THE UNIVERSITY OF ALABAMA IN HUNTSVILLE

THE UNIVERSITY OF ALABAMA IN HUNTSVILLE
CSPAR
CENTER FOR SPACE PLASMA & AERONOMIC RESEARCH
THE DEPARTMENT OF SPACE SCIENCES

OBSERVATIONAL ANALYSIS OF TRANSIENT AND COHERENT STRUCTURES IN SPACE PLASMAS

Ph.D. Dissertation Defense
Jinlei Zheng
Advisor: Dr. Qiang Hu
Department of Space Science
University of Alabama in Huntsville
September 29th, 2017

OUTLINE

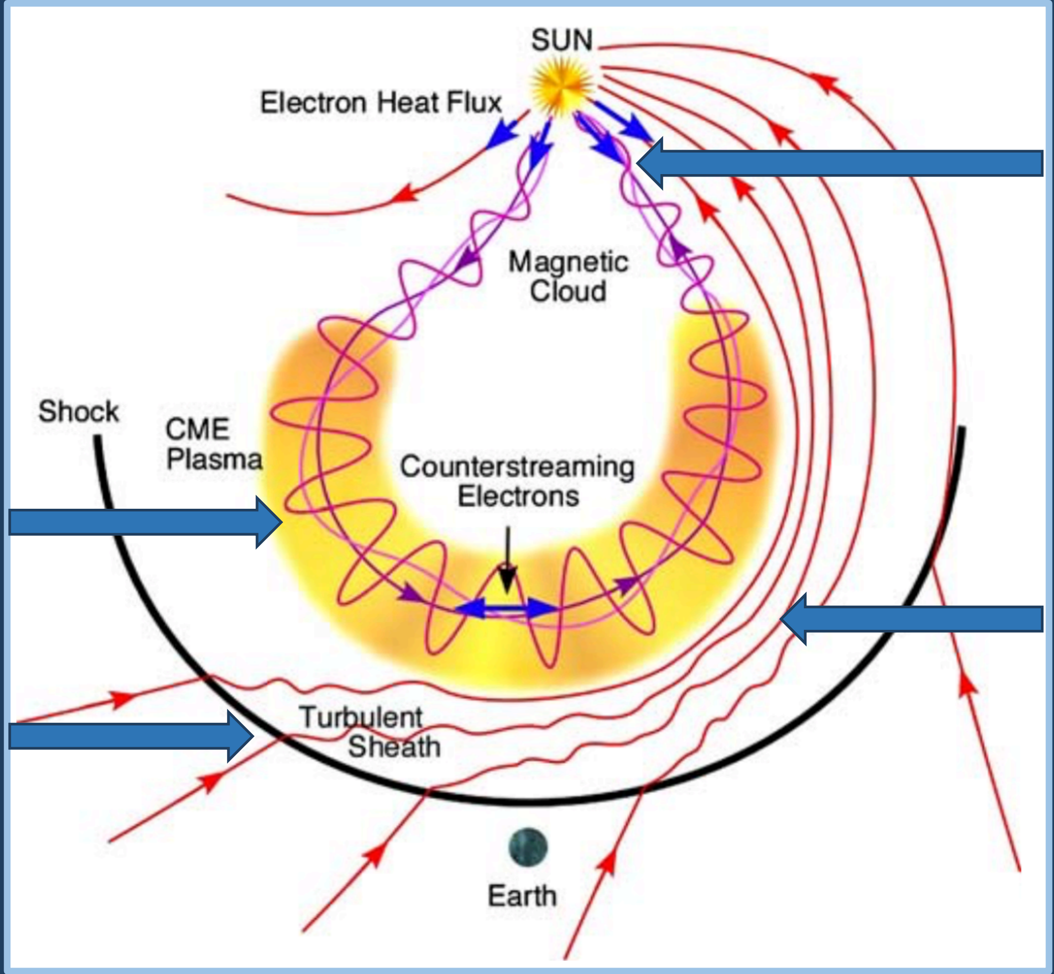
- Introduction to Small-scale Magnetic Flux Ropes (FRs)
- Grad-Shafranov (GS) Reconstruction Technique
- Automated Detection Algorithm Based on the GS Method
  - Algorithm
  - Online Database
- Statistical Analysis
  - Statistical Properties
  - Waiting Time Distribution Analysis
  - Location w.r.t Heliospheric Current Sheet (HCS)
  - Jz Distribution compared with MHD simulation
- Association between Small-scale Magnetic Flux Ropes and Interplanetary Shocks

INTRODUCTION

ICME SCHEMATIC

Magnetic Cloud Embedded

Shock at Leading Edge



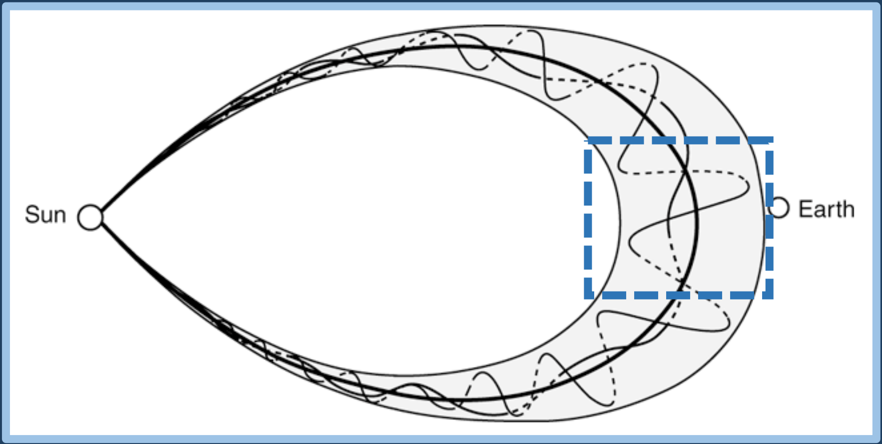
Two Roots Connected to the Sun

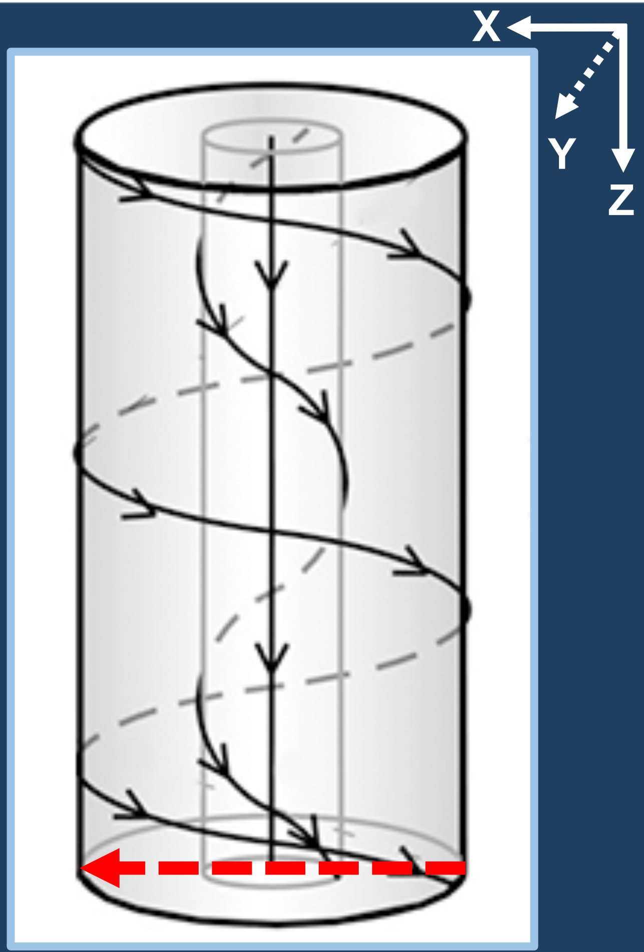
Turbulence and Shear Flows

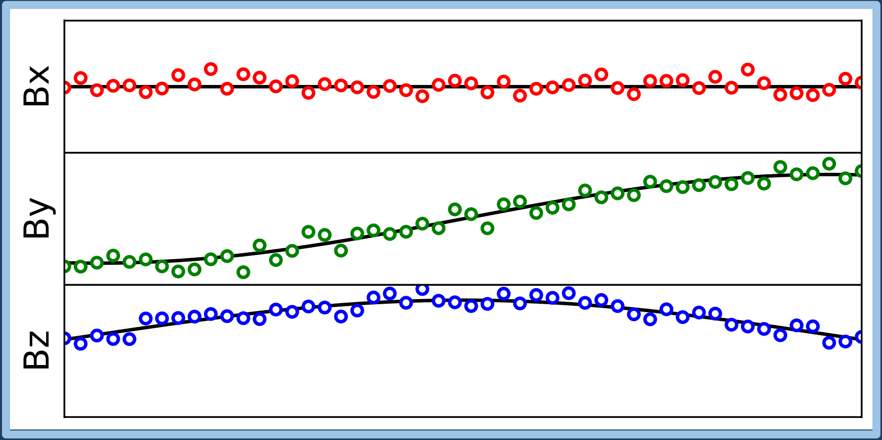
Current Sheets Vortices Plasmoids (Flux Ropes)

Zurbuchen and Richardson (2006)

INTRODUCTION



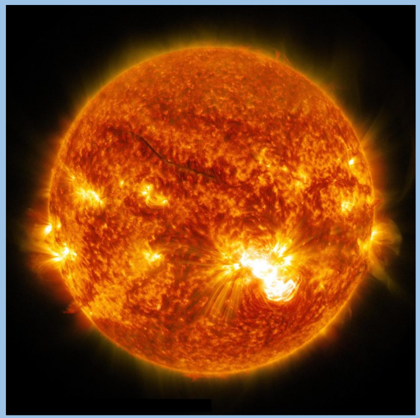




INTRODUCTION

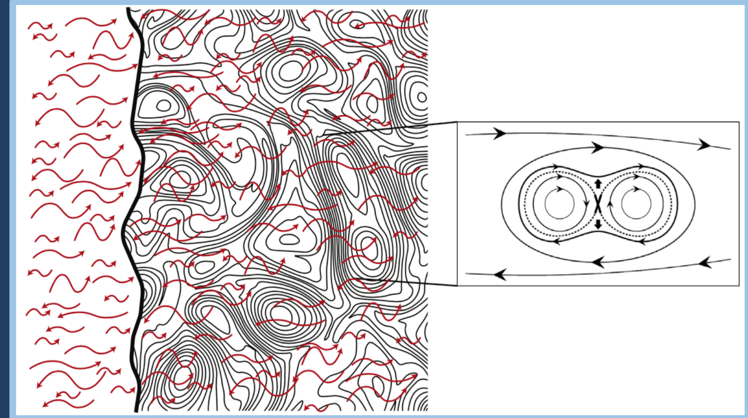
Large-scale Magnetic Flux Ropes	versus	Small-scale Magnetic Flux Ropes
Helical structure; $B_{FR} > B_{SW}$; $P_M > P_P$	$=$	Helical structure; $B_{FR} > B_{SW}$; $P_M \sim P_P$
R = 0.1 ~ 0.4 AU at 1AU	$\neq$	R = 0.001 ~ 0.01 AU at 1AU
Proton temperature depressed	$\neq$	Proton temperature varies
Ultra-low proton Beta (P_P/P_M)	$\neq$	Proton Beta (P_p/P_m) varies
Radial evolution exists	$\neq$	Radial evolution not obvious
Have counterstreaming electrons	$\neq$	Counterstreaming electrons varies
Solar activity cycle dependence	?	To be verified
Originate from the Sun	?	To be verified

INTRODUCTION



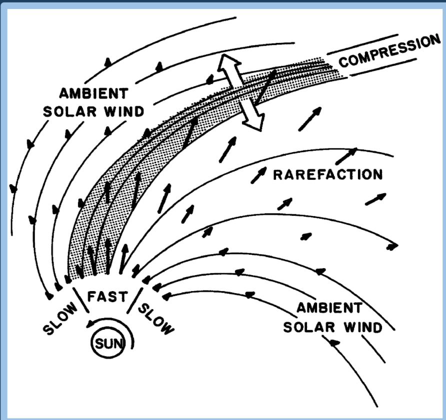
Magnetic Islands Downstream shocks

Coronal Mass Ejection (CME)



Heliospheric Current Sheet (HCS)

Co-rotating Interaction Region (CIR)



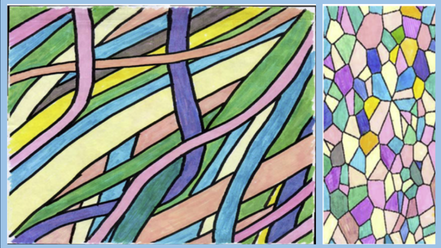
Zank et al. (2015); John Wilcox and Werner Heil; Pizzo (1978)

INTRODUCTION

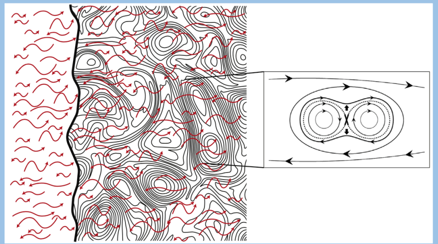
Why Do We Care about Small-scale Magnetic Flux Ropes?

Large Number and Ubiquitous → **Thousands Times more than MCs**

Are We in a Sea of Flux Ropes? →



Particle Acceleration in Flux Ropes →



Formation Mechanism Less Known → **Pre-existing? Reconnection?**

Origination Less Known → **Solar Origin? Created Locally?**

Geoeffectiveness → **Do They Trigger Substorms?**

Borovsky et al. (2008)

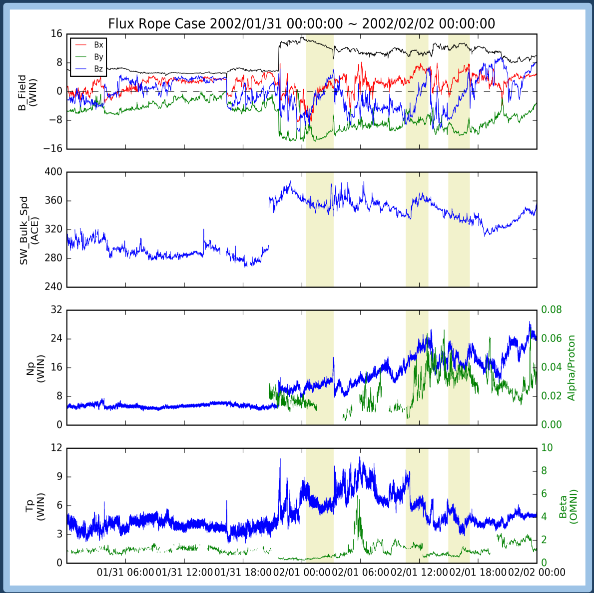
INTRODUCTION

Research Objectives

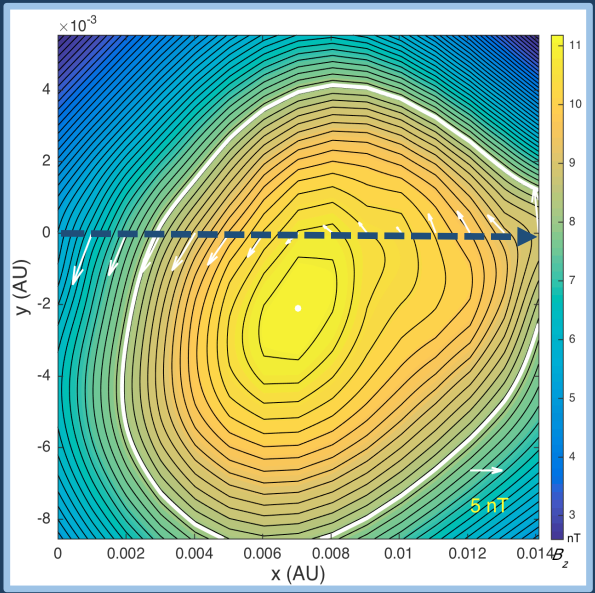
A Comprehensive Small-scale Magnetic Flux Rope Database

- Intuitive Understanding on FRs; Exam "Flux Rope Sea" Hypothesis
- Formation Mechanisms; Origination of FRs
- Association with Other Transients and Structures in Heliosphere
- Observational Evidence for Particle Acceleration Theories

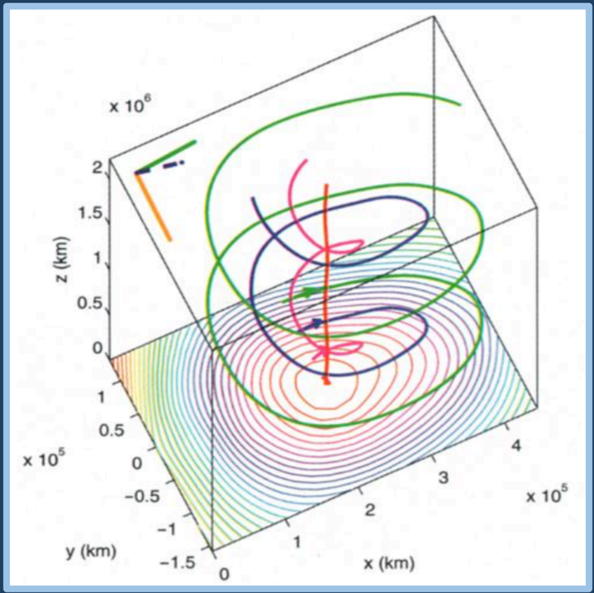
Grad-Shafranov (GS) Reconstruction Technique



1-D



2-D



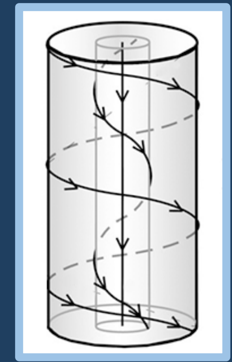
2.5-D

Sonnerup and Guo, (1996); Hau and Sonnerup, (1999); Hu and Sonnerup, (2001, 2002).

GS METHOD

$$\left.\begin{array}{l}\rho\dfrac{\partial \mathbf{v}}{\partial t} + \rho\mathbf{v}\cdot\nabla\mathbf{v} = \mathbf{j}\times\mathbf{B} - \nabla p + \rho\mathbf{g} \\ \mathbf{g} = 0 \qquad \mathbf{v} \equiv 0 \qquad \dfrac{\partial}{\partial t} = 0\end{array}\right\} \Rightarrow \boxed{\nabla p = \mathbf{j}\times\mathbf{B}}$$

$$\left.\begin{array}{r}\boxed{\nabla p = \mathbf{j}\times\mathbf{B}} \\ \dfrac{\partial}{\partial z} = 0 \\ \nabla\times\mathbf{B} = \mu_0\mathbf{j} \\ \mathbf{B} = \left[\dfrac{\partial A(x,y)}{\partial y}, -\dfrac{\partial A(x,y)}{\partial x}, B_z\right]\end{array}\right\}$$



$$\Rightarrow \boxed{\frac{\partial^2 A}{\partial x^2} + \frac{\partial^2 A}{\partial y^2} = -\mu_0\frac{dP_t}{dA} = -\mu_0 j_z(A)}$$

$A(x,y)$

Flux Function

$$P_t = p + \frac{{B_z}^2}{2\mu_0}$$

Total Transverse Pressure

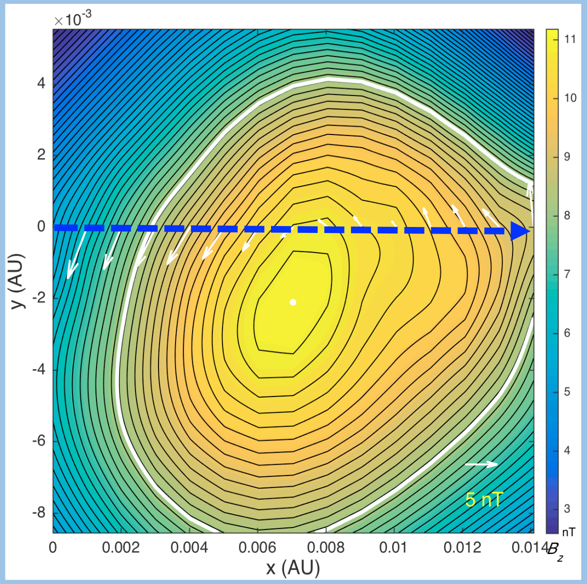
$dA(x,y) = 0$

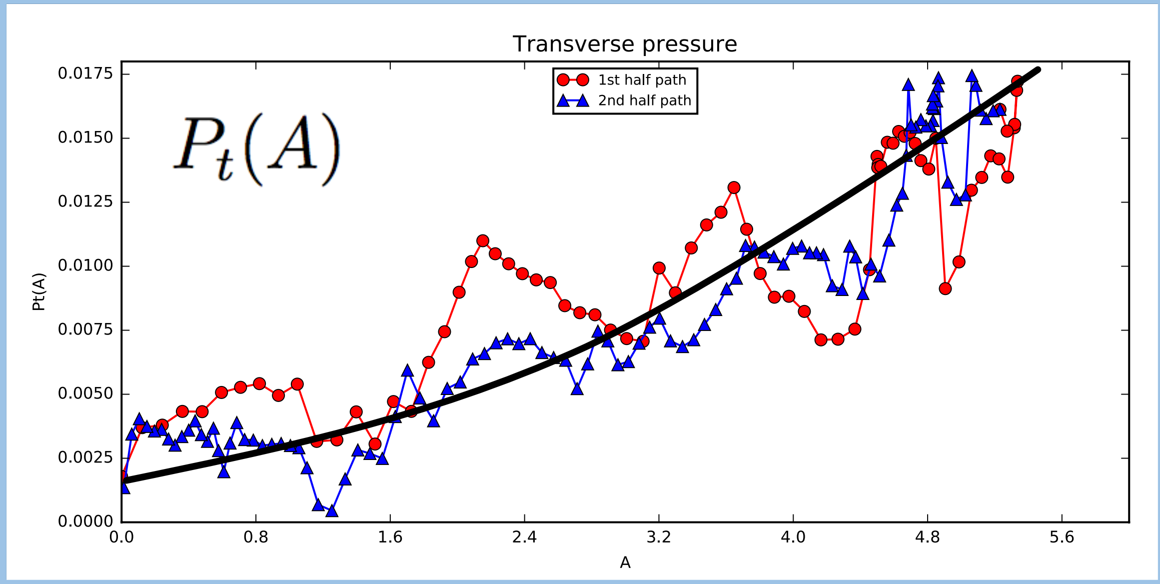
Flux Surface Constant

$P_t(A)$

Single Variable Single-valued Function

GS METHOD





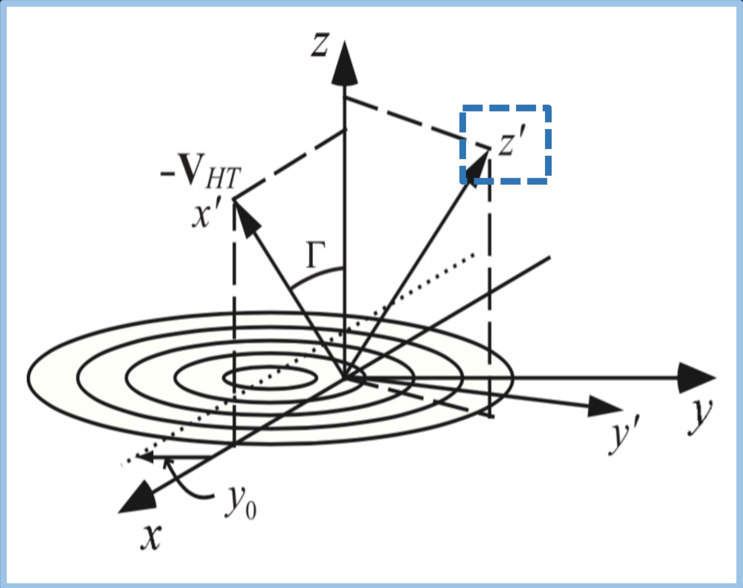
Spacecraft Pass Through the Cross-section of a FR

Pt(A) is Single-valued Function of A, and A is Field Line Constant. Pt(A) Curve Should be Double-folded.

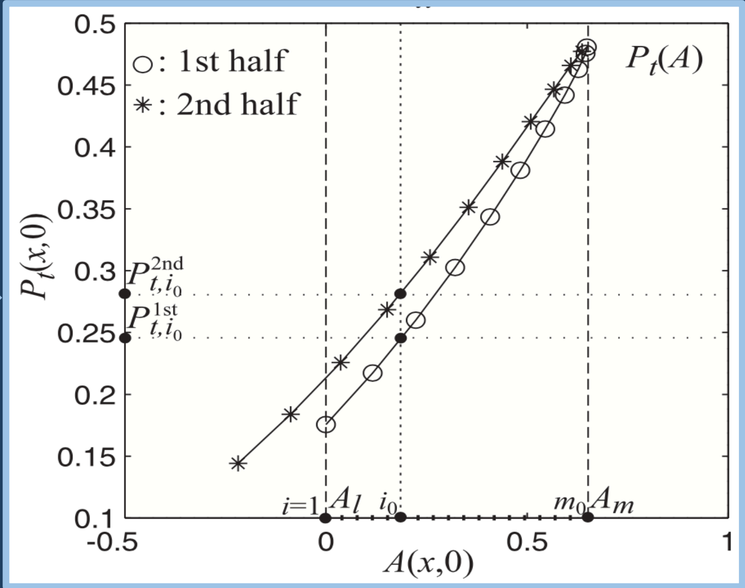
GS METHOD

Quasi-stationary Equilibrium ← de Hoffmann-Teller (HT) Frame

Flux Rope Axis Align with z-axis ← Find FR Axial Orientation



Misaligned



Hu and Sonnerup, (2002).

AUTOMATED DETECTION ALGORITHM

Flux Rope Reconstruction	versus	Flux Rope Detection	
Structure Must Be Transformed into de Hoffmann-Teller Frame			
Pre-determined Event Duration	$\neq$	Event Duration Unknown	A
Find Axial Orientation by Finding the Double-folded Pt(A) Curve	$\neq$	Axial Orientation Unknown Double-folded Pt(A) Not Guaranteed	B

A ← Set Different Detecting Window Width, Scan Data Multiple Iterations

B ← Set Metrics and Criteria to Evaluate the Quality of Double-folded Pt(A)

$$R_{dif} = [\frac{1}{2N}\sum_{i=1}^{N}((P_t)_i^{1st} - (P_t)_i^{2nd})^2]^{\frac{1}{2}}/|\max(P_t) - \min(P_t)|$$

Folding Residue

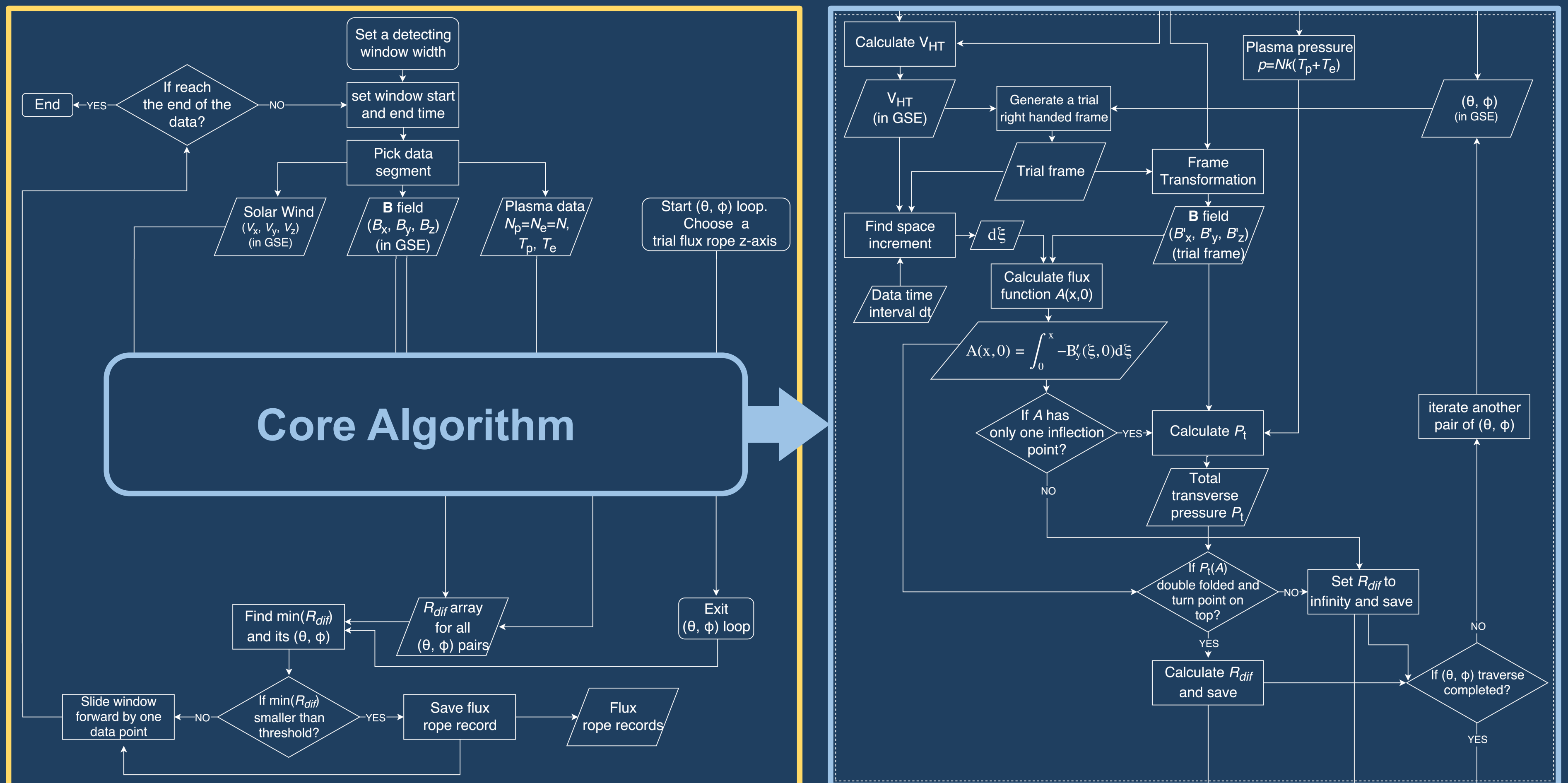
$$R_{fit} = [\frac{1}{L}\sum_{i=1}^{L}(P_t(x_i,0) - P_t(A(x_i,0)))^2]^{\frac{1}{2}}/|\max(P_t) - \min(P_t)|$$

Fitting Residue

THE UNIVERSITY OF ALABAMA IN HUNTSVILLE

AUTOMATED DETECTION ALGORITHM

THE UNIVERSITY OF ALABAMA IN HUNTSVILLE
CSPAR
CENTER FOR SPACE PLASMA & AERONOMIC RESEARCH
THE DEPARTMENT OF SPACE SCIENCES



AUTOMATED DETECTION ALGORITHM

Simplified Flow Chart of Core Algorithm

1. Select a detection window size
2. Find a co-moving frame (HT frame). Transform B field vectors to HT frame.
3. Apply trial-and-error process to find optimal z-axis orientation, based on the requirement of Pt ~ A being single-valued.
4. Check if the Pt ~ A curve has double-folded feature. If it does, take the z-axis with best single-valued Pt ~ A curve. If not, slide to next detection window.
5. If the difference of the two branches of double-folded section of Pt ~ A curve is small enough, label it as flux rope candidate.
6. Apply Walén test, and remove Alfvén waves from the candidates.
7. Clean the overlapped events, and save the candidates to event list.
8. Apply selection criteria on duration, residue, average magnetic field, etc., to refine the database.

AUTOMATED DETECTION ALGORITHM

Detection Metrics and Criteria

Duration	$\lvert\bar{B}\rvert$	R_{dif}	R_{fit}	Walén test slope
$9 \sim 361$ (minutes)	≥ 5 (nT)	≤ 0.12	≤ 0.14	≤ 0.3

The Number of Detected Small-scale Flux Ropes Each Year

Year	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006
Counts	2787	2878	4182	4454	4425	4203	5930	6086	4229	4017	2620
Year	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	**Total**
Counts	2040	1620	1076	2209	2731	3051	2658	3690	4987	4368	**74241**

AUTOMATED DETECTION ALGORITHM

THE UNIVERSITY OF ALABAMA IN HUNTSVILLE

THE UNIVERSITY OF ALABAMA IN HUNTSVILLE CSPAR CENTER FOR SPACE PLASMA & AERONOMIC RESEARCH THE DEPARTMENT OF SPACE SCIENCES

fluxrope.info

SMALL-SCALE MAGNETIC FLUX ROPE DATABASE

This is a small-scale magnetic flux rope database. The flux rope events in this database are detected by an automated program based on Grad-Shafranov reconstruction algorithm. The data used in detecting algorithm is from Wind spacecraft. The maximum detection window is 361 minutes. The minimum duration threshold is 9 minutes.

EVENT LISTS

1996	1997	1998	1999	2000	2001	2002
2003	2004	2005	2006	2007	2008	2009
2010	2011	2012	2013	2014	2015	2016

Author: Jinlei Zheng(jz0006@uah.edu) and Dr. Qiang Hu(qh0001@uah.edu)

We acknowledge partial support of NASA grant NNX12AH50G, and the ongoing support of SWEAP/SPP science mission.

Last updated: 2017/07/29

THE UNIVERSITY OF ALABAMA IN HUNTSVILLE

AUTOMATED DETECTION ALGORITHM

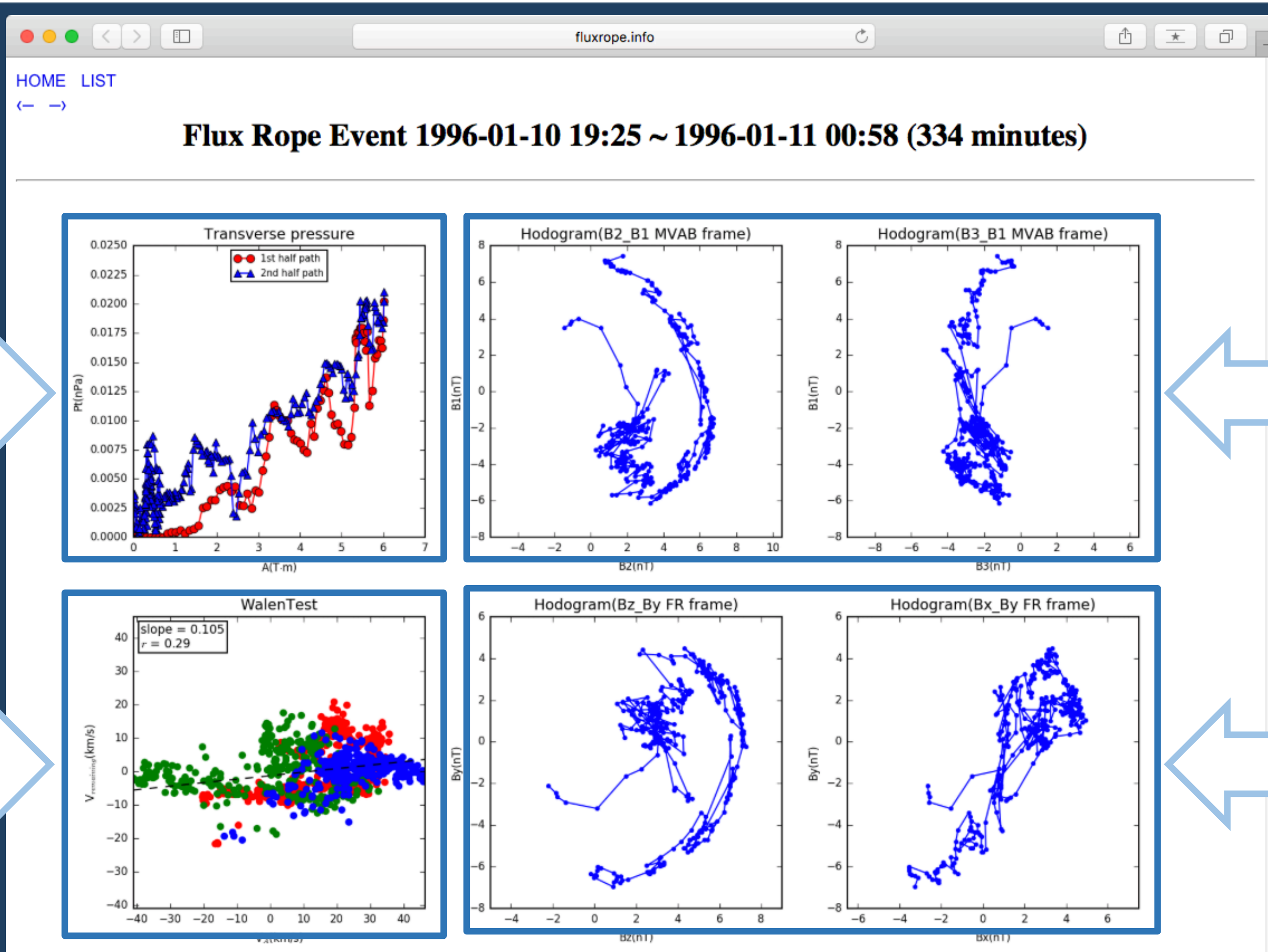
THE UNIVERSITY OF ALABAMA IN HUNTSVILLE CSPAR CENTER FOR SPACE PLASMA & AERONOMIC RESEARCH THE DEPARTMENT OF SPACE SCIENCES

fluxrope.info/1996/year1996.html

Small-scale Flux Rope Events in 1996

No.	Time Range	Duration	Residue	$\langle B \rangle$ (nT)	B_{max} (nT)	$\langle \beta \rangle$, $\langle \beta_p \rangle$	$\langle V_{sw} \rangle$ (km/s)	$\langle T_p \rangle$ (10^6K)	Orientation
1	1996/01/01 02:01 ~ 1996/01/01 02:56	56	0.1017	5.25	6.04	nan, 1.01	388	0.10	θ=60, ϕ=340
2	1996/01/01 03:27 ~ 1996/01/01 03:59	33	0.1284	5.47	6.00	nan, 0.65	388	0.09	θ=20, ϕ=220
3	1996/01/01 05:07 ~ 1996/01/01 05:45	39	0.1127	5.37	6.12	nan, 0.85	387	0.09	θ=50, ϕ=340
4	1996/01/01 05:47 ~ 1996/01/01 06:56	70	0.1336	5.42	6.25	nan, 0.91	389	0.08	θ=50, ϕ=280
5	1996/01/01 08:51 ~ 1996/01/01 09:37	47	0.1293	5.07	6.02	nan, 1.42	407	0.08	θ=70, ϕ=0
6	1996/01/01 09:40 ~ 1996/01/01 09:51	12	0.0812	5.17	5.79	nan, 1.05	409	0.07	θ=10, ϕ=40
7	1996/01/01 10:34 ~ 1996/01/01 10:53	20	0.1320	6.70	6.94	nan, 0.23	414	0.04	θ=50, ϕ=80
8	1996/01/01 11:39 ~ 1996/01/01 11:52	14	0.1098	5.60	5.89	nan, 0.58	411	0.06	θ=60, ϕ=80
9	1996/01/01 11:54 ~ 1996/01/01 12:02	9	0.1040	5.58	6.39	nan, 0.64	409	0.07	θ=70, ϕ=280
10	1996/01/01 12:09 ~ 1996/01/01 12:35	27	0.0903	5.74	6.16	nan, 0.61	407	0.07	θ=80, ϕ=240
11	1996/01/02 14:24 ~ 1996/01/02 14:42	19	0.0939	5.90	6.17	nan, 0.49	377	0.07	θ=10, ϕ=260
12	1996/01/02 17:58 ~ 1996/01/02 18:06	9	0.0564	7.73	9.16	nan, 0.55	386	0.07	θ=80, ϕ=320
13	1996/01/02 18:15 ~ 1996/01/02 18:23	9	0.1045	6.97	7.74	nan, 0.95	396	0.09	θ=60, ϕ=280
14	1996/01/02 18:24 ~ 1996/01/02 20:24	121	0.1343	9.49	11.70	nan, 0.37	425	0.09	θ=70, ϕ=280
15	1996/01/02 20:44 ~ 1996/01/02 20:57	14	0.0699	8.80	9.99	nan, 0.70	480	0.15	θ=50, ϕ=120
16	1996/01/02 20:59 ~ 1996/01/02 21:07	9	0.0733	5.55	6.50	nan, 3.56	491	0.28	θ=20, ϕ=320
17	1996/01/02 21:07 ~ 1996/01/02 21:17	11	0.0571	6.03	7.33	nan, 2.65	491	0.26	θ=60, ϕ=20
18	1996/01/02 21:48 ~ 1996/01/02 22:09	22	0.1045	6.78	7.53	nan, 1.22	459	0.21	θ=80, ϕ=160
19	1996/01/02 22:25 ~ 1996/01/02 22:33	9	0.0830	6.32	6.74	nan, 1.48	476	0.23	θ=70, ϕ=40
20	1996/01/03 00:39 ~ 1996/01/03 00:53	15	0.1056	5.72	6.37	nan, 1.53	489	0.19	θ=80, ϕ=100
21	1996/01/03 02:50 ~ 1996/01/03 02:59	10	0.1296	6.28	6.66	nan, 1.19	466	0.19	θ=60, ϕ=120
22	1996/01/03 03:27 ~ 1996/01/03 04:41	75	0.1149	6.82	7.99	nan, 0.77	456	0.15	θ=20, ϕ=100
23	1996/01/03 04:41 ~ 1996/01/03 04:50	10	0.1152	7.67	7.98	nan, 0.34	458	0.10	θ=10, ϕ=160
24	1996/01/03 04:51 ~ 1996/01/03 05:32	42	0.1253	7.70	8.06	nan, 0.33	460	0.09	θ=30, ϕ=20

AUTOMATED DETECTION ALGORITHM



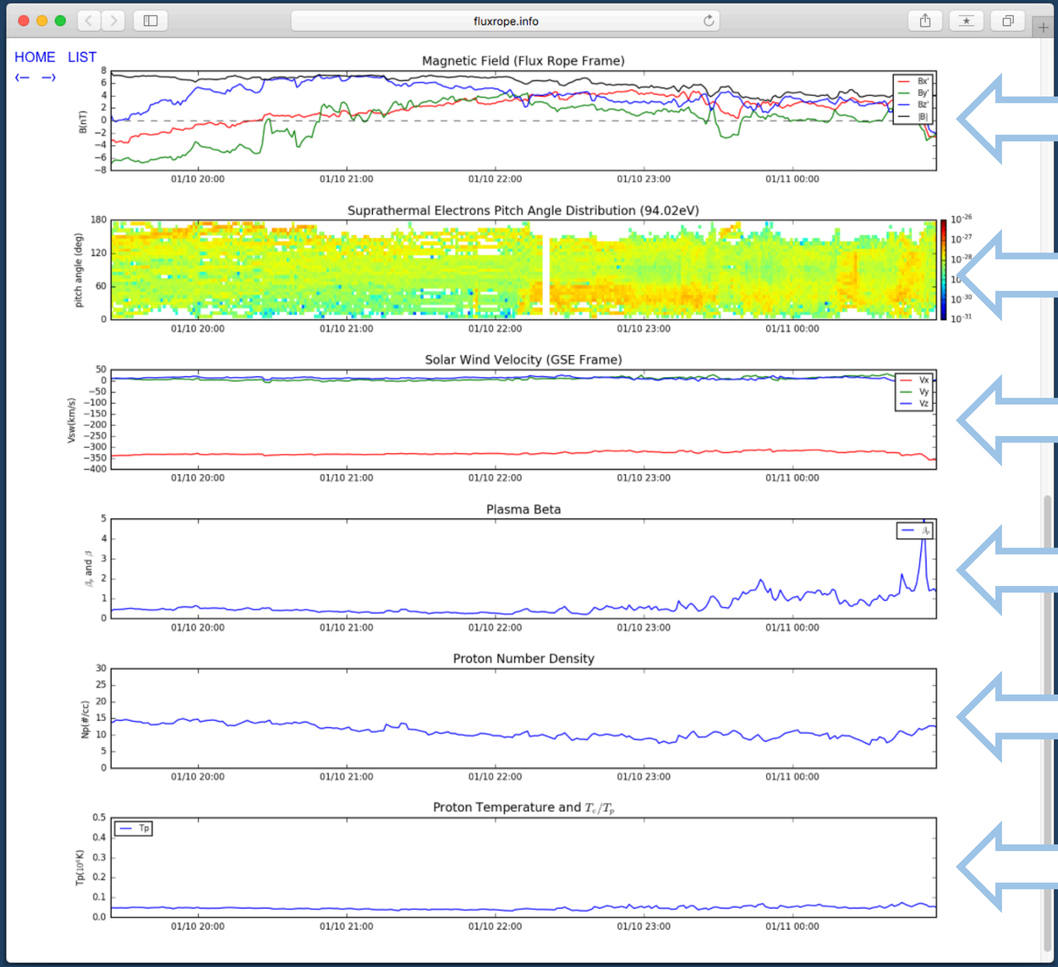
Pt(A) Curve

Hodogram MVAB

Walén test

Hodogram FR Frame

AUTOMATED DETECTION ALGORITHM



B Field

Electrons

Solar Wind

Beta

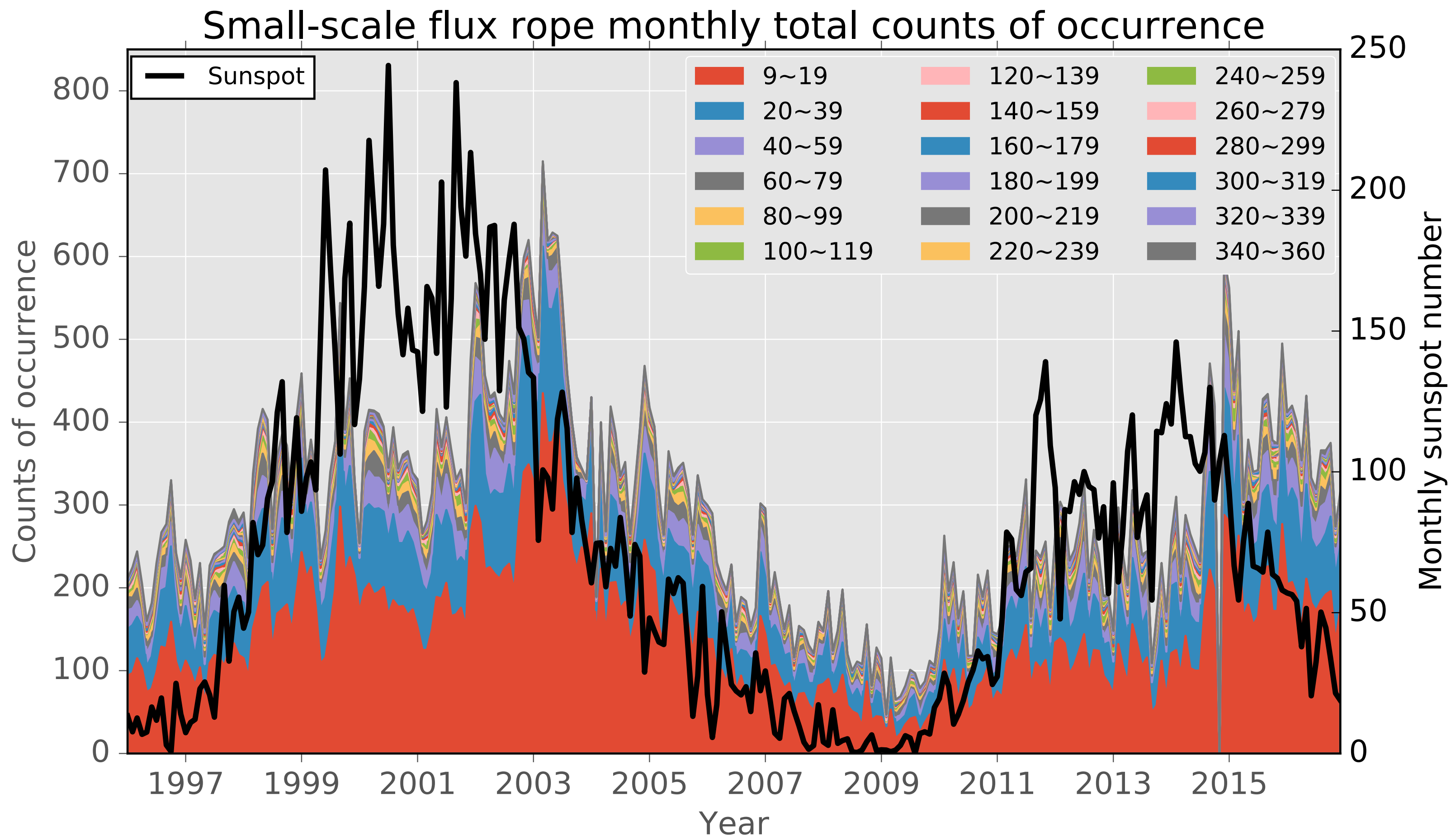
Np

Tp

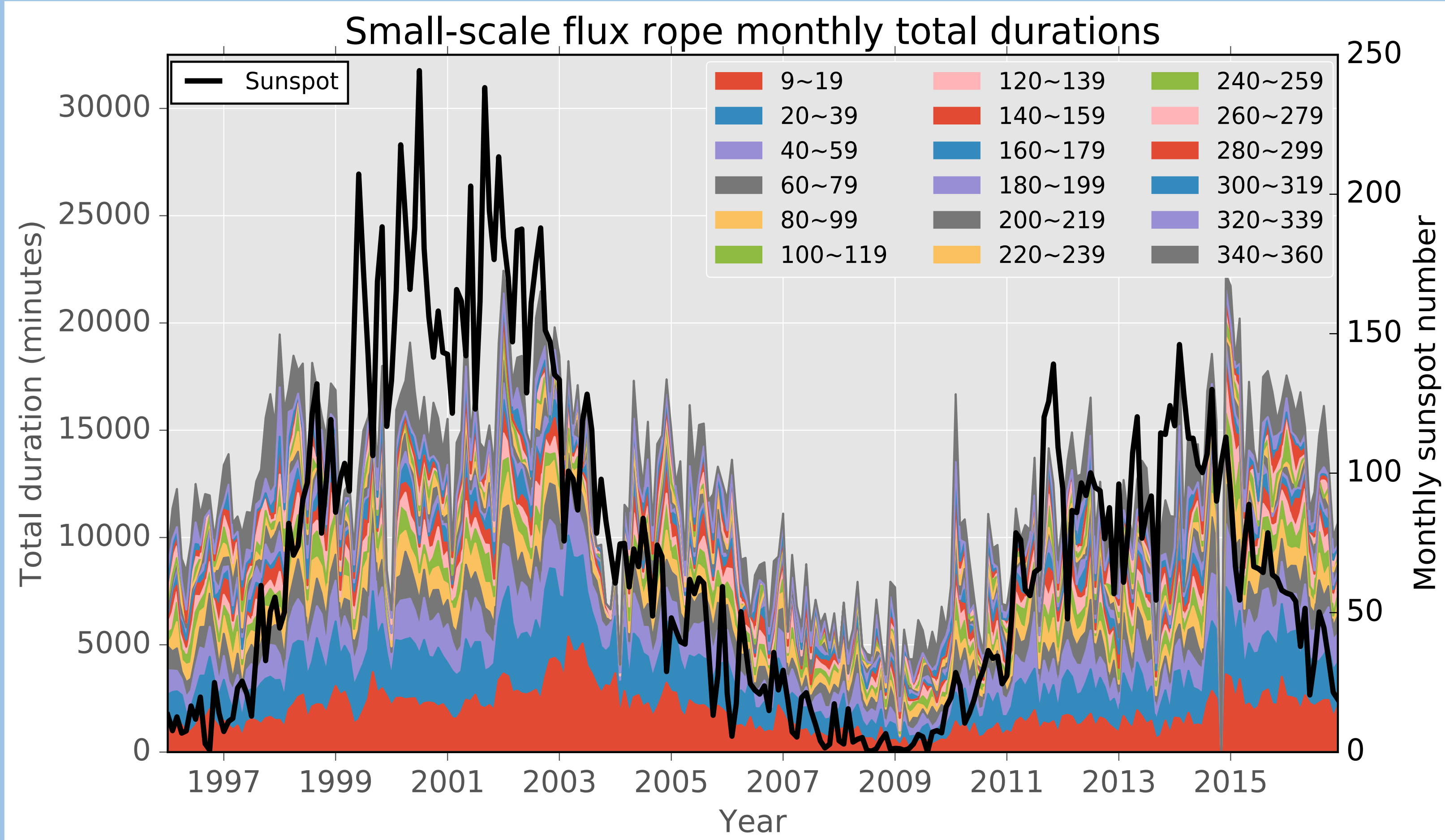
STATISTICAL ANALYSIS

- Occurrence Rate
- Axial Orientation
- Solar Wind Speed
- Duration
- Scale Size (Diameter)
- Proton Temperature
- Plasma Beta (Proton)
- Proton Number Density
- Days to Nearest HCSs
- Waiting Time Distribution

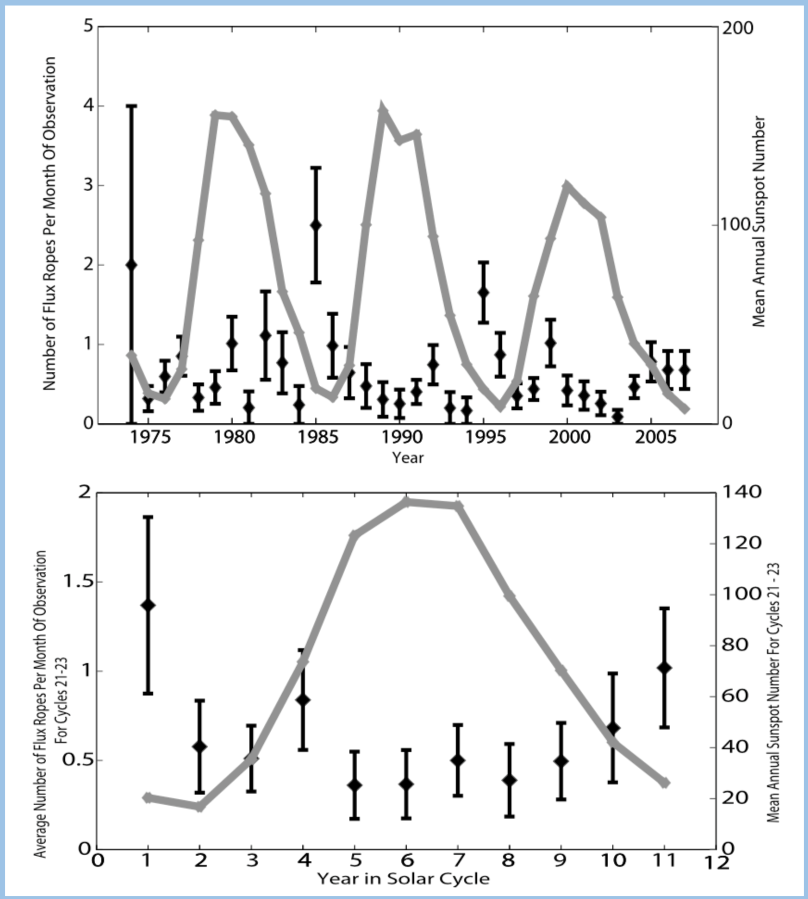
STATISTICAL ANALYSIS

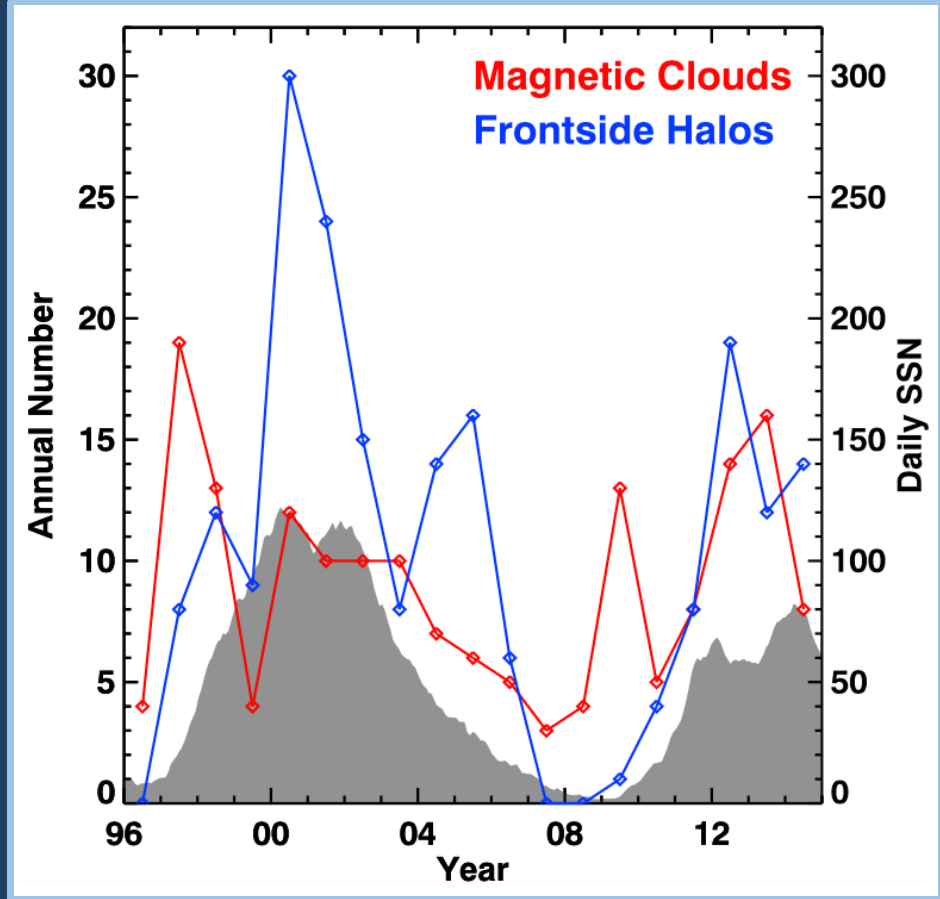


STATISTICAL ANALYSIS



STATISTICAL ANALYSIS

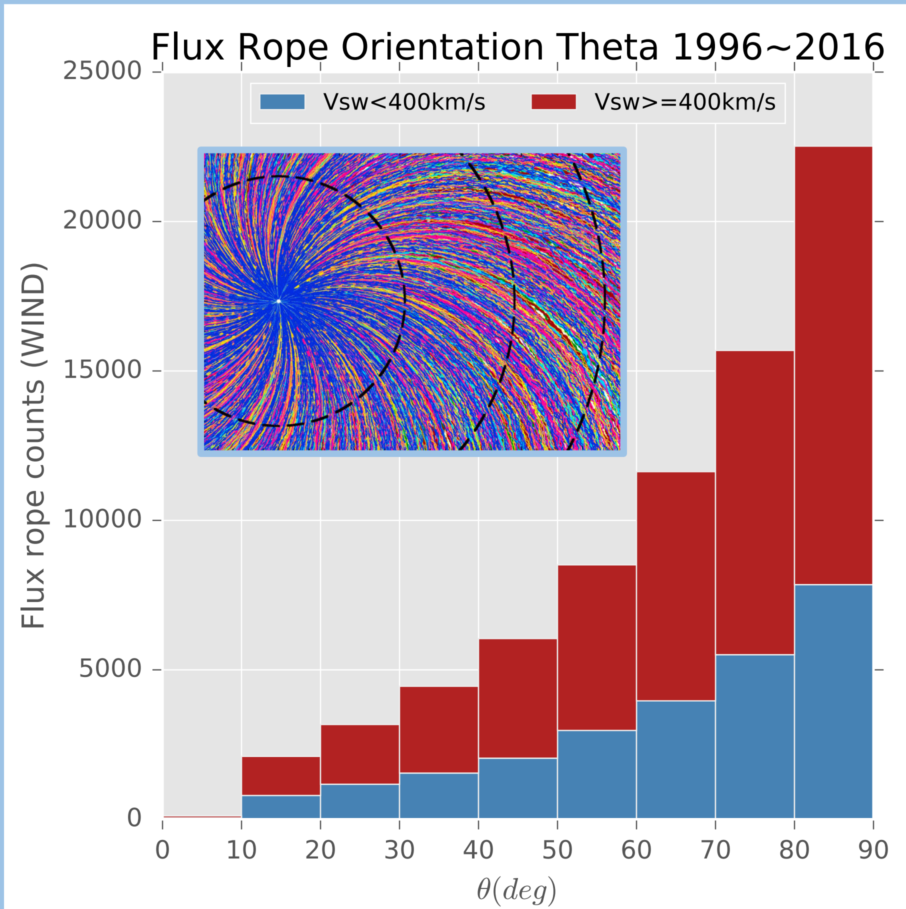


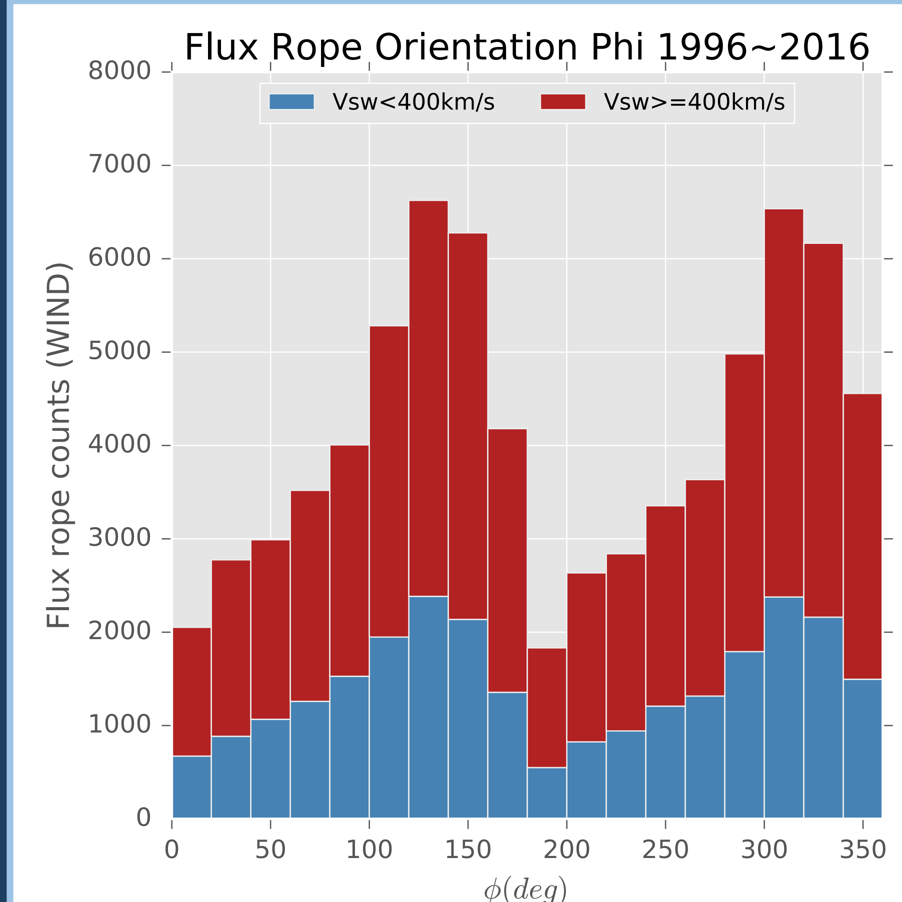


Cartwright and Moldwin (2010)

Gopalswamy et al. (2015)

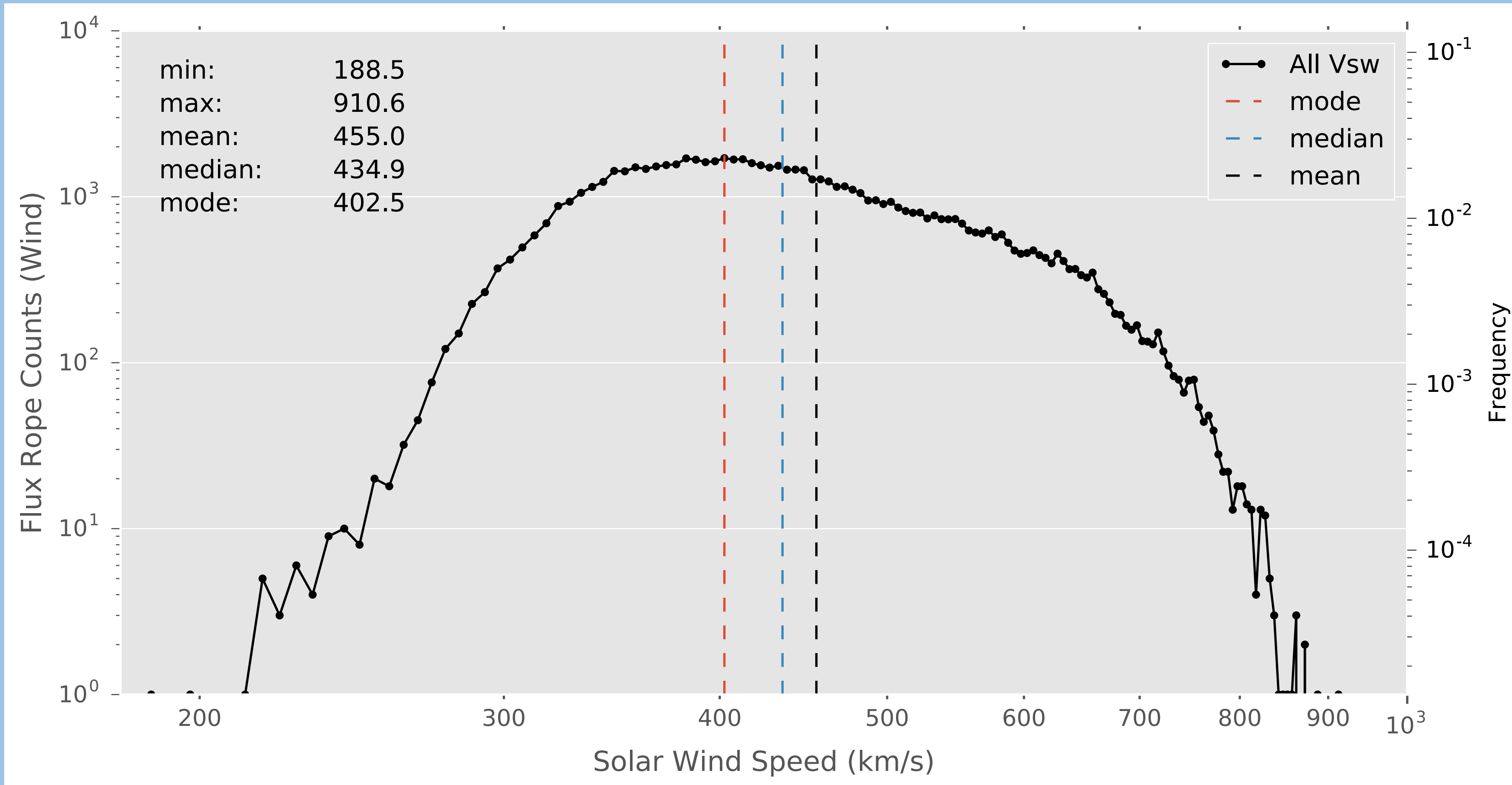
STATISTICAL ANALYSIS





Borovsky et al. (2010).

STATISTICAL ANALYSIS



STATISTICAL ANALYSIS