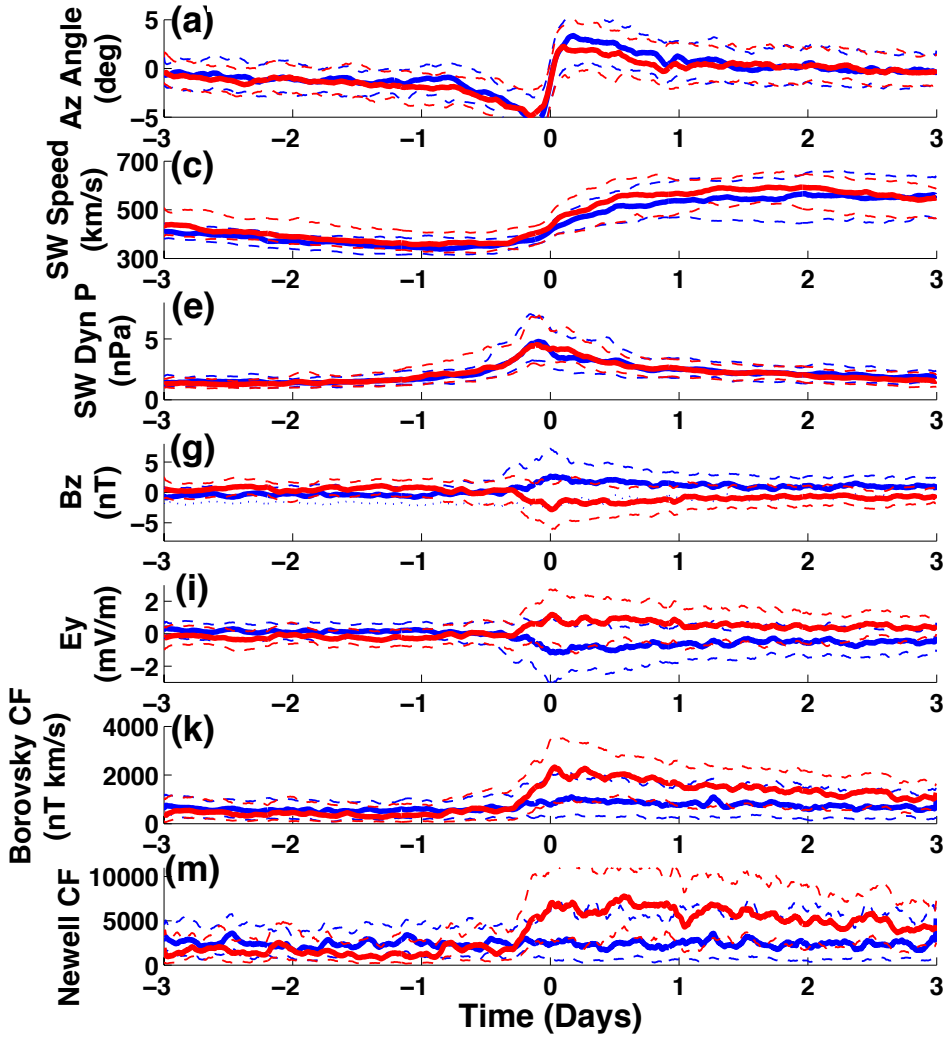
# Helmet Streamers + RM Effect

Colorado Center for Astrodynamics Research

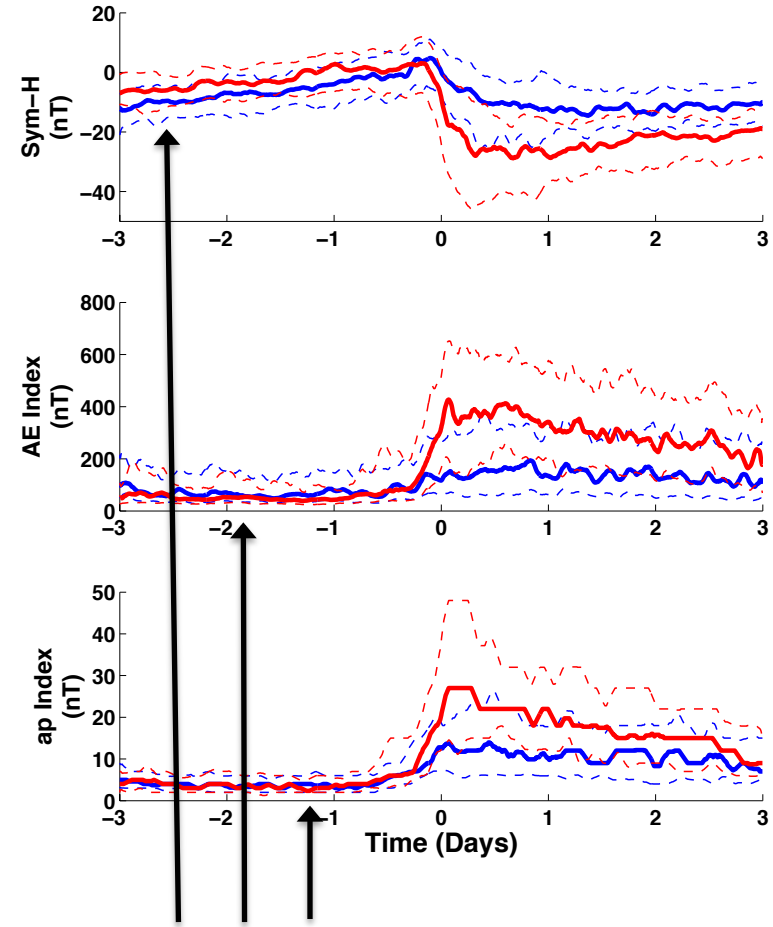
University of Colorado
Boulder, Colorado

112 helmet streamer CIR-HSSs

## Solar Wind Data: HS-IE, HS-EI




## Solar/GEO Indices: HS-IE, HS-EI



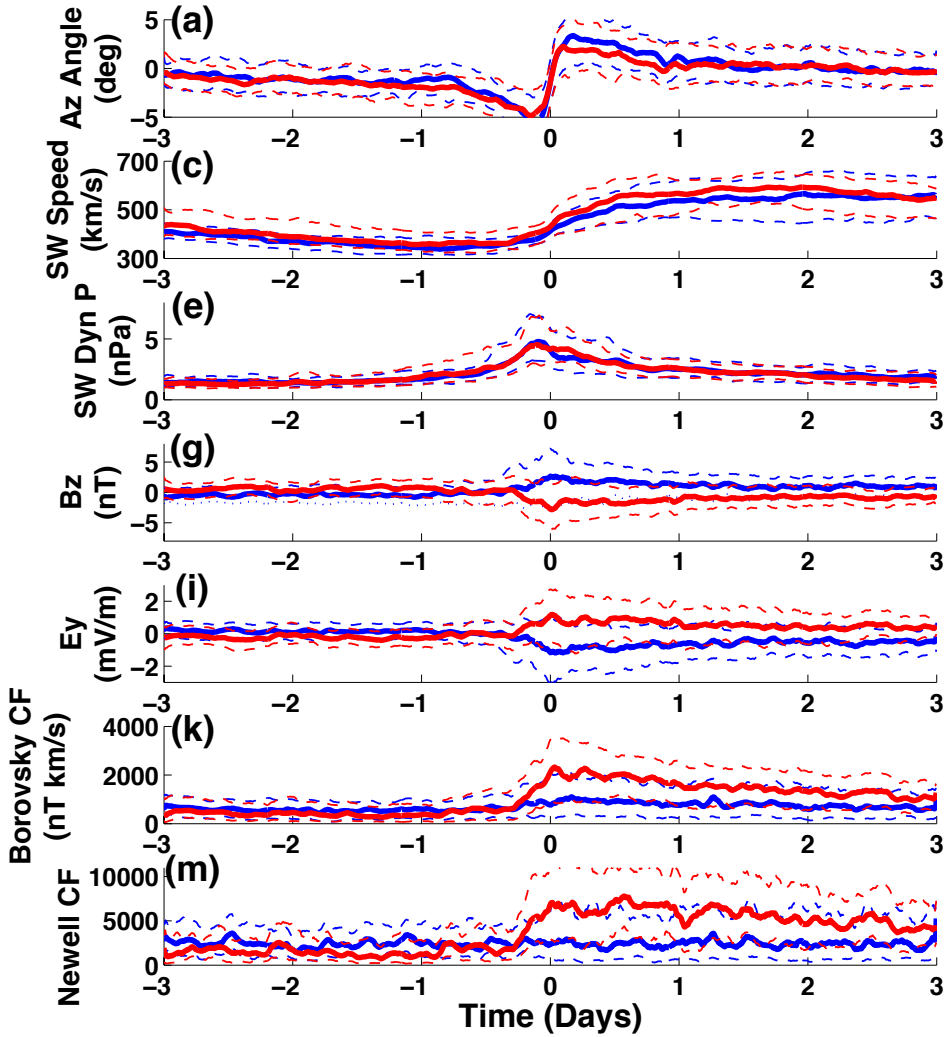

Calm before the Storm

# Helmet Streamers + RM Effect

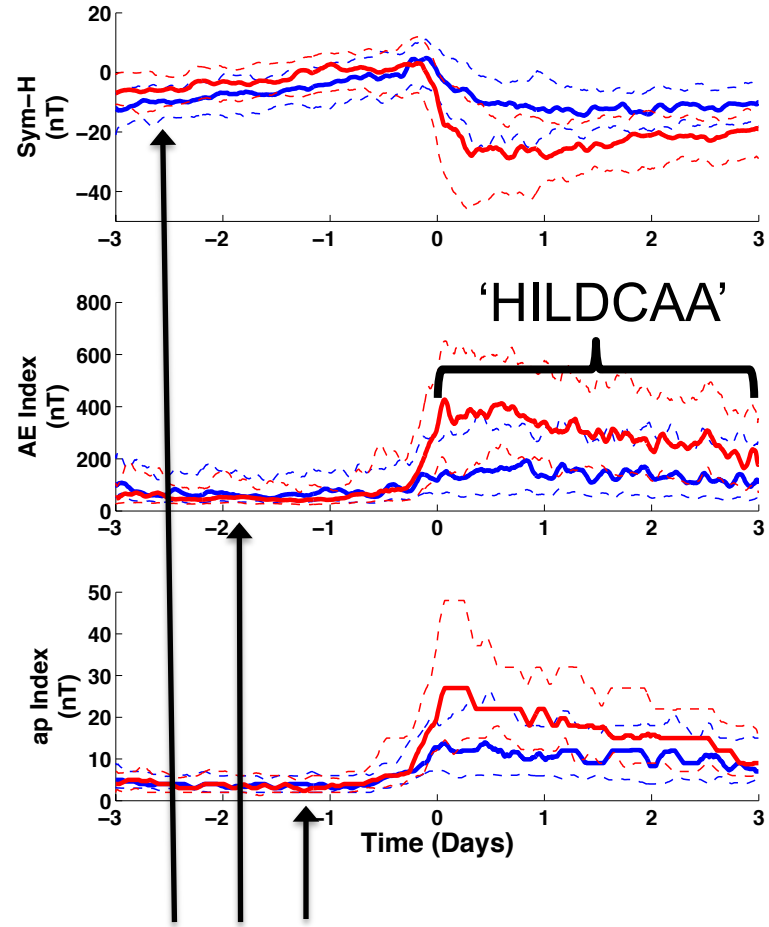
Colorado Center for Astrodynamics Research

University of Colorado
Boulder, Colorado

## Solar Wind Data: HS-IE, HS-EI




## Solar/GEO Indices: HS-IE, HS-EI



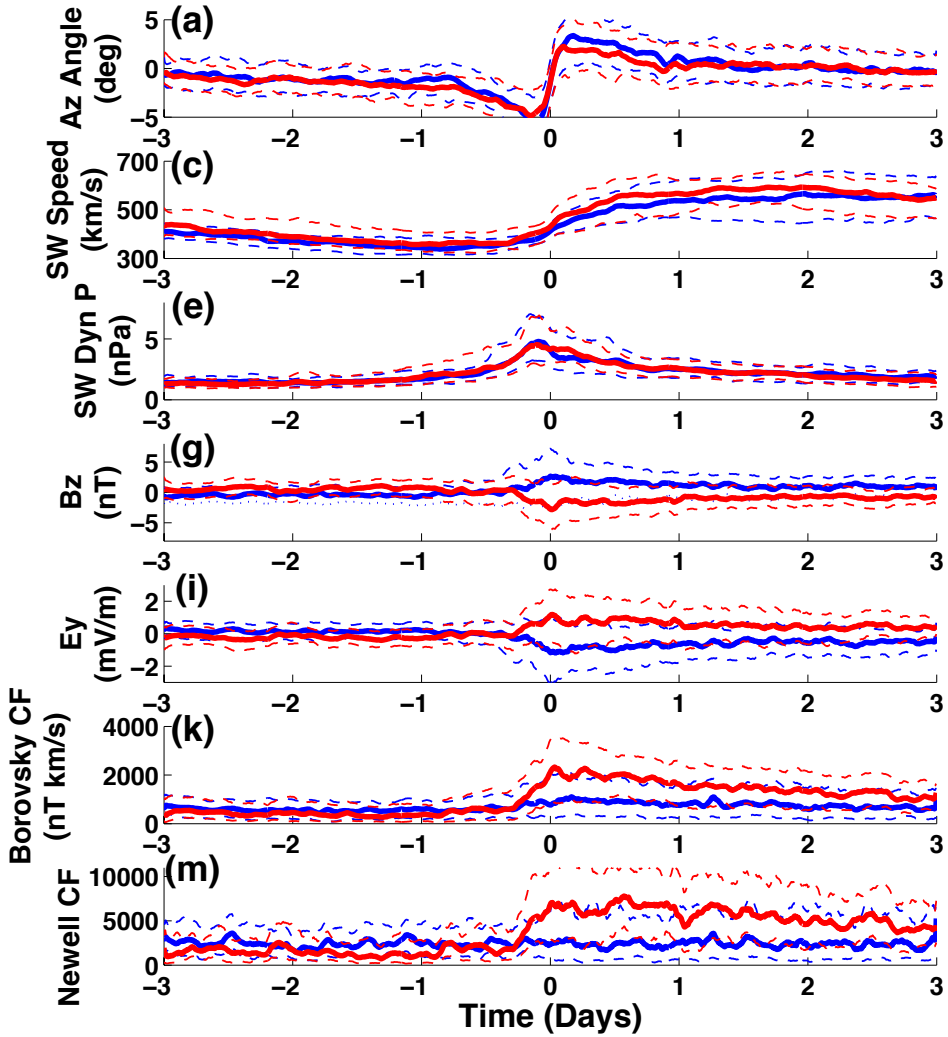

Calm before the Storm

# Helmet Streamers + RM Effect

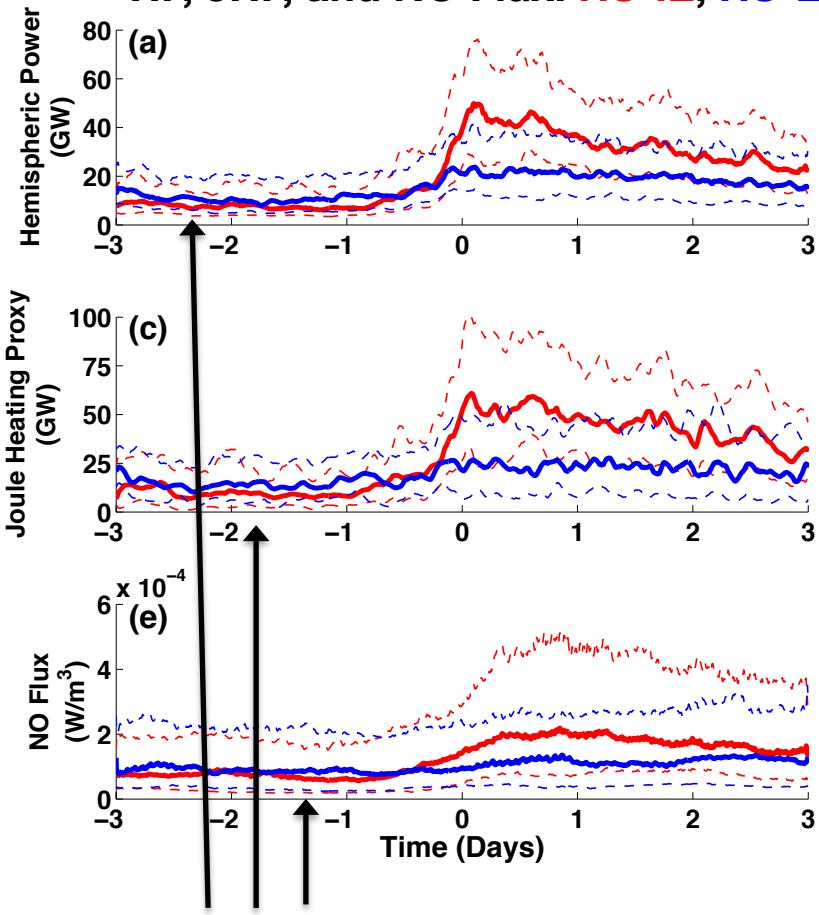
Colorado Center for Astrodynamics Research

University of Colorado
Boulder, Colorado

## Solar Wind Data: HS-IE, HS-EI




## HP, JHP, and NO Flux: HS-IE, HS-EI



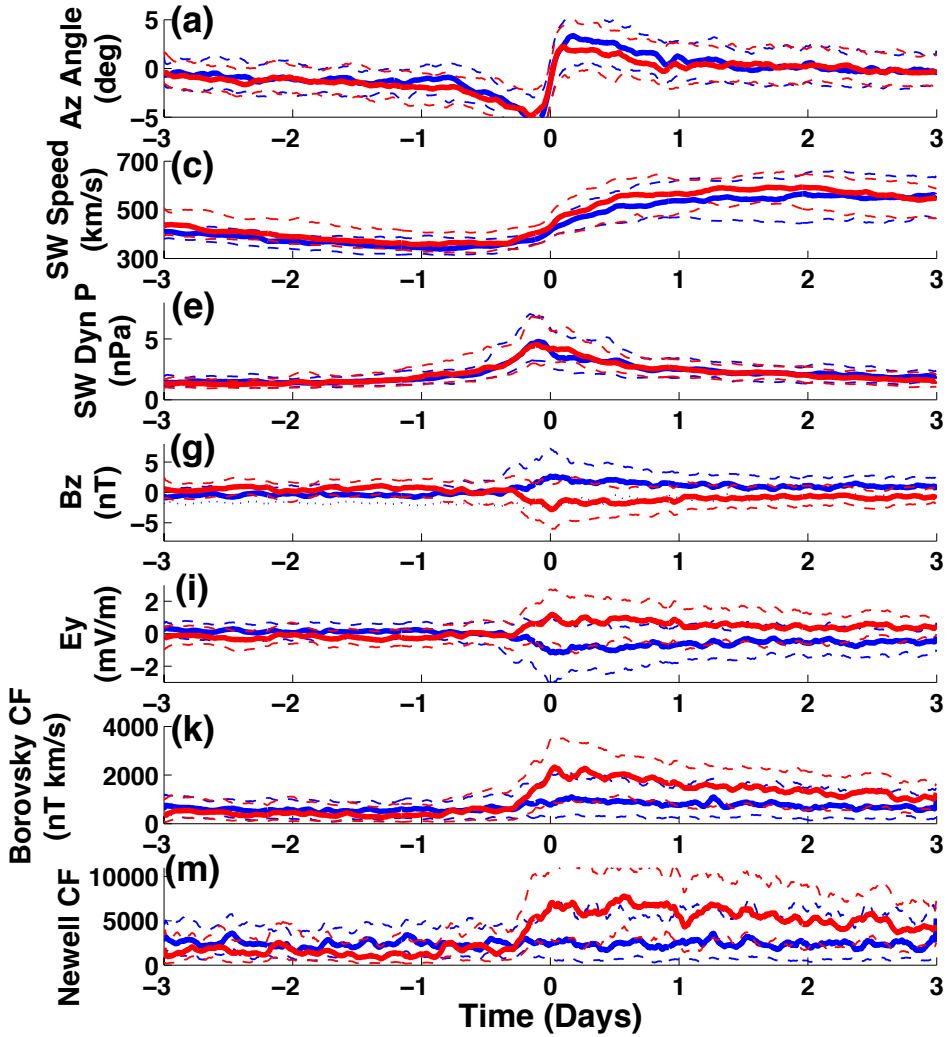

Calm before the Storm

# Helmet Streamers + RM Effect

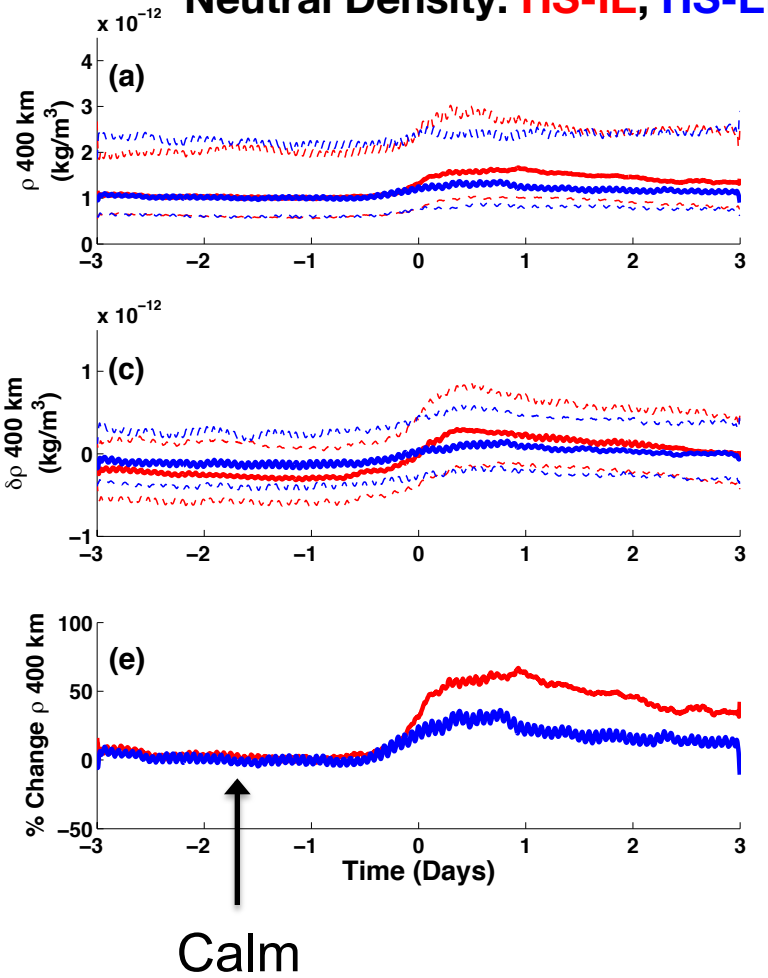
Colorado Center for Astrodynamics Research

University of Colorado
Boulder, Colorado

## Solar Wind Data: HS-IE, HS-EI




## Neutral Density: HS-IE, HS-EI



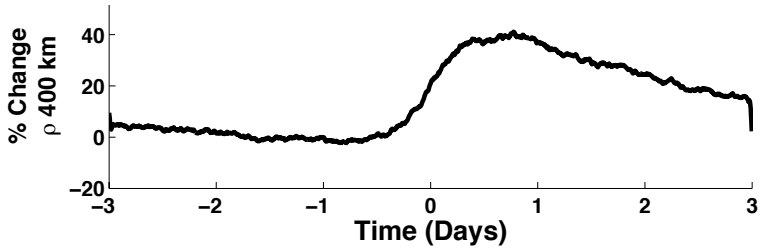
# Wrap-up

Colorado Center for Astrodynamics Research

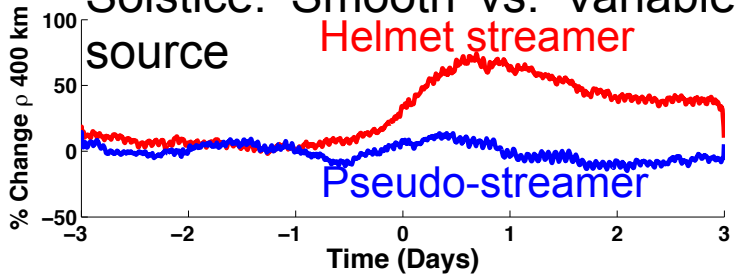
University of Colorado
Boulder, Colorado

## General Neutral Density Response

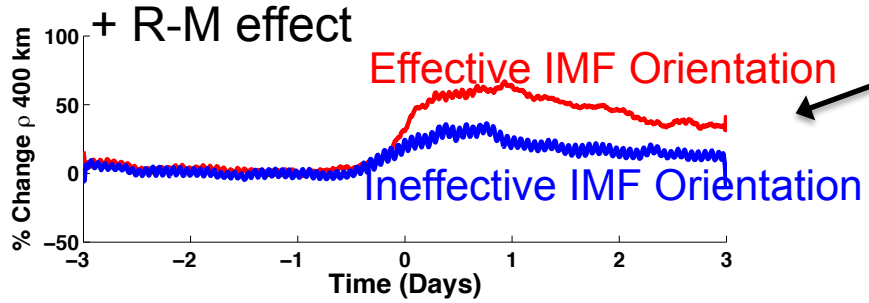
Low speed flow High speed flow




Solstice: 'Smooth' vs. 'Variable' coronal source




Equinox: 'Smooth' coronal source + R-M effect




Solar wind Alfvénic fluctuations appear to dominate magnetospheric response to high speed streams (HSSs) However……

**New Finding**: Lack of a "calm before the storm" inverts and shortens neutral density response if the solar wind structure is variable ('rough')

**Additional New Finding:** During equinox the IMF orientation within the stream structure, as well as 'smooth' solar wind structure that creates a "calm before the storm," modulates and bifurcates the density response

**➔Improved forecasting paradigm for neutral density during CIR-HSSs**

# Impact of High-Speed Stream Structures on Thermospheric Response: Solstitial and Equinoctial Events

Ryan M. McGranaghan* and Delores J. Knipp*†
*Colorado Center for Astrodynamics Research
University of Colorado at Boulder

†High Altitude Observatory
National Center for Atmospheric Research

Robert L. McPherron
Department of Earth, Planetary, and Space Sciences
University of California Los Angeles

Linda A. Hunt
Space Systems and Applications, Inc.

**Acknowledgements**:

We are grateful to Liyang Qian, Eric Sutton, Jiuhou Lei, Jeff Thayer, and Liam Kilcommons for many useful discussions. RMcG was partially supported by NSF Fellowship Award No. DGE 1144083 and NSF grant AGS 1025089. DJK was partially supported by NSF grants AGS 1025089 and AGS 1144154 and AFSOR FA9550-12-1-0264. RMcP was supported in part by NASA grant NNX10AF25G. The National Center for Atmospheric Research is sponsored by the National Science Foundation.

# Statistical Link between Solar Streamer Structure and Thermosphere Neutral Density Response

- Large helmet streamer structures
- Strongly damp pre-CIR solar wind Alfven (SWA) fluctuations in pre-CIR flow
- Damped SWA fluctuations diminishes auroral response during pre-CIR regime
- Diminishes nitric oxide cooling (thermostat) during pre-CIR regime
- Promotes enhanced neutral density response in post CIR/HHS regime

Solar/ Solar Wind Structure → Auroral Behavior → Thermospheric Chemistry

Pre-CIR

Post-CIR

- Small pseudo streamer structures
- Weakly damp pre-CIR solar wind Alfven (SWA) fluctuations in pre-CIR flow
- Normal SWA fluctuations maintain auroral response during pre-CIR regime
- Enhances nitric oxide cooling (thermostat) during pre-CIR regime
- Promotes damped neutral density response in post CIR/HHS regime

# Backup Slides

# References

Colorado Center for Astrodynamics Research

University of Colorado
Boulder, Colorado

Borovsky and Denton (2010) *Solar wind turbulence and shear: A superposed-epoch analysis of corotating interaction regions at 1 AU.*

Gosling and Pizzo (2009) *Formation and evolution of corotating interaction regions and their three dimensional structure*.

McGranaghan et al. (2014) *Impact of equinoctial high-speed stream structures on thermospheric responses.*

McPherron et al. (2009) *Role of the Russell–McPherron effect in the acceleration of relativistic electrons.*

Riley and Luhmann (2012). *Interplanetary signatures of unipolar streamers and the origin of the slow solar wind.*

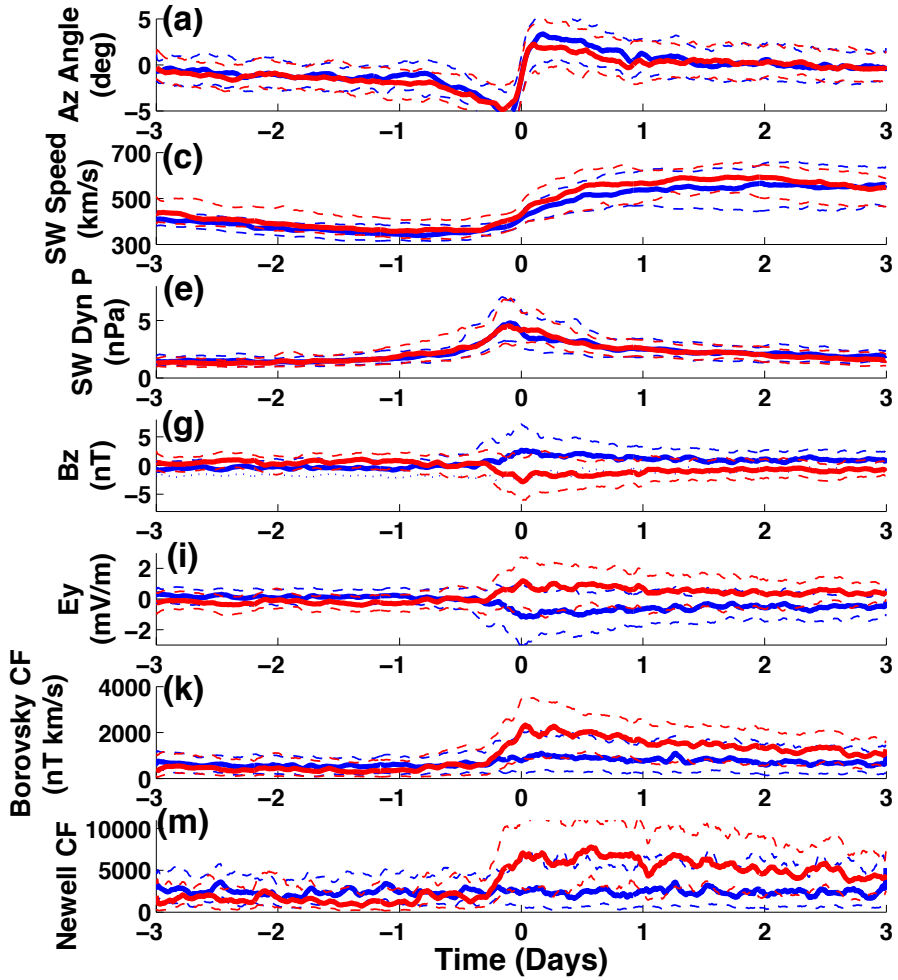
Tsurutani et al. (2006) *Corotating solar wind streams and recurrent geomagnetic activity: A review.*

# Helmet vs. Pseudo-Streamers

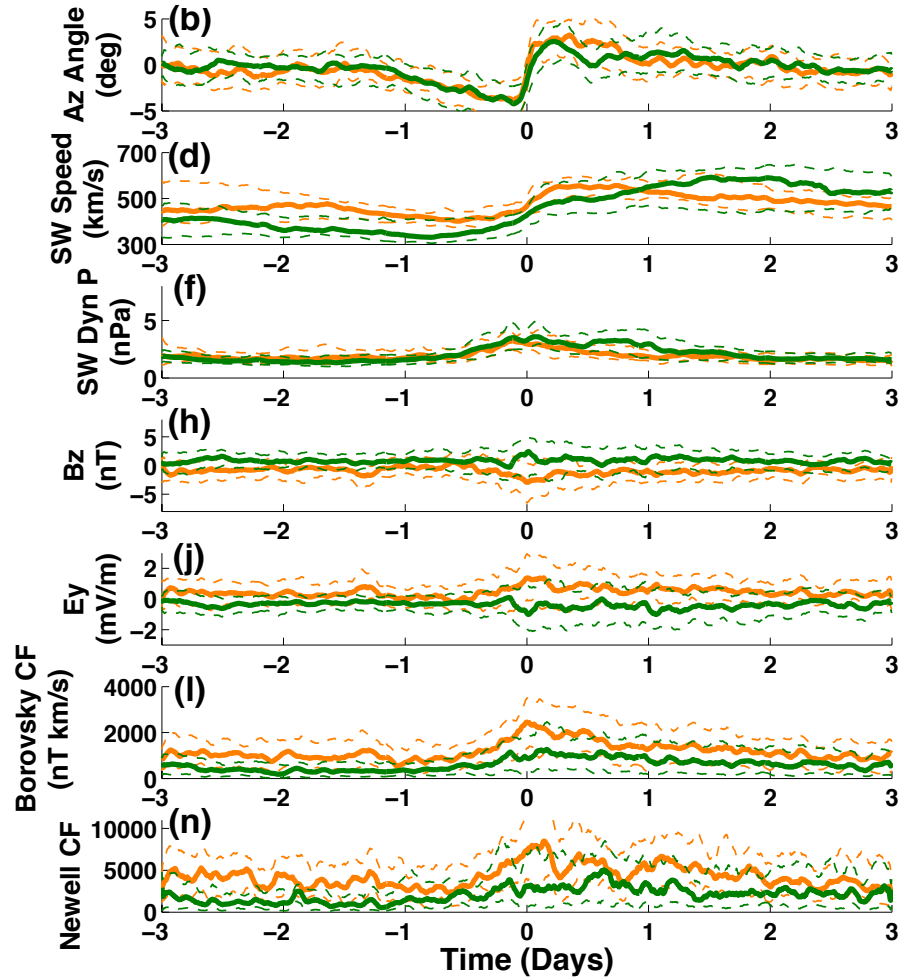
Colorado Center for Astrodynamics Research

University of Colorado
Boulder, Colorado

## Solar Wind Data: HS-IE, HS-EI




## Solar Wind Data: PS-EE, PS-II



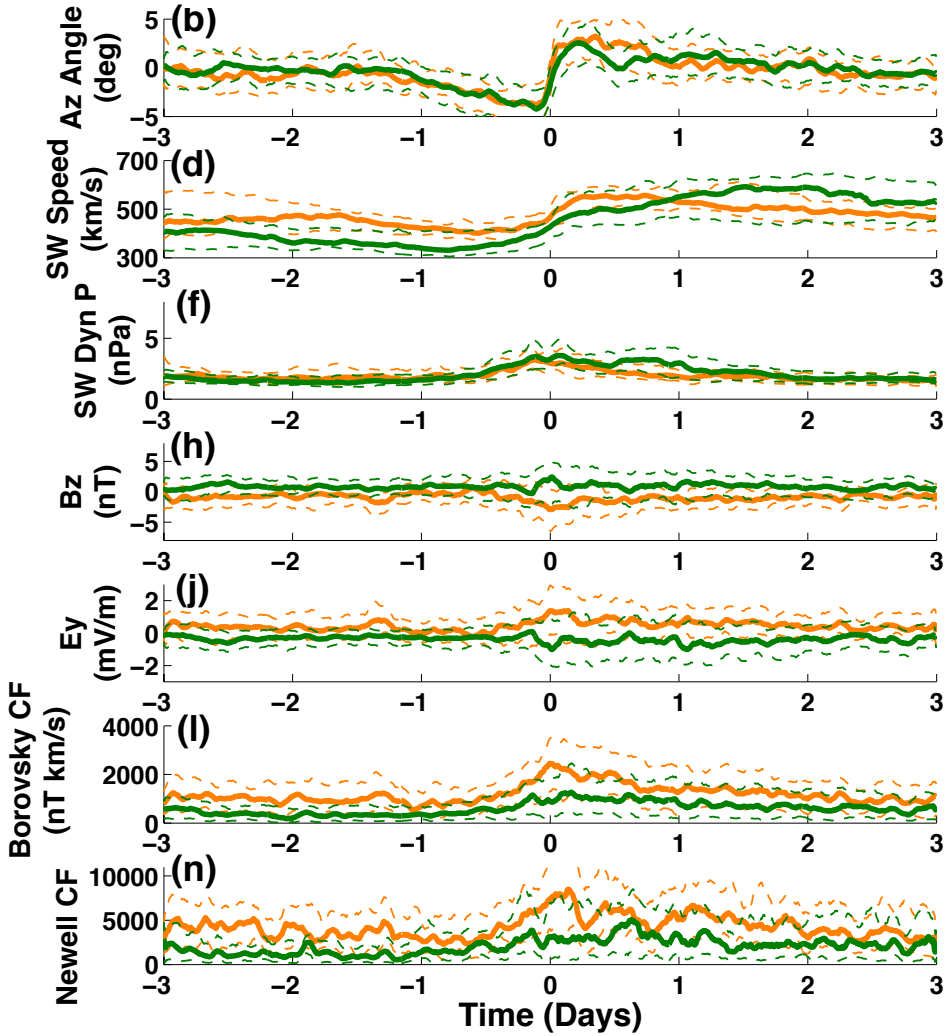

60 pseudo-streamer CIR-HSSs

# Pseudo-Streamers + RM Effect

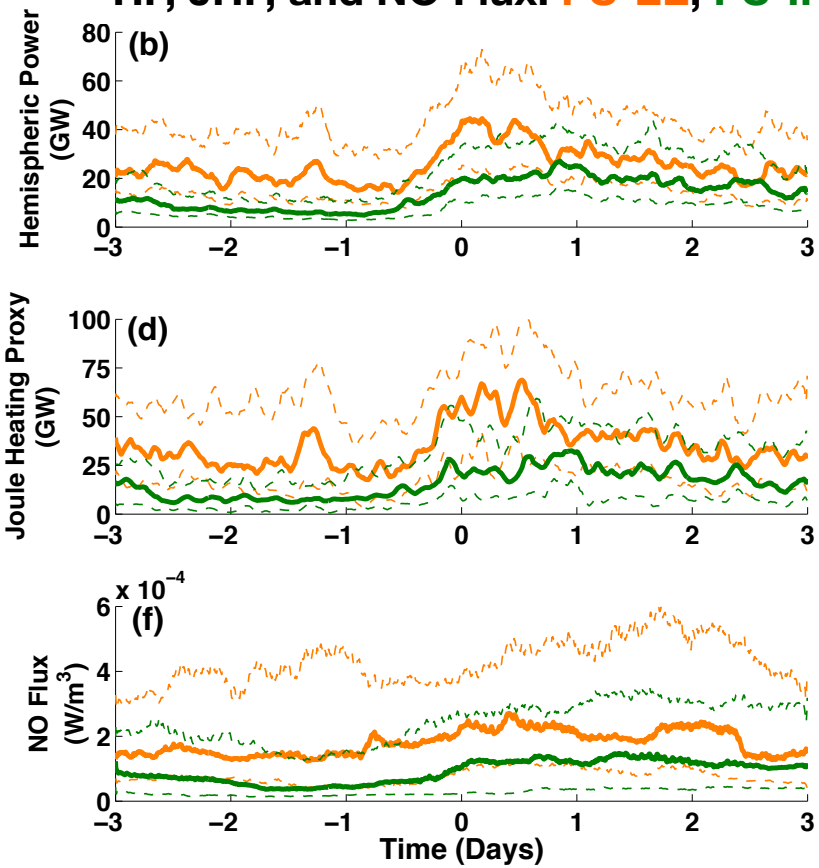
Colorado Center for Astrodynamics Research

University of Colorado
Boulder, Colorado

## Solar Wind Data: PS-EE, PS-II




## HP, JHP, and NO Flux: PS-EE, PS-II

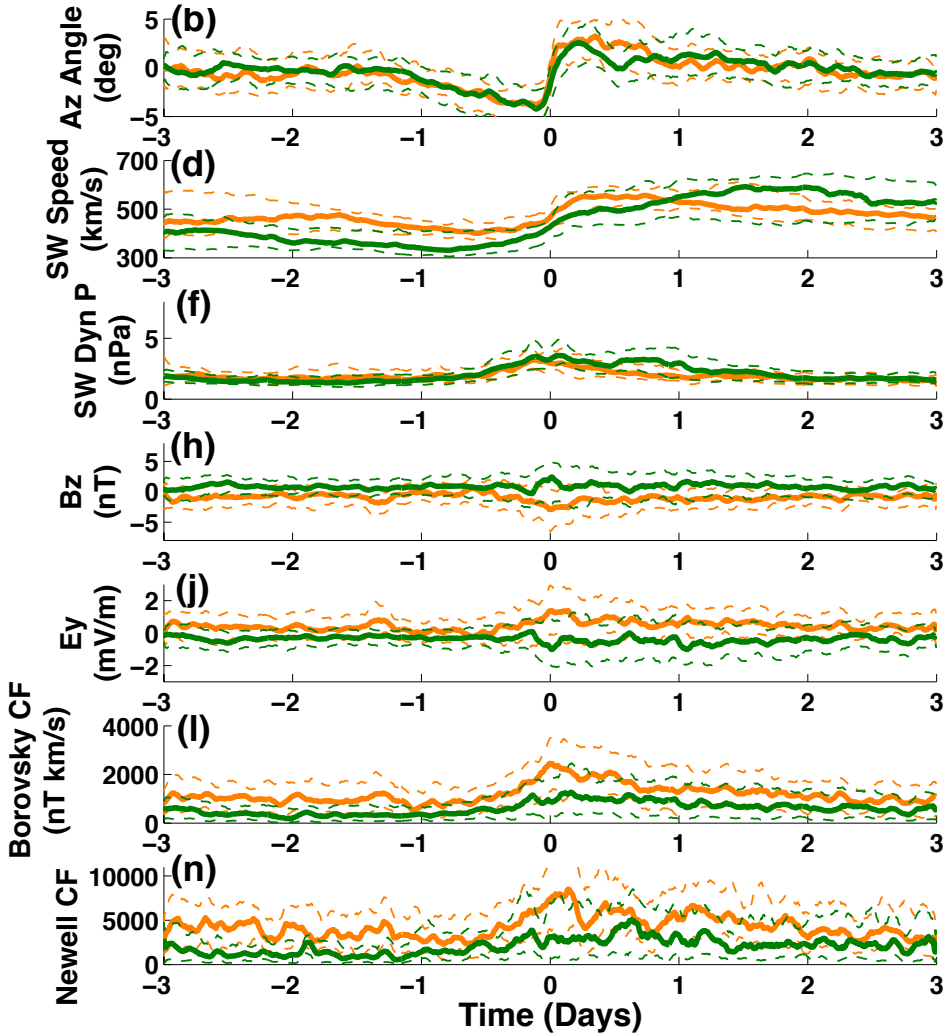


# Pseudo-Streamers + RM Effect

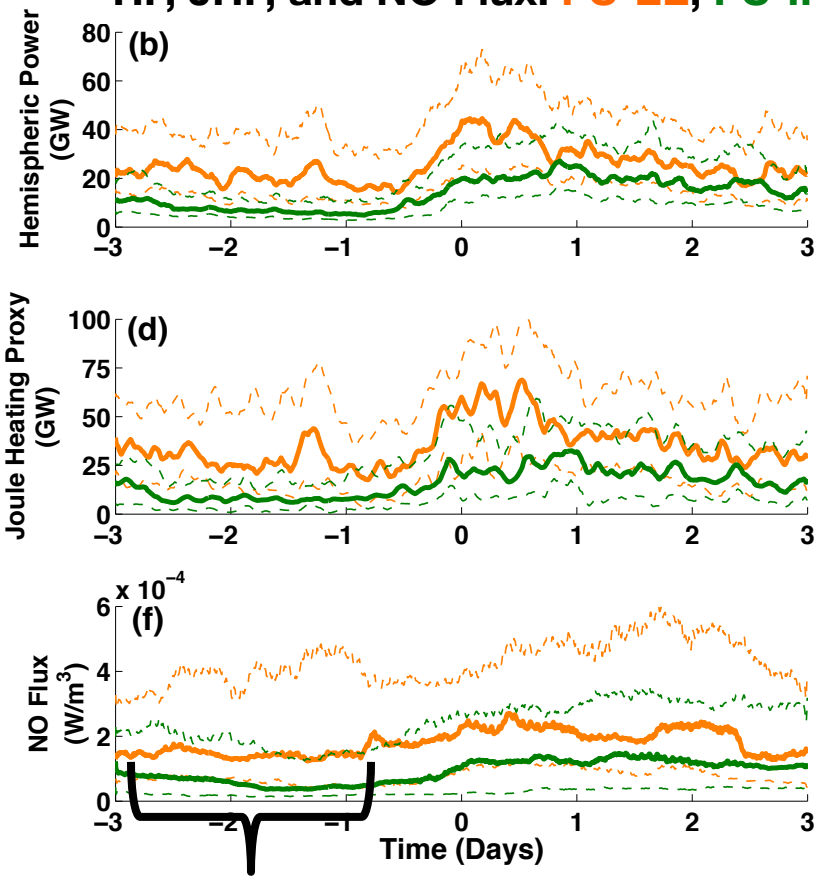
Colorado Center for Astrodynamics Research

University of Colorado
Boulder, Colorado

## Solar Wind Data: PS-EE, PS-II




## HP, JHP, and NO Flux: PS-EE, PS-II

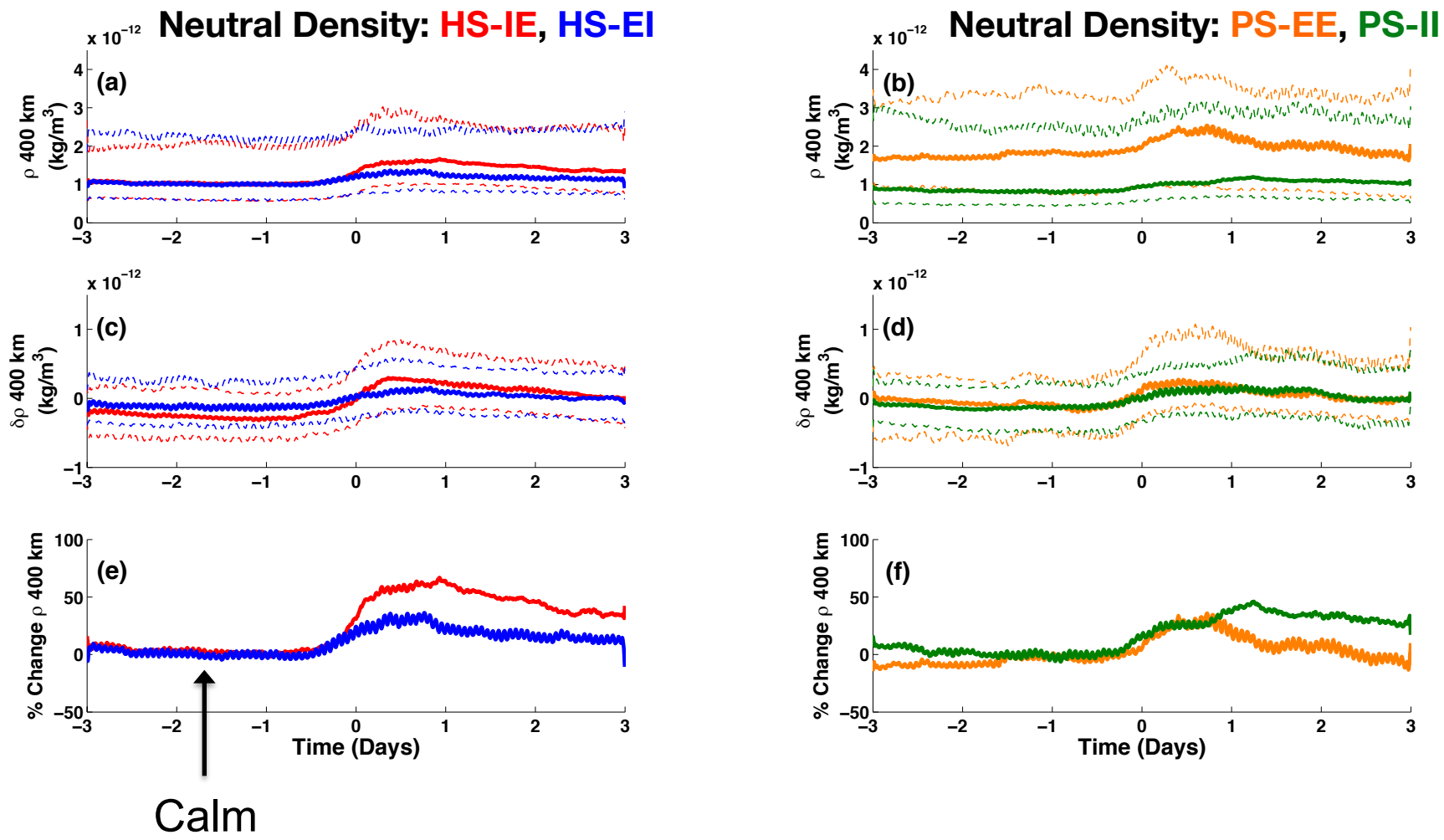



Lack of calm -> early NO production

# Pseudo-Streamers + RM Effect CHAMP

Colorado Center for Astrodynamics Research

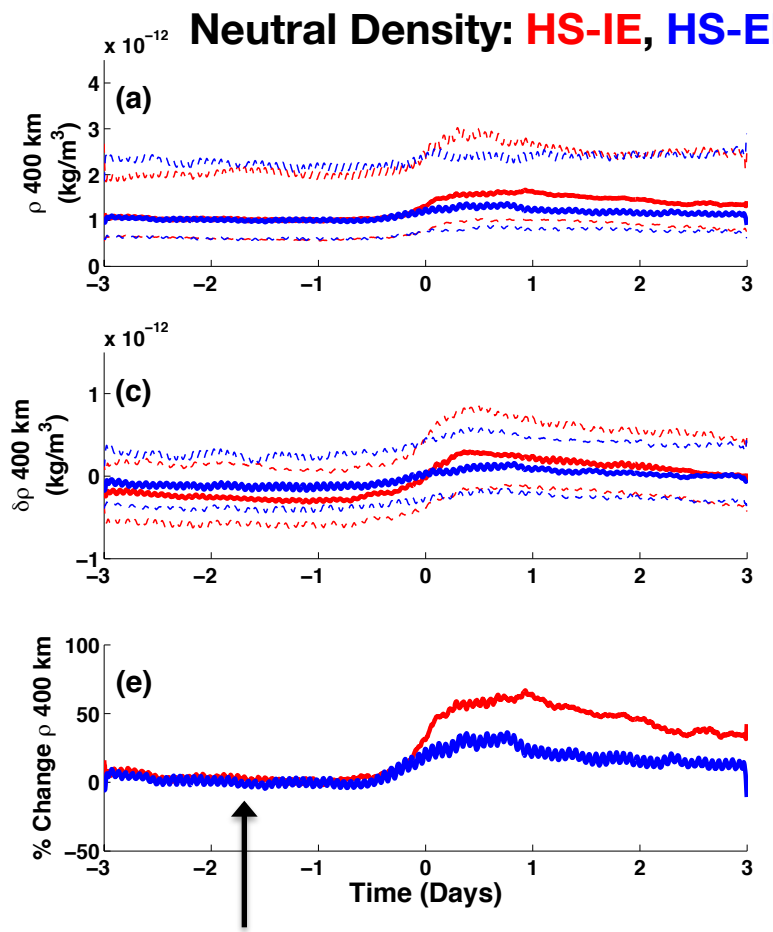
University of Colorado
Boulder, Colorado



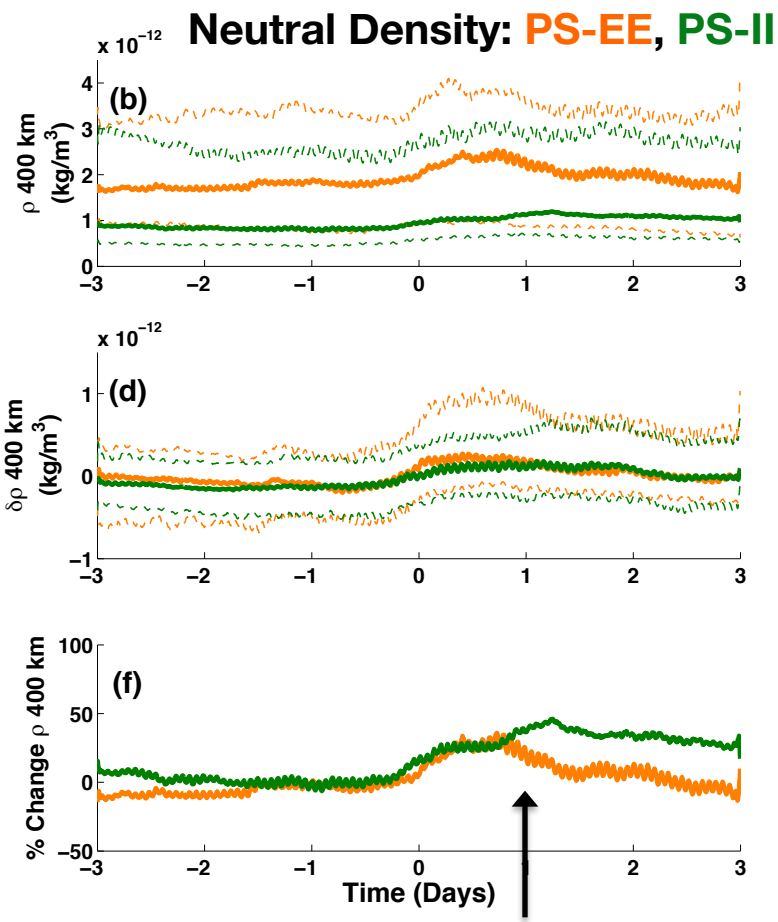
# Pseudo-Streamers + RM Effect CHAMP

Colorado Center for Astrodynamics Research

University of Colorado
Boulder, Colorado




Calm



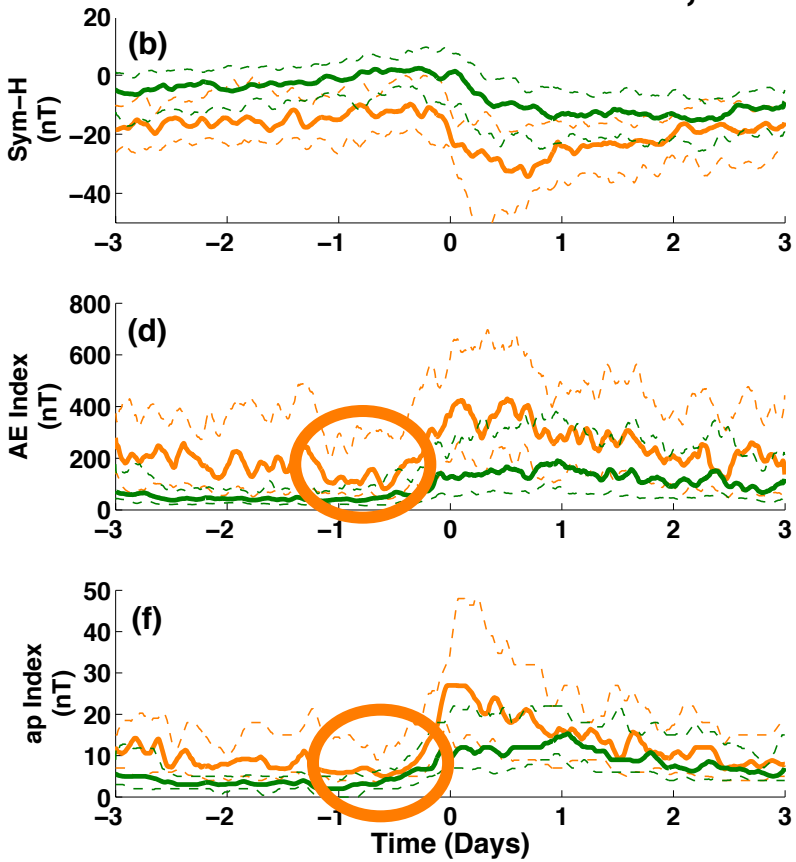

Counterintuitive shortened EE response

# PS-EE: Shorter 'calm'?

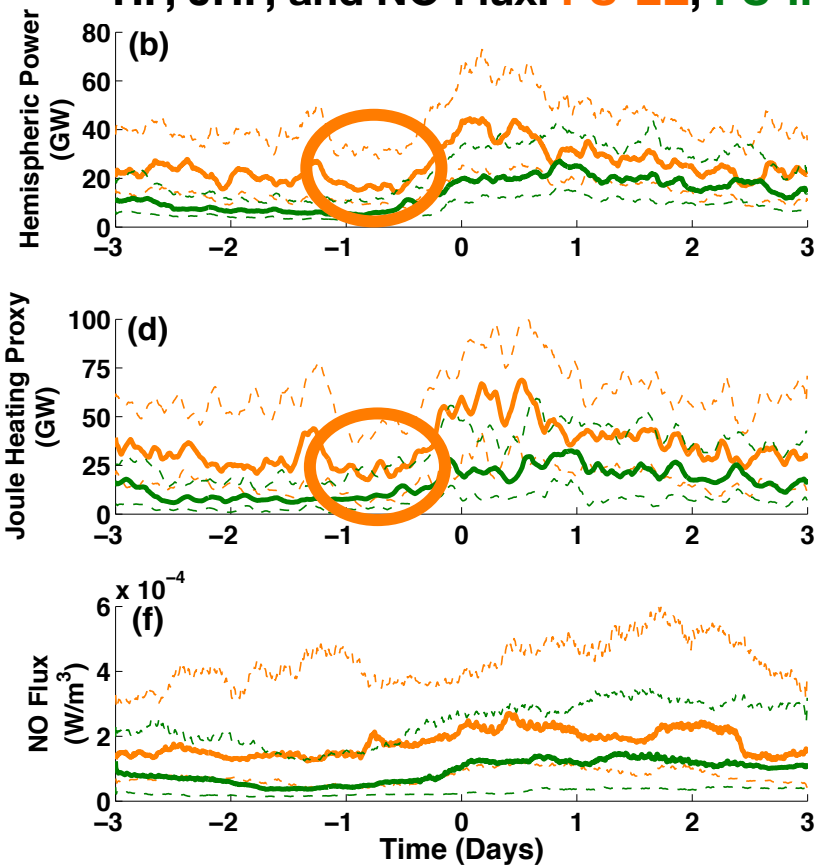
Colorado Center for Astrodynamics Research

University of Colorado
Boulder, Colorado

## Solar/GEO Indices: PS-EE, PS-II




## HP, JHP, and NO Flux: PS-EE, PS-II



# Owens et al. 2013 SB/HCS types

Colorado Center for Astrodynamics Research

University of Colorado
Boulder, Colorado

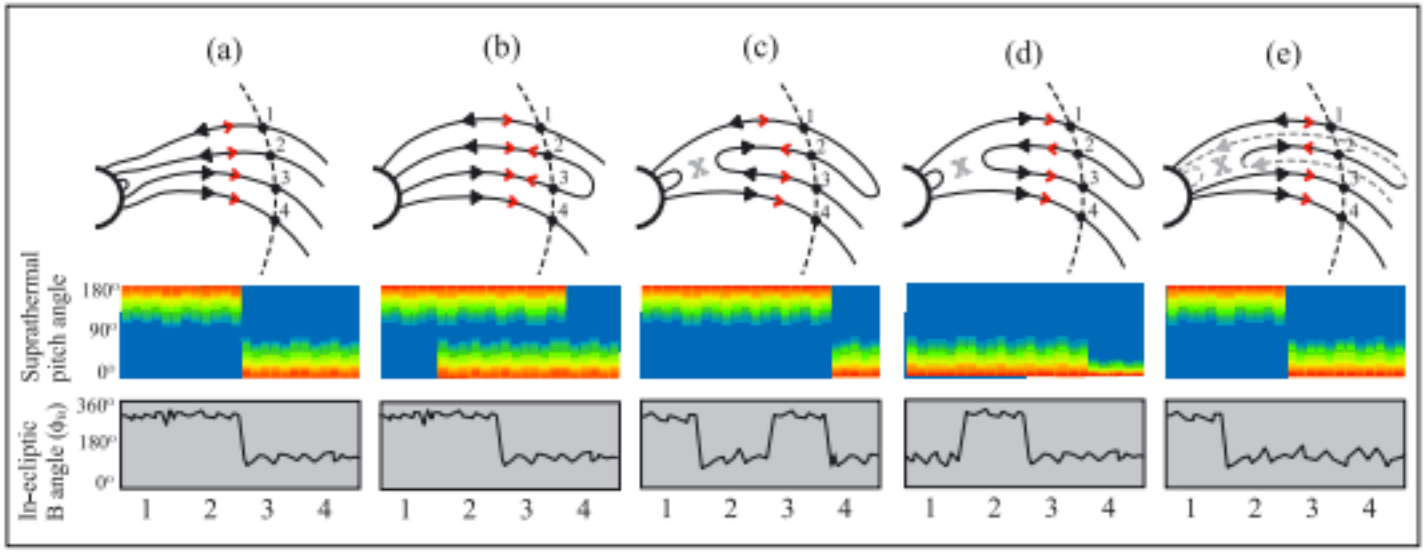
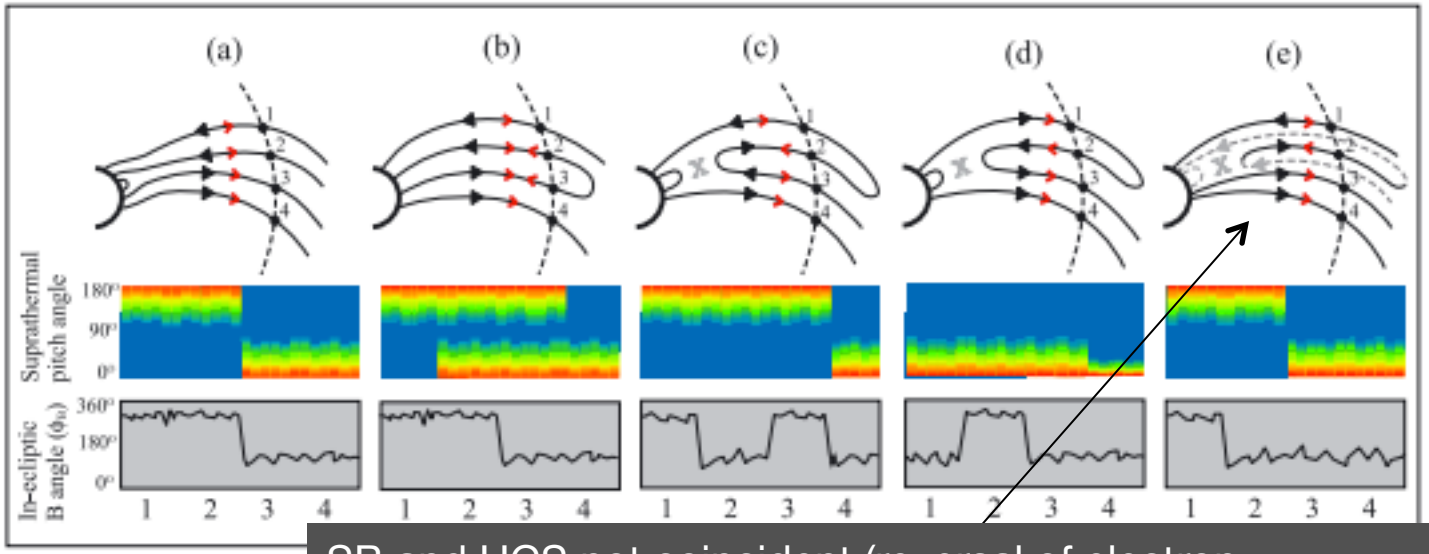



**Figure 1.** Sketches of possible HMF configurations and the resulting magnetic field and suprathermal electron signatures in near-Earth space. Red (black) arrows show the thermal electron strahl (magnetic field polarity), while gray crosses show the position of magnetic reconnection. (a) A typical sector boundary/HCS crossing. (b) A sector boundary accompanied by closed HMF loops, likely part of an interplanetary coronal mass ejection (ICME). (c) A sector boundary/HCS crossing containing an inverted HMF interval at time 2. (d) An inverted HMF interval at time 2 embedded within a unipolar region. (e) A sector boundary with mismatched electron and magnetic signatures. The dashed lines show portions of the inverted HMF structure which are out of the ecliptic plane and not encountered by the observing spacecraft [after *Crooker et al.*, 2004b].

# Owens et al. 2013 SB/HCS types

Colorado Center for Astrodynamics Research

University of Colorado
Boulder, Colorado



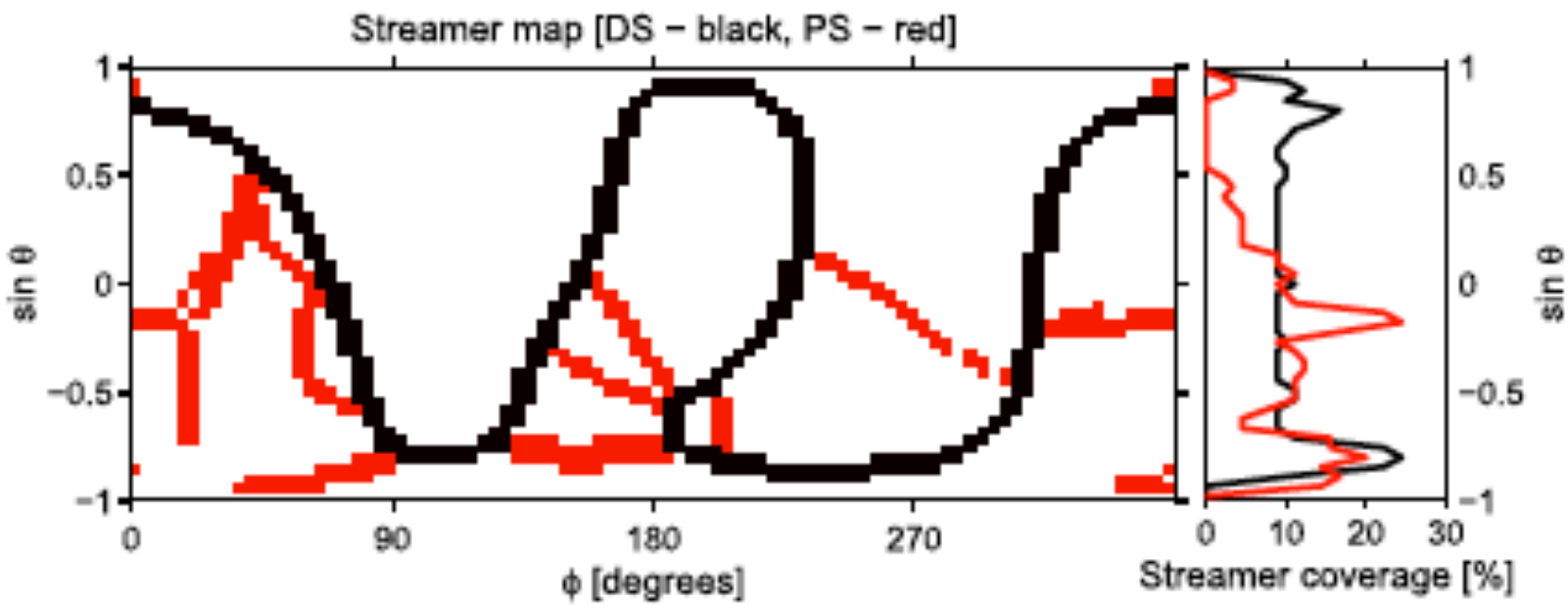

SB and HCS not coincident (reversal of electron strahl pitch angle and change in IMF from (315/135) to (135/315) not collocated) – these probably related to interchange reconnection (more dynamic – 'blobs' of HPS)

**Figure 1.** Sketches of
electron signatures in n
field polarity), while g
boundary/HCS crossing
interplanetary coronal mass ejection (ICME). (c) A sector boundary/HCS crossing containing an inverted HMF interval at time 2. (d) An inverted HMF interval at time 2 embedded within a unipolar region. (e) A sector boundary with mismatched electron and magnetic signatures. The dashed lines show portions of the inverted HMF structure which are out of the ecliptic plane and not encountered by the observing spacecraft [after *Crooker et al.*, 2004b].

# Web-like Structure of Pseudo-streamers

Colorado Center for Astrodynamics Research

University of Colorado
Boulder, Colorado




Source: Owens et al., 2014

# Distinction/Ambiguity of PS and HS structures

Colorado Center for Astrodynamics Research

University of Colorado
Boulder, Colorado

We find approximately 65% of the 172 equinoctial CIR-HSSs from 2002-2008 are HS events (1.8:1 HS:PS ratio)

- *Borovsky and Denton* [2013] give ~7:1 HS:PS ratio from 1995-2007 (equinox and solstice events)
  - We place ill-defined sector crossings in PS category
  - *Owens et al.* [2014] showed PS events were unusually high during SC23

Within each category, ‘E’ and ‘I’ are easily classified

IDing sector structure boundaries from potential field source surface solutions (such as that in [*Owens et al., 2014*])

# CIR-HSS Occurrences

Colorado Center for Astrodynamics Research

University of Colorado
Boulder, Colorado

| Data Set | | Total | Solar Decline | Solar Min |
|---|---|---|---|---|
| Pseudo-streamers (Unipolar) | PS-EE | 26 | 17 | 9 |
| | PS-II | 34 | 13 | 21 |
| **All Pseudo** 28.5 % | – | 60 | 30 | 30 |
| Helmet streamers (Bipolar) | HS-EI | 55 | 22 | 33 |
| | HS-IE | 57 | 25 | 32 |
| **All Helmet** 53.0 % | – | 112 | 47 | 65 |
| Uncategorized 18.5 % | – | 39 | 12 | 27 |
| **All Equinox** | – | 211 | 89 | 122 |
| June-July Solstice | – | 35 | 15 | 20 |
| December-January Solstice | – | 31 | 17 | 14 |
| **All Solstice** | – | 66 | 32 | 34 |

Earth clearly crosses through HCS in association with an equinoctial CIR ~65% of the time, and ~53% of all CIRs.

# CIR-HSS Occurrences

Colorado Center for Astrodynamics Research

University of Colorado
Boulder, Colorado

| Data Set | | Total | Solar Decline | Solar Min |
|---|---|---|---|---|
| Pseudo-streamers (Unipolar) | PS-EE | 26 | 17 | 9 |
| | PS-II | 34 | 13 | 21 |
| **All Pseudo** 28.5 % | – | 60 | 30 | 30 |
| Helmet streamers (Bipolar) | HS-EI | 55 | 22 | 33 |
| | HS-IE | 57 | 25 | 32 |
| **All Helmet** 53.0 % | – | 112 | 47 | 65 |
| Uncategorized 18.5 % | – | 39 | 12 | 27 |
| **All Equinox** | – | 211 | 89 | 122 |
| June-July Solstice | – | 35 | 15 | 20 |
| December-January Solstice | – | 31 | 17 | 14 |
| **All Solstice** | – | 66 | 32 | 34 |

Earth clearly crosses through HCS in association with an equinoctial CIR ~65% of the time, and ~53% of all CIRs.

# CIR-HSS Occurrences

Colorado Center for Astrodynamics Research

University of Colorado
Boulder, Colorado

| Data Set | | Total | Solar Decline | Solar Min |
|---|---|---|---|---|
| Pseudo-streamers (Unipolar) | PS-EE | 26 | 17 | 9 |
| | PS-II | 34 | 13 | 21 |
| **All Pseudo** 28.5 % | – | 60 | 30 | 30 |
| Helmet streamers (Bipolar) | HS-EI | 55 | 22 | 33 |
| | HS-IE | 57 | 25 | 32 |
| **All Helmet** 53.0 % | – | 112 | 47 | 65 |
| Uncategorized 18.5 % | – | 39 | 12 | 27 |
| **All Equinox** | – | 211 | 89 | 122 |
| June-July Solstice | – | 35 | 15 | 20 |
| December-January Solstice | | 31 | 17 | 14 |
| **All Solstice** | – | 66 | 32 | 34 |

Earth clearly crosses through HCS in association with an equinoctial CIR ~65% of the time, and ~53% of all CIRs.

# CIR-HSS Occurrences

Colorado Center for Astrodynamics Research

University of Colorado
Boulder, Colorado

| Data Set | | Total | Solar Decline | Solar Min |
|---|---|---|---|---|
| Pseudo-streamers (Unipolar) | PS-EE | 26 | 17 | 9 |
| | PS-II | 34 | 13 | 21 |
| **All Pseudo** 28.5 % | – | 60 | 30 | 30 |
| Helmet streamers (Bipolar) | HS-EI | 55 | 22 | 33 |
| | HS-IE | 57 | 25 | 32 |
| **All Helmet** 53.0 % | – | 112 | 47 | 65 |
| Uncategorized 18.5 % | – | 39 | 12 | 27 |
| **All Equinox** | – | 211 | 89 | 122 |
| June-July Solstice | – | 35 | 15 | 20 |
| December-January Solstice | – | 31 | 17 | 14 |
| **All Solstice** | – | 66 | 32 | 34 |

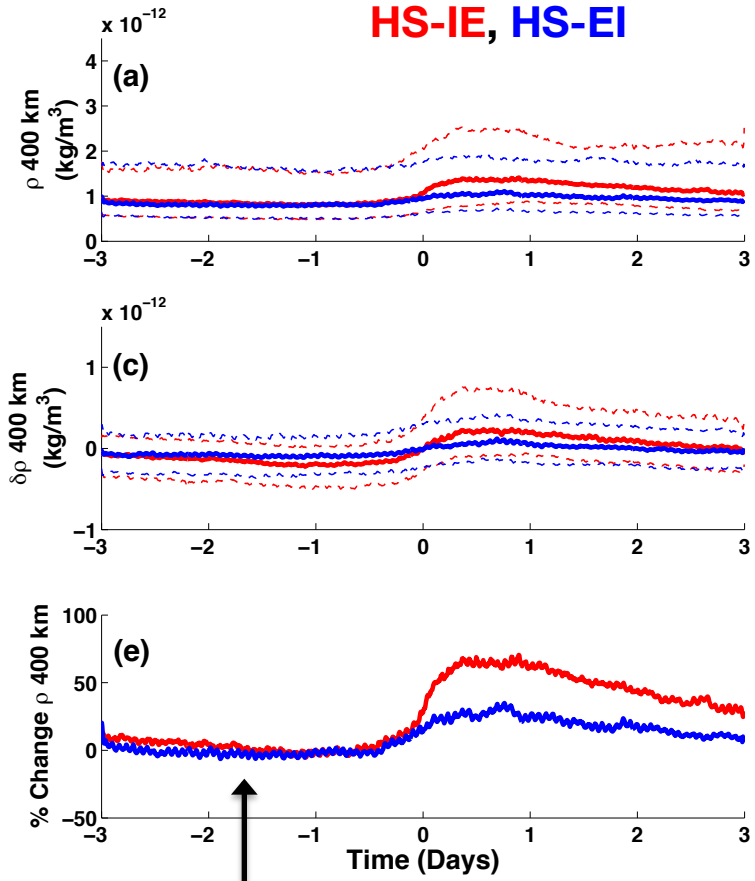
Earth clearly crosses through HCS in association with an equinoctial CIR ~65% of the time, and ~53% of all CIRs.

# Pseudo-Streamers + RM Effect GRACE A

Colorado Center for Astrodynamics Research

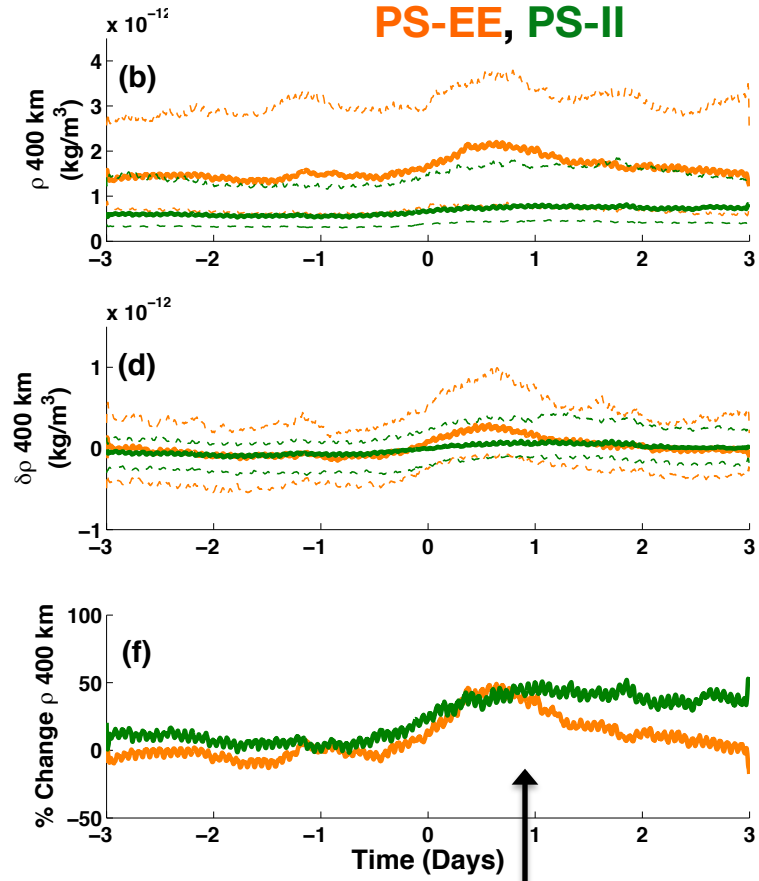
University of Colorado
Boulder, Colorado

## GRACE A Neutral Density: HS-IE, HS-EI



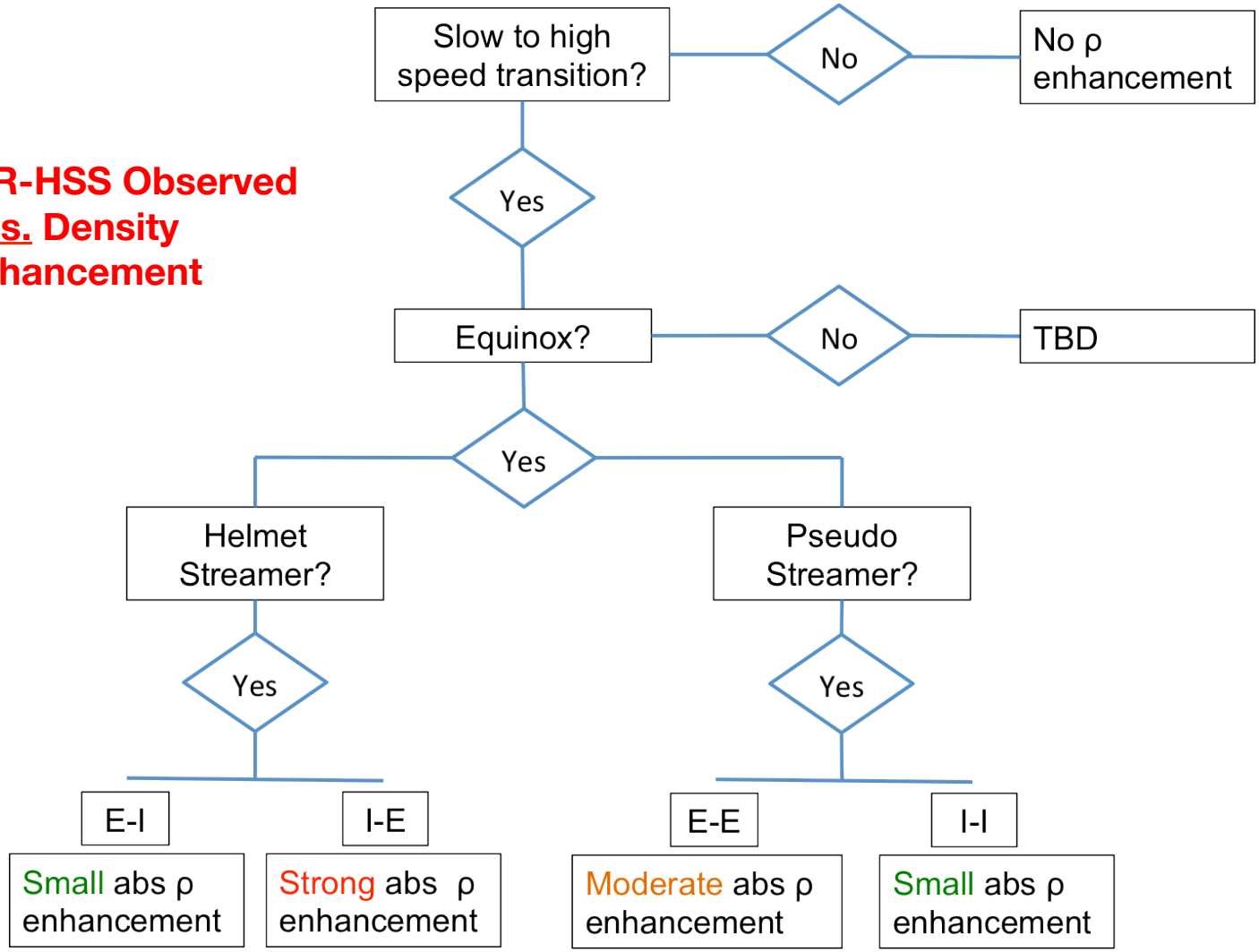

Calm

## GRACE A Neutral Density: PS-EE, PS-II

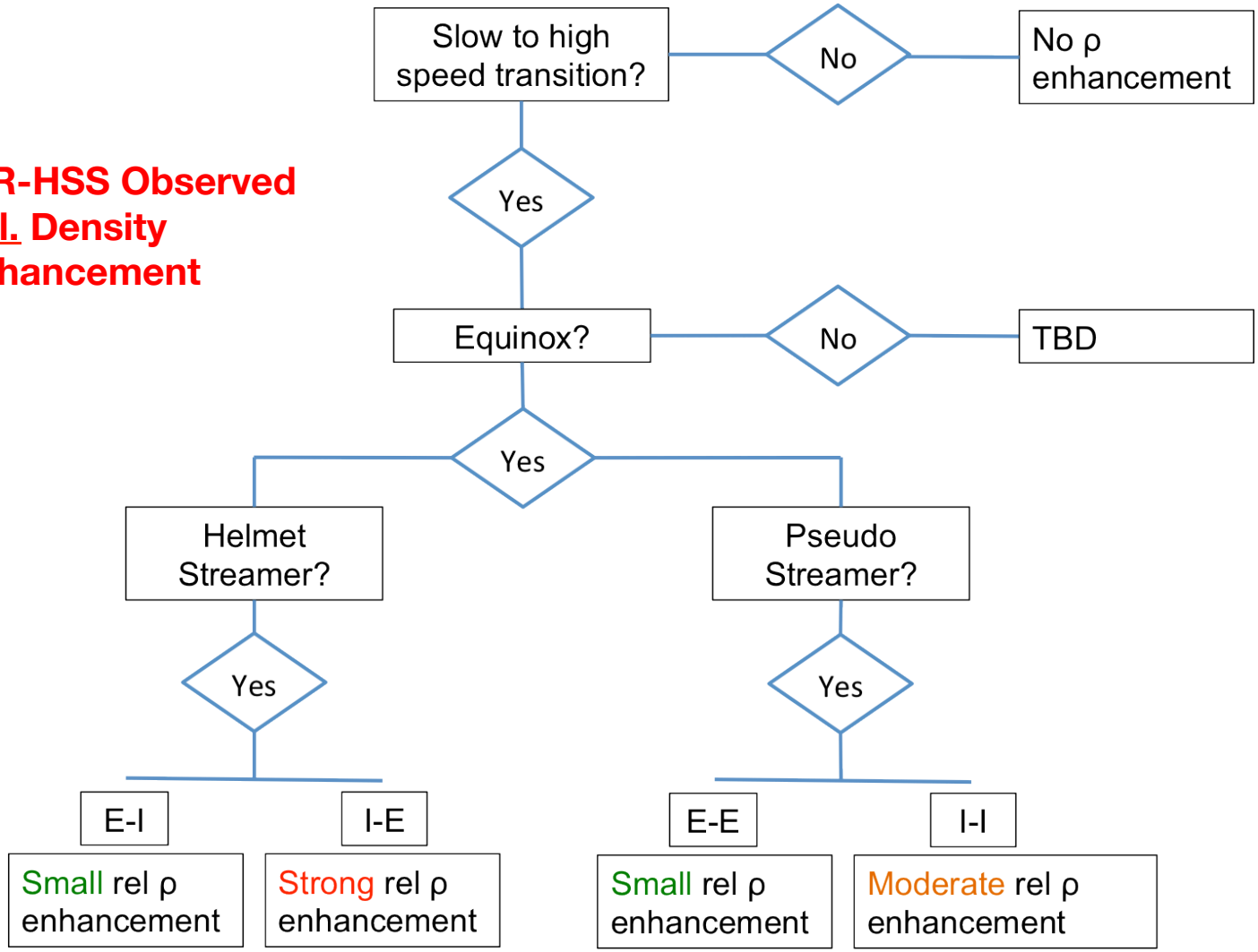



Counterintuitive shortened EE response

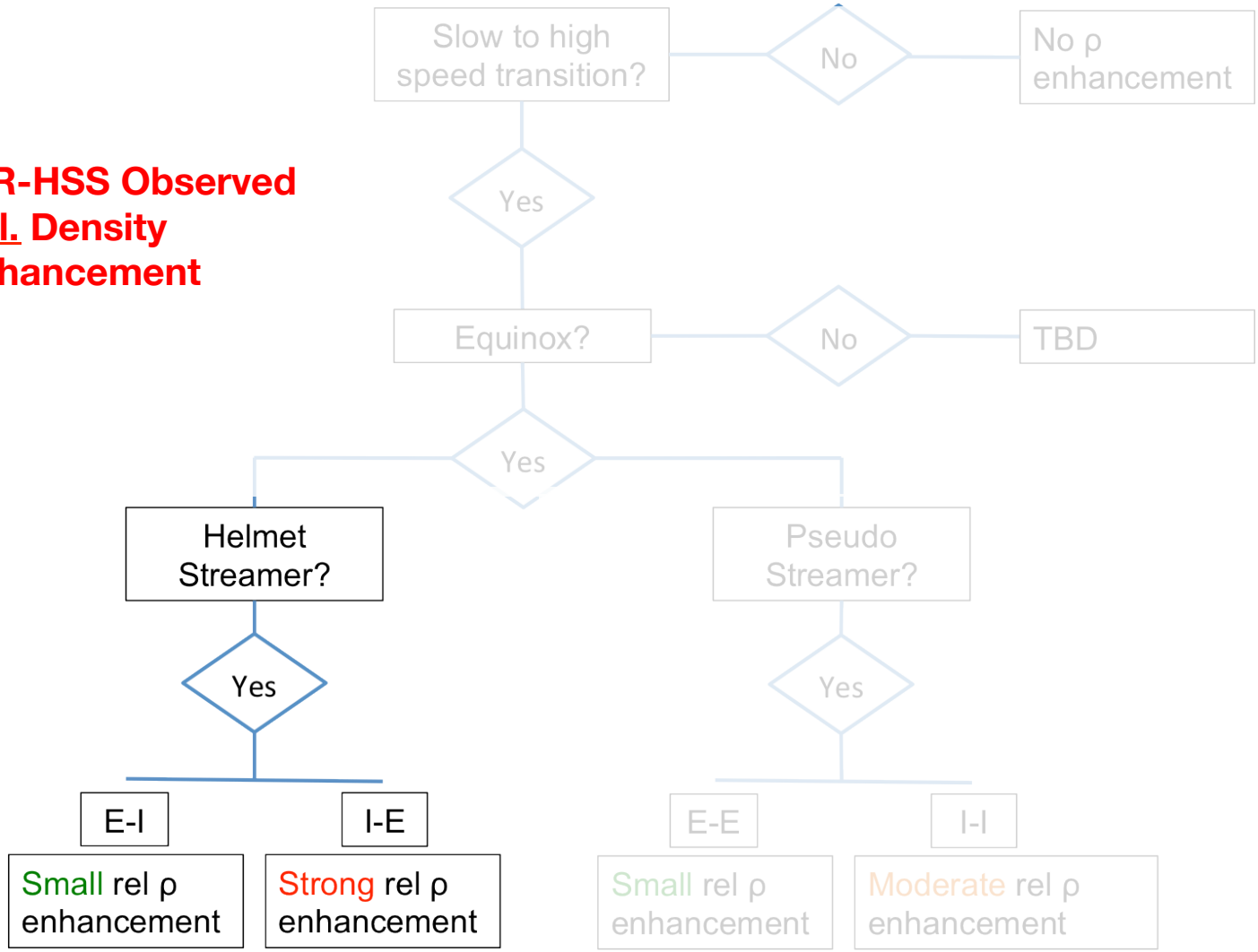
## CIR-HSS Observed Abs. Density Enhancement

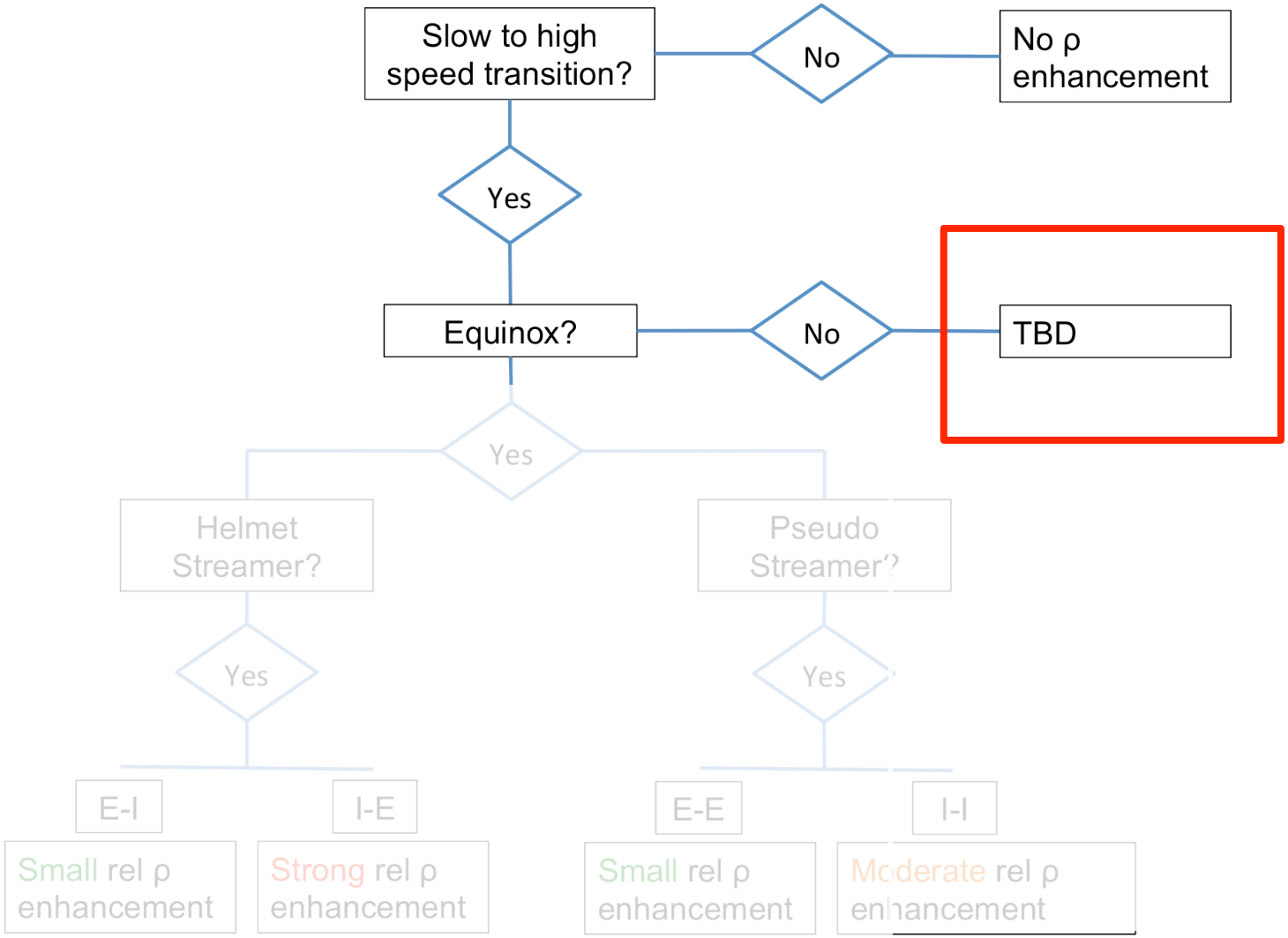


## CIR-HSS Observed Rel. Density Enhancement



# CIR-HSS Observed Rel. Density Enhancement




Slow to high speed transition?
No
No ρ enhancement
Yes
Equinox?
No
TBD
Yes
Helmet Streamer?
Pseudo Streamer?
Yes
Yes
E-I
I-E
E-E
I-I
Small rel ρ enhancement
Strong rel ρ enhancement
Small rel ρ enhancement
Moderate rel ρ enhancement